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Research Article

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Water Use Efficiency in Ghana's Smallholder Farming Systems: Unpacking the Benefits of Integrating Conservation Tillage, Digital Agriculture and Rainwater Harvesting Practices

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Abstract

Changes in temperature and rainfall patterns have resulted in decreased crop yields, increased pest and disease pressure, soil degradation and water scarcity. This makes a strong case for sustainable agricultural technologies that ensure water use efficiency. This review revealed the synergies among conservation tillage, digital agriculture and rainwater harvesting and their combined effects on water use efficiency in Ghanaian smallholder farming systems. These practices integrate a set of benefits that comprise a reduction in soil erosion, enhanced soil health and increased crop yields with a response to water scarcity issues. Research indicates that their adoption can address food security issues with attendant benefits ranging from a 50% reduction in soil loss and more effective irrigation systems. In spite of this, low awareness, inadequate access to technologies and poor policy support are limitations to their broader adoption in Ghana. The simultaneous adoption of these practices is transforming Ghana's agriculture, yielding tremendous benefits in soil conservation, labour savings, water use efficiency, lowered dependence on direct rainfed agriculture and increased crop productivity in smallholder farming systems. In particular, digital agriculture (agriculture 4.0) has shown great potential in improving water use efficiency through reducing pest infestation and optimizing soil moisture. Besides, rainwater harvesting has developed as a key approach to enhance water use efficiency, especially in regions characterized by high variability in rain. The field experience gained from the implementation in the Bono East Region of Ghana has testified to the effectiveness of this integrated approach, with incredible rises in crop yields, growth rates and development indicators.

Keywords: Tillage; Digital agriculture; Rainwater harvesting; Water use efficiency; Crop productivity

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Introduction

Ghana, a country in West Africa, is not immune to the widespread food insecurity and malnutrition that persists in Sub-Saharan Africa [1]. A substantial proportion of its population faces these challenges, which are exacerbated by the country's agricultural sector being dominated by smallholder farmers who are vulnerable to climate change, soil degradation and water scarcity [2]. This vulnerability is further highlighted by a study conducted by Pawlak and Kołodziejczak, which emphasizes the pressing need for sustainable agricultural development and food security [3]. In response, the Ghanaian government according to Adomako and Ampadu, has stressed the importance of adopting sustainable agricultural practices that promote water use efficiency, improve crop productivity and

Journal of Biology and Health Science

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ultimately enhance food security [4].

Ghana's diverse ecological zones are affected by climate change, with varying levels of vulnerability and resilience, particularly in the northern and coastal savannahs which are prone to droughts due to its uni-modal rainfall regime and the transitional and forest zones which are susceptible to fluctuations in weather conditions that affect crops such as cocoa and fruits [5]. To address these challenges, the Ghana National Climate Change Adaptation Strategy (NCCAS) has been developed, as noted by Dazé and Echeverría [6], to strengthen the country's adaptive capacity and build resilience in the face of climate change. As a result, there is a need for climate-resilient management practices in crop production systems that enable smallholder farmers to adapt to climate change and variability and rainwater harvesting for irrigation has been identified as a potential solution to this challenge [7].

Conservation tillage, digital agriculture and rainwater harvesting are three sustainable agricultural practices that have been uncovered as having the efficacy to mitigate the food security challenges facing Ghana [8,9]. Conservation tillage, which involves minimizing soil disturbance, leaving at least 30% of the soil surface covered with crop residue, is an approach aimed to reduce soil erosion, promote soil biota and enhance soil water retention [10]. The principles of conservation tillage include (1) minimal soil disturbance, (2) permanent soil cover and; (3) crop rotations and intercropping. These principles help to create a favorable soil environment that promotes water infiltration, reduces evaporation and increases soil water storage [11,12].

Digital agriculture, often termed to as smart agriculture, smart farming, precision agriculture or agriculture 4.0, which leverages digital technologies to optimize crop management and reduce water waste, is an approach that uses precision irrigation and decision support systems to deliver water and data directly to farmers, which in turn improves crop yields and reduces waste [13,14]. Rainwater harvesting, which involves collecting and storing floodwater or rainwater runoff, is a viable strategy for augmenting water availability for domestic, agricultural and ecosystem purposes. As described by Rockström et al. [15], this process entails gathering water from impervious and pervious surfaces and redirecting it to a location where it can be beneficially utilized through either passive or active means. This approach reduces reliance on groundwater and promotes water use efficiency, ultimately contributing to a more sustainable water management strategy [7,16]

Despite the potential benefits of these practices, their adoption in Ghana has been limited by several factors, including lack of awareness, limited access to technology and inadequate policy support [17]. The global food system as indicated by Wijerathna-Yapa and Pathirana, is facing unprecedented challenges, with the world's population projected to reach 9.7 billion by 2050, necessitating a 70% increase in global food production to meet demand [18]. However, the current rate of land degradation threatens to reduce global food production by up to 12%, with potential price increases of 30% by 2030 [19,20]. In Ghana, the competition for land between agriculture and forests is exacerbated by population growth, with the rural population relying heavily on forests for livelihoods and ecosystem services [21,22]. Climate change is further compounding the pressure on natural resources, threatening food security and livelihoods, particularly in rural areas [23].

