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The potential of Zai pit technology and Integrated soil fertility management to enhance crop productivity in semi-arid regions of Sub-Sahara Africa: A review

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Abstract— *Low and continuously deteriorating soil fertility coupled with frequent droughts and extended mid-season dry spells scenarios brought about by low and unreliable rainfalls have had a significant negative influence on agricultural productivity in most semi-arid regions of the world. The farmers' limited capacity to change their farming practices and adjust to the changing climatic circumstances further exacerbates these effects. Various in-field rainwater collection techniques, including Zai pits, have been promoted in recent years to assist farmers, particularly in dry and semi-arid locations, to harvest, store, and use rainfall for increased crop productivity. Zai pit is a form of dryland farming technique that involves the unitization of holes or troughs aimed at ensuring soil maintenance, soil erosion control and water preservation in agricultural fields. Additionally, combining effective soil fertility management strategies, such as integrated soil fertility management, with rainwater harvesting methods has the potential to further boost crop yields. Integrated soil fertility management involves the combined use of inorganic fertilizers and organic fertilizers such as cattle manure with the aim of improving soil fertility. Zai pit technology and integrated soil fertility management techniques have been utilized as climate smart agricultural approaches to reduce soil moisture stress and improve crop productivity in arid and semi-arid regions. This paper reviews previous research results on crop productivity as influenced by Zai pit technology and integrated soil fertility management techniques.*

Keywords— ***Zai Pit, Integrated Soil Fertility Management, Adoption, Crop productivity***

I. INTRODUCTION

In dry and semiarid regions of the world, insufficient rainfall, soil water stress, and inadequate nutrient availability are the key factors limiting crop productivity (Yazar & Ali, 2016). Insufficient rainfall and poor rainfall distribution have resulted in reduced crop yield and food insecurity in the majority of sub-Saharan Africa's dry regions (Kimaru-Muchai et al., 2020). Additionally, the regular occurrence of extreme weather events such as droughts and dry spells in Africa's rainfed agricultural systems poses a threat to food security (Ayanlade et al., 2018; Grafton et al., 2015). Low rainfall, soil moisture stress, infertile unproductive soils, and increased land degradation have all been linked to low crop productivity in the majority of these areas (Njeru et al., 2015). Majority of farmers in arid areas face drought and prolonged dry spells (Muller, 2014), which promotes food insecurity (Ayanlade et al., 2018).

In these environments, agricultural output is significantly impacted by drought episodes that are frequently linked to climate variability (Tumushabe, 2018). According to Zougmoré et al. (2014), the arid and semi-arid lands (ASALs) are characterized by low and uneven rainfall during the growing season, crusted, degraded soils that are low in nutrients, and low soil fertility that adversely affects crop output. Climate change, which impact the majority of the sub-Saharan African nations, has made the situation worse in these arid regions (Sakadzo & Kugedera, 2020). According to Muller (2014), more than 13 million people, including 3.75 million Kenyans, were affected by drought in the Horn of Africa region between 2008 and 2010. Additionally, Omenda et al. (2021) argues that African rain-fed agricultural systems will severely be affected by the ongoing climate change and variability. Irrigation often occurs on less than 5% of the total cultivated area in the majority of Sub-Saharan African nations (Peacock et al., 2004). The potential influence of innovations targeted at enhancing farm productivity has been downplayed due to the unpredictability and risk for existing farm level production linked with the fluctuation of rainfall volume and distribution within and between seasons (Biazin et al., 2012).

The United Nations' Globe Water Development Report notes that there has never been a more thirstier world than what we have today (Richard, 2015). The basis for international action is provided by this worrying reality (Nyamekye et al., 2018). FAO (2010) estimated that rain-fed agriculture contributes to about 60% of the world crop production. However, on the African continent, 27% of the total land area has already been degraded, with 65% of it comprising of farmland (Dubois, 2011). Ninety five percent of the land in sub-Saharan Africa (SSA) is used for rainfed agriculture, while an estimated 41% of the population dwells in drought-prone areas (Biazin et al., 2012). The rate of productivity growth in African agriculture is the lowest in the entire globe (Biazin et al., 2012). Less than 2% of the world's irrigated land is located in SSA due to its costly nature and the physical water availability constraint (Kaluli et al., 2012).