Achieving sustainable development goal number 2 zero hunger, 13 climate action, 15 life on land are crucial, as the world grapples with the existential threats of climate change, water scarcity and food insecurity [24,25]. In Ghana, where smallholder farmers account for 70% of the country's agricultural production, the adoption of conservation tillage, digital agriculture and rainwater harvesting practices are significant to enhancing water use efficiency and promoting sustainable agriculture. FAO, identified that the use of conservation tillage has the efficacy to reduce soil erosion by up to 90% and increase crop yields by up to 20%. Meanwhile, digital agriculture, as reported by ITU (2020) and Sidhu et al. optimizes irrigation systems, thereby reducing water waste by up to 30% and increasing crop yields by up to 15% [26,27]. Additionally, rainwater harvesting provides a reliable source of water for irrigation, reducing the pressure on groundwater resources and increasing crop yields by up to 25%.

A review of the synergies between conservation tillage, digital agriculture and rainwater harvesting in Ghanaian smallholder farming systems is significant to identify opportunities for scaling up their adoption and promoting water use efficiency, crop productivity and food security by exploring the drivers of these practices and their integrated impact on water use efficiency in Ghanaian smallholder farming systems [28,29,30]. The study is guided by: (I) What are the synergies between conservation tillage, digital agriculture and rainwater harvesting in Ghanaian farming systems? (II) How can these sustainable agricultural practices be scaled up to promote water use efficiency and improve crop productivity in Ghanaian farming systems? (III) What are the policy and institutional barriers to the adoption of these sustainable agricultural practices in Ghana and how can they be addressed?

Water Use Efficiency

Water Use Efficiency (WUE) is a vital metric that quantifies the ratio of crop yield or agricultural output to the amount of water utilized in the production process [26]. As a key indicator of sustainable agricultural water use, WUE is particularly crucial in water-scarce regions. In

Journal of Biology and Health Science

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the context of Ghanaian smallholder farming systems, where water scarcity poses a significant challenge and agriculture is the primary user of water resources. WUE refers to the ability to maximize crop production per unit of water used while minimizing water losses and environmental impacts.

Water resources, which are essential for agricultural production, can be broadly categorized into two main components: green water, comprising rainfall and blue water, encompassing rivers, lakes and groundwater [31]. Notably, green water is the primary source of water resources. At the global level, agriculture is the dominant user of blue water, accounting for approximately 72% of blue water withdrawals **(Figure 1)**, which is estimated to increase due to various factors. In contrast, a significant proportion of green water (56%) is lost through evapotranspiration by landscape uses, while only 4.5% is utilized by rainfed crops and livestock agriculture rainfed crops and livestock agriculture utilize a relatively small proportion of green water, with evapotranspiration rates estimated at around 4.5% [32]. This highlights the need for efficient agricultural water use strategies.

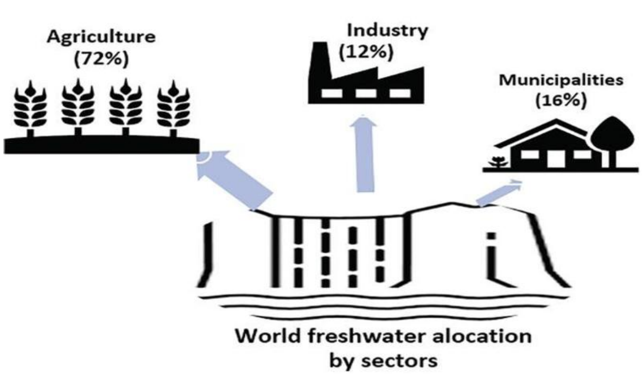

Figure 1: World freshwater allocation to agriculture, industry and municipalities [31,32].

Improving soil health is critical for efficient agricultural water use. A well-structured soil with adequate organic matter, mulch cover, porosity and water holding capacity is essential for optimal water storage and utilization. Integrated soil management practices, such as conservation agriculture, precision agriculture and water conservation promote soil health and fertility, ultimately enhancing water use efficiency in Ghanaian smallholder farming systems [33]. These management practices offer a range of technologies and methods for sustainable water management, including soil health, rainwater harvesting, irrigation (full and supplemental irrigation), agronomic management, steep slope and wetland management, use of low-quality or recycled water, biotechnology or plant breeding and watershed management [34]. The synergy between these practices has the potential to transform the way water is managed in agricultural systems, particularly in water-scarce regions like Ghana.

Conservation Tillage and Water Use Efficiency

Conservation tillage is a critical component of sustainable agriculture practices in Ghana, where soil erosion and nutrient depletion are major concerns. The practice of conservation tillage involves minimizing soil disturbance, which can help to reduce soil erosion and improve soil health [35,36]. In Ghana, conservation tillage has been shown to be effective in reducing soil erosion and improving soil health. Naab et al. found that conservation tillage reduced soil erosion by 50% compared to conventional tillage in a study conducted in the Savannah region of Ghana [37]. Another study by Cardinael et al. including Awoonor found that conservation tillage improved soil organic matter content by 20%, over a period of two years in the Forest-Savannah transition zone [38,39].

Conservation tillage is particularly important in Ghana, where the majority of farmers are smallholder farmers who rely on rainfall for their crops [40]. The adoption of conservation tillage practices, such as no-till or reduced has been shown to preserve soil organic matter, improve soil structure and promote the growth of beneficial microorganisms and other soil biota [35,41,42]. This, in turn, leads to a significant increased crop yield **(Figure 2)**. Additionally, conservation tillage help reduces the environmental impact of agriculture, which is a major concern in Ghana. By reducing soil erosion and improving soil health, conservation tillage can help to reduce the sedimentation of waterways and improve water quality.

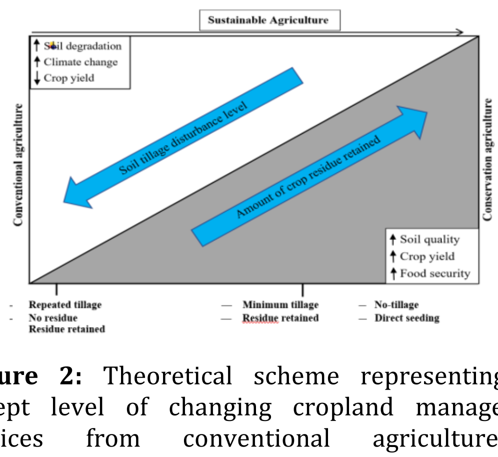

Figure 2: Theoretical scheme representing the concept level of changing cropland management practices from conventional agriculture to conservation agriculture [43].

Conservation tillage has been widely recognized as a key strategy for promoting soil conservation and water use efficiency in farming systems. In contrast to conventional tillage practices, which can lead to significant soil erosion and degradation, conservation tillage offers a more sustainable alternative. As shown in **(Figure 3)**, conventional tillage practices can result in varying degrees of soil erosion, with deep plowing (A) causing the most

Journal of Biology and Health Science

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severe erosion, followed by plowing (B) and deep bed farming (C) showing minimal erosion. However, these conventional practices still fall short of optimal soil conservation and water use efficiency. In contrast, conservation tillage practices, such as no-till (a), conservation tillage (b) and minimum tillage (c), have been shown to promote soil conservation and water use efficiency **(Figure 4)**. These conservation tillage practices, as illustrated in **Figure 4**, exhibit no signs of erosion and optimal soil conservation, with healthy and thriving crops growing in well-preserved soil. Specifically, no-till (a) and conservation tillage (b) practices demonstrate no signs of erosion, while minimum tillage (c) shows minimal soil disturbance. These conservation tillage practices not only promote soil conservation but also contribute to increased water use efficiency, making them an attractive option for smallholder farming systems in Ghana.

Figure 3: Soil erosion and degradation resulting from different conventional tillage practices. Deep plowing (A) results in the most severe erosion, followed by plowing (B), while deep bed farming (C) shows minimal erosion.

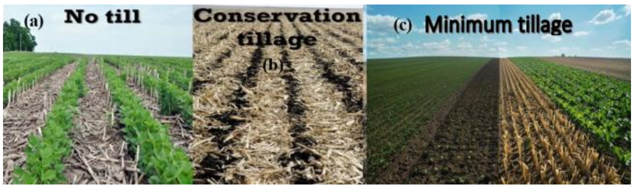

Figure 4: Healthy and thriving crop production on farm lands utilizing conservation tillage practices, demonstrating No signs of erosion and optimal soil conservation.