The majority of smallholder farmers in Sub-Saharan Africa use the traditional farming system. The advantages are obvious: efficient seeding operations and successful weed control (Gichangi et al., 2007; Itabari et al., 2003; Ngetich et al., 2014). In contrast, this method of cultivation affects the amount of soil moisture retained, the rate of evaporation, and the susceptibility to runoff generation (Kebenei et al., 2021). Due to the exposure of surface soil, conventional tillage techniques are rarely environmentally sustainable and advantageous in terms of soil conservation and water management (Gathala et al., 2011; Liu et al., 2014; Obalum et al., 2019; Thierfelder & Wall, 2009; Zhao et al., 2021). Soil disruption brought on by frequent tillage encourages direct water vaporization from the soil surface, which furthers the apparent effect on erosion and runoff (Bottinelli et al., 2017; Shepherd et al., 2001). Due to the tilled surface's complete exposure, conventional tillage has also been linked to increased soil moisture evaporation (Miriti, 2011).

In developing countries, rainfed grain yields average 1.5 t ha^{-1} (Rosegrant et al., 2002) compared with 5-6 t ha^{-1} (Rockström & Falkenmark, 2000) in regions with reliable rainfall and sufficient nutrient availability (Clarke et al., 2017). The yield gap between the actual yields being harvested from farmers' fields and what could be potentially realized attests the need to develop new approaches of agricultural production in sub-Saharan Africa (Wani et al., 2009). Through the use of the appropriate technology, the challenge of low soil fertility and water scarcity has spurred more creative agricultural techniques to increase food security and subsistence, particularly for agricultural smallholder farmers(Nyang'au et al., 2021). A number of climate change interventions have been implemented to address the issues of water scarcity and low crop yields, including irrigation, planting trees, soil and water conservation techniques, and enhanced crop seeds (Gebru et al., 2020; Wawire et al., 2021).

These experiences suggest that the challenges of low yields in rainfed farming systems in developing countries might be overcome with nutrient management combined with soil water conservation (Rockström & Karlberg, 2010). Incorporating water harvesting technologies with improved soil fertility management methods generates synergies that further increase water efficiency and yields in smallholder farms (Winterbottom et al., 2013). Use of suitable water and soil management techniques such as zai pit (Evett & Tolk, 2009) increase rainfall use efficiency and bridge intra-seasonal dry spells (Dile et al., 2013).

Zai have been found to be capable of collecting up to 25% or more of a run-off coming from 5 times its area (Malesu *et al*., 2006). *Zai* pits are known to allow crops do well in areas with high risk of crop failure as a result of harsh climatic conditions (Critchley & Gowing, 2013). Water stored in the *Zai* pits delay the onset and occurrence of severe water stress thereby buffering the crop against damage caused by water deficits during dry periods (Nyamadzawo *et al*., 2013). The pits increase the amount of water stored in the soil profile by trapping or holding rainwater where it falls (Mutunga, 2001). Besides enhancing water storage, *Zai* pits increases water infiltration and reduces run-off for plant uptake during the dry periods (Danjuma & Mohammed, 2015).

II. ZAI PIT SYSTEM

Zai pit is a traditional dryland agricultural method that was developed in Burkina Faso, however some sources attribute it to the Dogon in Northern Mali (Danjuma & Mohammed, 2015). It entails using basins or holes with a depth of 10 cm to 15 cm and a diameter of 20 cm to carry out agricultural chores (Sawadogo, 2011). Since they guarantee soil upkeep, soil erosion control, and water preservation, their use has been found to reduce the consequences of droughts. This method has been utilized by farmers around the world to fight land degradation and restore soil fertility (Fatondji, 2002). According to the findings of Fatondji (2002), using Zai pits could improve nutrient usage efficiency, agronomic efficiency, and pearl millet crop output. In Burkina, Zougmoré *et al*. (2014) reported that *Zai* pit reduces runoff by increasing infiltration through creating and enhancing depressional water storage and reducing erosion.