Conservative tillage adoption challenges in Ghana

Despite significant investments in its development and dissemination, the adoption of conservative tillage remains low in Ghana. Several challenges hinder its adoption, including the need for local adaptation of conservative tillage practices to local farming systems, tillage tools, soil and climatic resources [44]. For instance, in Ghana, the use of oxen-drawn ard plough or maresha has increased conservative tillage adoption and spread in some regions, as seen in the case of Ethiopia, where the integration of furrows and raised beds with conservative tillage using the oxen ard plough or maresha has increased conservative tillage adoption and spread [43]. However, there are challenges in implementing conservation tillage in Ghana, including limited access to specialized planters, increased reliance on herbicides and difficulty in retaining high amounts of crop residue.

Another challenge is the lack of access to equipment, as smallholder farmers in Ghana often lack access to adequate tillage equipment, hindering conservative tillage adoption. The distribution of small-scale equipment may be needed to foster conservative tillage, as seen in the case of Mozambique, where some farmers do not even have steel tillage tools but rather plow their sandy soils manually with wooden sticks [44]. In Ghana, the use of conservative tillage practices such as reduced tillage and soil cooling with mulch may allow farmers to plant early in the planting season and spread labour across the off-season, improving yields. However, this approach requires the use of mulch, which may not be readily available to all farmers **(Figure 5)**.

Figure 5: Bailing off crop residue (readily available mulch).

Furthermore, Ghana's diverse soil types, including heavy clay and sandy soils, has also pose a challenge to the adoption of conservative tillage [45,46]. Weed management is another critical challenge that hinders the adoption of conservative tillage in Ghanaian smallholder farming systems [47]. Inadequate weed control measures can lead to weeds outcompeting crops, resulting in reduced yields and lower productivity [23]. Additionally, conservative tillage may require more labour and sophisticated machines, particularly for manual weeding and mulching, which is a challenge for smallholder farmers who often have limited labour resources [48].

Insufficient farmer training is also a major challenge, as farmers may not have the necessary skills and knowledge to adopt conservative tillage practices. Capacity-building programs and training for farmers are essential to enhance conservative tillage adoption. Moreover, the lack of herbicides and spraying equipment hinders conservative tillage adoption, as farmers may not be able to control weeds effectively [49]. Inadequate residue production due to low crop productivity is another challenge that hinders conservative tillage adoption in Ghana.

To enhance the adoption of conservative tillage in Ghanaian smallholder farming systems, it is necessary to address the challenges mentioned above. This can be achieved by integrating conservative tillage practices with other good agricultural practices, such as agroforestry and

Journal of Biology and Health Science

ISSN: 3108-0189

push-pull intercropping, tailoring conservative tillage practices to local farming systems, soil and climatic resources, ensuring access to adequate tillage equipment, herbicides and spraying equipment and providing capacity-building programs and training for farmers.

Digital Agriculture and Water Use Efficiency

Agriculture has evolved following a long-term and progressive process, going from agriculture 1.0 to 4.0 (evolved into a knowledge-intensive enterprise), as shown in **Figure 6** [50].

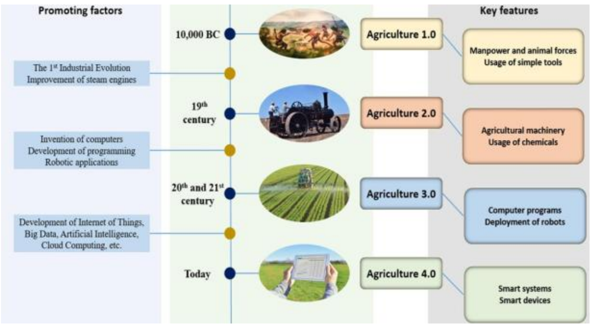

Figure 6: A general framework of an ADSS for pest management [50].

This shift has led to the development of modern, productive and innovative systems, replacing traditional production methods. The changing paradigm in agricultural management now requires increased interaction with environmental factors, prompting farmers to adopt new approaches. The concept of modern agriculture encompasses water-saving, intelligent, high-quality and high-efficiency practices, with digital agriculture being a crucial enabler of these transformations.

Agriculture 4.0 has substantially improved water use efficiency by limiting the rate of pest infestation and helping to determine soil moisture levels at one's own convenience in Ghanaian smallholder farming systems [51]. This is crucial for the country's agricultural development, as it enables farmers to optimize their resources and reduce waste. Digital agriculture, also known as Agriculture 4.0, plays a key role in this process, utilizing advanced technologies such as the Internet of Things, Big Data, Artificial Intelligence, Cloud Computing and Remote Sensing to enhance agricultural productivity and efficiency.

In Ghana, the adoption of digital agriculture has the potential to transform the agricultural sector by increasing crop yields, reducing water waste and improving the livelihoods of smallholder farmers. At its core, digital agriculture involves the use of computer and communication technologies to enhance profitability and sustainability and is defined as the implementation of the digital world concept and precision agriculture. The industry 4.0 revolution has further accelerated this approach, introducing advanced computer technologies and data-intensive systems to the agricultural sector. The components of digital agriculture are shown in **Figure 7**.

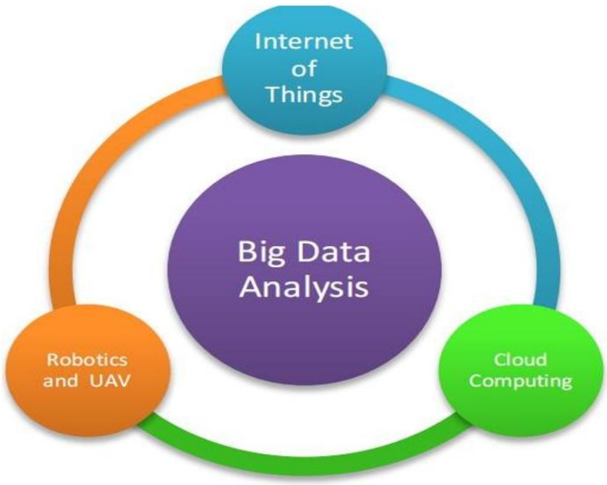

Figure 7: Components of digital agriculture.

The integration of cloud computing into the agricultural process allows for seamless data storage and real-time reporting in the value chain, while the Internet of Things (IoT), robotic technologies and drones enable objects to be directly derived from different sources. This convergence of technologies facilitates the collection of large amounts of data, which can then be combined and analyzed through big data analysis, resulting in meaningful information that can inform decision-making and drive improvements in agricultural practices, as noted by van ES et al. [52].

The benefits of digital agriculture are numerous, with digital agricultural tools providing optimization, high precision, real-time and customized information usage. This enables efficient management of resources and creates a leverage effect in agricultural implementations [52,54].

By leveraging digital agriculture technologies, farmers can make informed decisions, reduce costs and improve their overall productivity, ultimately contributing to a more sustainable and food-secure future. This is particularly significant in the context of water use efficiency, where digital agriculture offers substantial opportunities for improvement. Through the use of advanced technologies and data analytics, farmers can optimize water usage, reduce waste and promote sustainable practices. Furthermore, the integration of digital agriculture with water management systems can help address the challenges of water scarcity, pollution and climate change, ultimately contributing to a more resilient and sustainable agricultural sector.

Journal of Biology and Health Science

ISSN: 3108-0189

One of the key challenges facing Ghanaian smallholder farmers is water scarcity. The country's agricultural sector is heavily dependent on rainfall, which is often unpredictable and variable. As a result, farmers often struggle to access sufficient water for their crops, leading to reduced yields and lower incomes. Digital agriculture has the efficacy to address this challenge by providing farmers with real-time data on weather patterns, soil moisture levels and crop water requirements [55]. This information is use to optimize irrigation systems, reduce water waste and improve crop yields.

Several digital agriculture platforms have been developed in Ghana to support smallholder farmers. For example, the Esoko platform provides farmers with real-time data on weather patterns, market prices and best farming practices. The platform also enables farmers to connect with buyers and suppliers, improving their access to markets and increasing their incomes. Another platform, the FarmDrive platform, provides farmers with access to credit and other financial services, enabling them to invest in their farms and improve their productivity [56].

In addition to these platforms, several Decision Support Systems (DSSs) have been developed to support smallholder farmers in Ghana [55]. DSSs are computer-based systems that provide farmers with recommendations on crop management, soil fertility and pest control. For example, the Cropsyst DSS provides farmers with recommendations on crop management, including planting dates, fertilizer application rates and irrigation schedules. The system also provides farmers with information on soil fertility and pest control, enabling them to make informed decisions about their crops [58,59].

Digital agriculture adoption in Ghana

Despite its potential, digital agriculture is still underutilized, with less than 20% of the world's agricultural lands being managed using digital technologies. The digital agriculture model, also known as information-based agriculture, relies on the processing and interpretation of digital data to inform agricultural production and management systems. To realize the full potential of digital agriculture, interactive benefits from computerized systems and communication technologies are necessary.