A study by Sawadogo (2011) showed increased yields variations from 300 to 400 kg ha^{-1} by the *Zai* system in degraded land. Oduor *et al*. (2021) reported that *Zai* pit technique with manure increased crop yield. Sawadogo (2011) reported substantial grain yield increases where he reported sorghum yields increase in farmer's fields from 319-642 kg ha^{-1} without *Zai* pit system to 975-1600 kg/ha with *Zai* pit system. The use of *Zai* pit system has also been utilized in South Africa (Magombeyi & Taigbenu, 2008), Zambia (Thierfelder & Wall, 2009; Haggblade & Tembo, 2003), Ethiopia (Amede *et al*., 2011) and Niger (Fatondji *et al*., 2009) and in Zimbabwe (Gumbo *et al*., 2012).

In Kenya, *Zai* pits technology has been recommended as a water harvesting technique for the production of maize in the coastal region (Saha *et al*., 2007) and in the eastern region (Recha *et al*., 2014). Tumbukiza is a variation of the *Zai* pit technique that has been widely utilized by farmers in western Kenya as a method of napier grass production (Orodho, 2007). Variations of *Zai* pits have been used in various parts of Kenya including the katumani pit and 'five by nine' pit in Thraka nithi, Murang'a and Machakos Counties (Malesu *et al*., 2006).

III. Effects of Zai pit system on soil moisture

Water is an important factor of plant growth. In-situ soil moisture conservation entails capturing rainwater and retaining it in the soil for in-situ plant utilization for growth and increase in grain and biomass yield (Itabari & Wamuongo, 2003). Water harvesting and storage is vital to ensure water availability for plant growth especially in the arid and semi-arid areas. *Zai* have been found to be capable of collecting up to 25% or more of a run-off coming from 5 times its area (Malesu *et al*., 2006). *Zai* pits are known to allow crops do well in areas with high risk of crop failure as a result of harsh climatic conditions (Critchley & Gowing, 2013). Water stored in the *Zai* delay the onset and occurrence of severe water stress thereby buffering the crop against damage caused by water deficits during dry periods (Nyamadzawo *et al*., 2013). *Zai* pits increase the amount of water stored in the soil profile by trapping or holding rainwater where it falls (Mutunga, 2001). Besides enhancing water storage, *Zai* pits increases water infiltration and reduces run-off for plant uptake during the dry periods (Danjuma & Mohammed, 2015). The pits play a key water harvesting role. Instead of being lost to runoff, rainfall water is trapped in the *Zai* pits close to crop roots. *Zai* pits are especially relevant to areas receiving 300- 800 mm annual rainfall (Mwangi, 2020).

Despite their importance in increasing soil moisture in low rainfall areas, studies have also revealed the significance of using *Zai* pits in high rainfall areas with steep slopes. Such areas receive high rainfall but due to steep slopes, most of the water end up as run-off and results to massive soil erosion. A study by Amede *et al*. (2011) showed that *Zai* pits were effective in a highland area of Ethiopia that receives in excess of 1300 mm annual rainfall and where water infiltration into the soil is limited by losses of rainwater to runoff, a lack of organic matter, and hardpans. In their study Amede *et al*. (2011) found out that Crop water productivity of potato and beans was 300–700% higher with *Zai* pits than with control plots. In summary, the *Zai* system allows farmers to concentrate both fertility and moisture close to crop roots and, in so doing, addresses some of the major challenges to crop production in Sub-Saharan Africa (Mwangi, 2020).