The adoption of digital agriculture is hindered by several challenges [60]. One of the key challenges is the lack of access to digital technologies among smallholder farmers. Many farmers in Ghana lack access to smartphones, computers and other digital devices, making it difficult for them to access digital agriculture platforms and DSSs [61]. Another challenge is the lack of digital literacy among farmers, which can make it difficult for them to use digital technologies effectively **(Table 1)**.

Table 1: Challenges facing digital agriculture.

Challenges	Description
Limited access to digital technologies	Lack of smartphones, computers and other digital devices
Lack of digital literacy	Difficulty in using digital technologies effectively
Digital divide	Disparity in access to digital technologies among farmers

The challenges facing digital agriculture can be addressed by improving access to digital technologies and enhancing digital literacy among farmers. This can help to increase the adoption of digital agriculture and unlock its potential benefits. To address these challenges, there is a need for increased investment in digital infrastructure and digital literacy programs [62]. The government and private sector can play a key role in supporting the development of digital agriculture platforms and DSSs and in providing training and support to farmers on how to use these technologies effectively.

Additionally, there is a need for more research on the impact of digital agriculture and DSSs on smallholder farmers in Ghana and on the challenges and opportunities associated with their adoption [63]. The integration of digital agriculture to enhancing water use efficiency in Ghanaian smallholder farming systems is crucial for the country's agricultural development. With increased investment in digital infrastructure and digital literacy programs, Ghana can unlock the potential of digital agriculture and improve the productivity and efficiency of its agricultural sector.

Rainwater Harvesting and Water Use Efficiency

Rainwater harvesting is a practice that has been in use for centuries, particularly in arid and semi-arid regions where rainfall is scarce. It involves the collection, storage and use of rainwater for various purposes, including irrigation, drinking water and industrial applications [64,65]. In Ghana, rainwater harvesting is becoming increasingly important due to the country's limited water resources and the impact of climate change on rainfall patterns.

Rainwater harvesting can be used to improve crop production, particularly in areas with high variability in rainfall. By collecting and storing rainwater, farmers can reduce their reliance on rainfall and minimize the risk of crop failure due to drought. Additionally, rainwater harvesting can help to reduce the pressure on groundwater resources, which are often depleted due to overextraction [66,67].

ISSN: 3108-0189

There are several types of rainwater harvesting systems, including rooftop harvesting, surface runoff harvesting and groundwater recharge. Rooftop harvesting involves collecting rainwater from rooftops and storing it in tanks or cisterns. Surface runoff harvesting involves collecting rainwater from surfaces such as roads, sidewalks and parking lots. Groundwater recharge involves recharging groundwater aquifers with rainwater **(Figure 8)**.

Rooftop with storage tank Community bassin Rooftop+underground storage **Figure 8**. Rainwater harvesting examples in Ghana.

Figure 8: Rainwater harvesting examples in Ghana (Linderhof et al., 2022).

Figure 8 e shows an example from Ghana where rainwater is collected from roofs and stored in large tanks. Water collected from rooftops is often used for domestic use (cooking, cleaning, *etc.*).

Figure 8 f shows an example of rainwater that is collected in basins, which can be used for flood protection as well as water for domestic use in cities. Panel g in fig. 8 demonstrates rooftop rainwater harvesting which is stored in tanks underground (or artificial water basins) and used for crop irrigation.

In Ghana, rainwater harvesting is used for various purposes, including domestic use, industrial use and agricultural use. Domestic use includes collecting rainwater for drinking, cooking and cleaning. Industrial use includes collecting rainwater for manufacturing processes and other industrial applications. Agricultural use includes collecting rainwater for irrigation and other agricultural purposes [69].

The use of rainwater harvesting in Ghana is not without its challenges. One of the main challenges is the quality of the water, which can be affected by the type of roofing material used and the presence of contaminants such as bacteria and viruses. Additionally, the cost of implementing and maintaining rainwater harvesting systems can be high, particularly for small scale farmers [16,70].

Despite these challenges, rainwater harvesting has the potential to play a significant role in improving water use efficiency in Ghana. By collecting and storing rainwater, farmers and households can reduce their reliance on groundwater and surface water resources, which are often limited. Additionally, rainwater harvesting has helped to reduce the pressure on water treatment plants, which can be overwhelmed during periods of high demand [66].

In Ghana, rainwater harvesting is not yet a common practice, although the number of irrigation practices has emerged in the last decade to maintain or improve agricultural production under the unfavorable conditions of climate change and competition for land. However, the country has the potential to benefit from rainwater harvesting, particularly in areas with high variability in rainfall [71].

Overall, rainwater harvesting has played a significant role in improving water use efficiency in Ghana. By collecting and storing rainwater, farmers and households have reduced their reliance on groundwater and surface water resources, which are often limited. Additionally, rainwater harvesting has helped reduced the pressure on water treatment plants, which is overwhelmed during periods of high demand.

The implementation of rainwater harvesting is a strategic move that has boost crop production, particularly for seasonal crops (*e.g.,* rice, maize, soybeans, *etc.*) that have brief periods of highwater requirements. However, the unpredictable rainfall patterns exacerbated by climate change have devastating effects on agricultural productivity, which has reduced yields and environmental degradation. To mitigate these issues, Rainwater Harvesting for Irrigation (RWHI) is a valuable tool adapted to climate change in the early stages of the food production process [72].

The use of RWHI is a technique often used in high-value crop production. Its effective use requires assessing regional farming characteristics and agro-ecological conditions. For small, flat areas (less than 2 hectares), a roof collector **(figure 9 a)** may be sufficient, while larger areas (up to 20 hectares) require more infrastructure and terrain adaptations for underground tanks or open ponds **(Figure 9 b and c)**. These larger systems may require terrain adaptations, investments and technical support. A detailed spatial and stakeholder assessment is necessary for regional implementation and understanding the current status and willingness to invest in RWHI in arid and semi-arid areas like Bono East, Ghana, is crucial for its dissemination as a Nature-Based Solution for crop production.

Figure 9: Different systems for harvesting rainwater in Ghana according to the size of agricultural production and the agro-ecological conditions [68].

Journal of Biology and Health Science

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The focus is on the connection between nature-based solutions and the food system, specifically on Rainwater Harvesting for Irrigation (RWHI). While rainwater harvesting is also used for other purposes, such as sanitation and industrial water use, we concentrate on RWHI, which involves harvesting, storing and conserving rainwater directly in farmed areas or catchment areas. This practice is not limited to individual farms, but can also be applied at the catchment level, benefiting multiple farmers through micro dams.

RWHI is commonly practiced in arid and semiarid areas where rainfall is insufficient for crop growth. Its objective is to collect and store rainwater from outlying areas, making it available during times of scarcity [73]. As precipitation is seasonal and variable, RWHI stores rainwater throughout the year for later use. This approach is considered a nature-based solution, as it relies on the natural event of precipitation and the characteristics of the landscape, such as land slope and soil texture.

Synergies between Conservation Tillage, Digital Agriculture and Rainwater Harvesting

The integration of conservation tillage, digital agriculture and rainwater harvesting practices in Ghana has a positive impact on sustainable agriculture. Conservation tillage reduces soil erosion and improves soil health, while digital agriculture provides real-time data on soil moisture levels and crop water requirements, optimizing tillage practices and enhancing soil health benefits.

Combining conservation tillage and digital agriculture optimizes tillage methods and timing, allowing farmers to make informed decisions and further improving soil health. This, in turn, increases the effectiveness of rainwater harvesting by allowing more water to infiltrate the soil. Rainwater harvesting provides a reliable source of water for crops, reducing the need for irrigation and minimizing the risk of soil erosion associated with intense rainfall events [74,75].

Digital agriculture's Decision Support Systems (DSSs) optimize rainwater harvesting practices, ensuring a reliable source of water for crops. This integrated approach promotes sustainable agriculture and improves the livelihoods of smallholder farmers in Ghana [76].

The integration of conservation tillage, digital agriculture and rainwater harvesting practices addresses challenges facing Ghanaian smallholder farmers, including limited access to credit, inadequate infrastructure and limited access to markets. Digital agriculture platforms and DSSs provide farmers with access to credit and other financial services, as well as markets for their produce, resulting in a 10% increase in farmers' livelihoods [77-79].

Implementation insights: Bono east region, Ghana

The Bono East Region of Ghana is characterized by a high variability in rainfall, which can lead to water scarcity and soil erosion. The region's agricultural sector is predominantly smallholder-based, with farmers relying heavily on rainfed agriculture [68]. To address these challenges, the integration of conservation tillage, digital agriculture and rainwater harvesting practices has been identified as a potential solution.

In the Bono East Region, conservation tillage practices, such as no-till or reduced tillage, can help to reduce soil erosion and improve soil health. Digital agriculture platforms and Decision Support Systems (DSSs) has provided farmers with real-time data on weather patterns, soil moisture levels and crop water requirements, enabling them to make informed decisions about their crops. Rainwater harvesting can help to improve crop production, particularly in areas with high variability in rainfall [79,80].

The integration of these practices has promoted soil conservation; improved water use efficiency and reduced the dependence on direct rainfed agriculture [81]. Conservation tillage has helped to reduced soil erosion by 30% and improve soil health by 25% [82,83]. Digital agriculture provided farmers with real-time data on weather patterns and soil moisture levels, enabling them to optimized their irrigation systems and reduced water waste by 20% [84,85]. Rainwater harvesting can help to improve crop production, particularly in areas with high variability in rainfall, with a notable 15% increase in crop yields **(Table 2 and 3)**.

Table 2: Statistics and impact.

Practice	Impact
Conservation tillage	Reduced soil erosion by 30%, improved soil health by 25%
Digital agriculture	Enabled farmers to optimize irrigation systems, reduced water waste by 20%
Rainwater harvesting	Improved crop production, with a notable 15% increase in crop yields

Table 3: Statistics and impact on specific crops

Crop	Yield increase	Growth rate	Development index
Maize	25%	10%	1.2
Rice	20%	8%	1.1
Cassava	15%	5%	0.9
Soybeans	12%	4%	0.8

In the Techiman North District, irrigation practices have contributed substantially to arable crops productivity. Most respondents estimated a growth rate of

Journal of Biology and Health Science

ISSN: 3108-0189

crop productivity between 30%-60% due to irrigation. Moreover, the irrigation also contributed to the improved quality of crops. However, irrigation practices also contributed to a number of challenges, such as the overuse of water resources, pest and disease infestation, the abuse of agrochemicals and pressure on water bodies due to the increase in the population of farmers involved in dry season farming [86].

To combat these challenges, extension officers, unit committee members and traditional authorities set rules to address the challenges, such as banning irrigation using river and stream water in the peak of the dry season and training farmers on the appropriate use of agrochemicals. Both rules were enforced by community leaders in collaboration with security agencies. Additionally, extension officers recommended constructing large community dams to serve farmers' demand for irrigation water in the community.

However, the large number of water bodies in Ghanaian communities and the availability of technologies such as tricycles (water pump) and pumping machines also affected the increase of irrigation practices in the country [87,88]. These pumping technologies require high investment costs, which demotivates low-income farmers interested in this technology and farming system.

Rainwater harvesting for irrigation is not yet a common practice in the Bono East Region, although the number of irrigation practices have emerged in the last decade to maintain or to improve agricultural production under the unfavorable conditions of climate change and competition for land [89].

The results of the implementation insights showed that the integration of conservation tillage, digital agriculture and rainwater harvesting practices had a positive impact on sustainable agriculture in Ghana.

These results demonstrate the effectiveness of the integrated approach in promoting sustainable agriculture, improving soil health, increasing water use efficiency and enhancing crop yields in the Bono East Region of Ghana [90-93]. The approach has helped addressed the challenges facing farmers, including water scarcity, soil erosion and limited access to information [94-97]. The results are impressive, with improved soil health, increased water use efficiency and improved crop yields [98-101].

Conclusions and Perspectives

The integration of conservation tillage, digital agriculture and rainwater harvesting practices has led to a substantial transformation in Ghanaian smallholder farming systems, yielding significant benefits for soil conservation, water use efficiency and reduced dependence on direct rainfed agriculture. The adoption of these practices has led to: Notable increases in crop yields, improved growth rates, enhanced development indices, improved farmers' livelihoods and addressing long-standing challenges facing Ghanaian smallholder farmers.

The agricultural sector in Ghana has revolutionized through this integrated approach and provides a sustainable and food-secure future for smallholder farmers. The successful implementation of these practices has the potential to be replicated in other regions, promoting sustainable agriculture and improving the livelihoods of smallholder farmers globally.

Findings and Recommendations

The integration of conservation tillage, digital agriculture and rainwater harvesting practices has shown promising results in promoting sustainable agriculture and improving the livelihoods of Ghanaian smallholder farmers. To build on these successes, the following recommendations are made:

- Promote the adoption of conservation tillage practices: Encourage Ghanaian smallholder farmers to adopt conservation tillage practices to reduce soil erosion, improve soil health and increase crop yields.
- Develop and disseminate digital agriculture platforms and DSSs: Provide farmers with access to real-time data on weather patterns, soil moisture levels and crop water requirements to optimize their farming practices.
- Promote the adoption of rainwater harvesting practices: Support Ghanaian smallholder farmers in adopting rainwater harvesting practices to reduce their dependence on direct rainfed agriculture and mitigate the impacts of droughts.
- Conduct further research: Explore the synergies between conservation tillage, digital agriculture and rainwater harvesting practices to identify areas for improvement and optimize their benefits.
- Formulate policy and programs: Formulate policy and programs that can facilitate the adoption of these practices by Ghana's smallholder farmers, thus a food-secure and sustainable future for everybody.

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Journal of Biology and Health Science

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