IV. INTEGRATED SOIL FERTILITY MANAGEMENT (ISFM) TECHNOLOGY

Integrated soil fertility management (ISFM) is a means to increase crop productivity in a profitable and environmentally friendly way (Bationo & Waswa, 2011; Vanlauwe *et al*., 2010). It aims at offering wide-ranging solutions that are socially acceptable and practical in the management of soil fertility (Misiko, 2007). The ISFM paradigm became crystallized at the turn of the millennium with a new emphasis on improving the use efficiency of inorganic and organic fertilizer combinations while adapting nutrient management strategies to local conditions (Kolawole, 2013; Bationo & Waswa, 2011).

ISFM is a means to increase crop productivity in a profitable and environmentally friendly way (Vanlauwe *et al*., 2010), and thus eliminating one of the main factors that perpetuates rural poverty and natural resource degradation in sub-Saharan Africa (SSA). Current interest in ISFM results from global demonstration of the benefits of ISFM interventions, such as the combined use of organic manure and mineral fertilizers (Zingore *et al*., 2008), dual purpose legume – cereal rotations (Sanginga & Woomer, 2009) or micro-dosing of fertilizer and manure for cereals in semi-arid areas (Tabo *et al*., 2007). ISFM is also aligned to the principles of Sustainable Intensification (Vanlauwe *et al*., 2014; Pretty *et al*., 2011), one of the paradigms guiding initiatives to increase the productivity of smallholder farming systems.

The benefits of ISFM technologies in enhancing fertilizer use efficiency and improving maize productivity are widely acknowledged in literature (Lambrecht *et al*., 2014; Mucheru-Muna *et al*., 2014; Fairhurst, 2012; Mugwe *et al*., 2009; Marenya & Barrett, 2007). According to Kamau *et al*. (2014), ISFM has the potential to reduce the need for chemical fertilizers owing to its ability to raise the efficiency of the applied nutrients. The adoption of ISFM technologies can also lead to economic benefits if gains in profits due to improved input productivity exceed the cost of adoption (Kamau *et al*., 2014). The use of inorganic and organic fertilizers such as compost manure, green manures, crop residues and legume integration in farming systems is one component of ISFM (Mhango *et al*., 2013). These organic fertilizers improve soil organic matter, nutrient and water retention in soils. ISFM technologies can enhance fertilizer use efficiency and thereby improve productivity (Fairhurst, 2012). Practices in ISFM technologies such as integration of legumes and incorporation of crop residues improve soil organic matter (Mucheru-Muna *et al*., 2010). Snapp *et al*. (2014) reported that rotating maize with a legume crop is another factor that consistently influences maize yield response to nitrogen. Use of ISFM technologies have led to increase in crop yields in many parts of SSA. Kaboré and Reij (2004) indicated that an additional dose of inorganic fertilizer and organic, in combination with the *Zai* pits and manure, increased yields by 640 kg ha^{-1} compared to the control treatment in Mali.

V. EFFECTS OF ZAI PIT SYSTEM COMBINED WITH ISFM TECHNOLOGY ON CROP YIELD

To increase crop yield, a variety of soil and water conservation techniques have been utilized (Getare et al., 2021). Numerous studies (Bedada et al., 2014; Bolo et al., 2021; Chen et al., 2017; Dunjana et al., 2012; Mucheru-Muna et al., 2007, 2014; Mugwe et al., 2009; Mutegi et al., 2012; Xu et al., 2018; Yuan et al., 2021) have demonstrated that the application of organics or in combination with inorganics increases the overall yield of the crops .The results of a study conducted by Fatondji *et al*. (2006) in Niger to examine the effect of *Zai* and organic amendments on millet grain yield reported higher yields in *Zai* plots as compared to the conventional ones, and 68 times more yields in *Zai* plots with manure amendments. In Kitui, the results of a study by Getare *et al*. (2021) revealed that all treatments under *Zai* system amended with organic inputs recorded significantly higher sorghum grain and stover yields compared to all similar treatments under conventional planting. Similarly, in Tharaka Nithi County, Kenya, Kimaru-Muchai *et al*. (2021) reported significantly higher sorghum grain and stover yields in treatments under *Zai* as opposed to similar treatments under conventional systems, with highest yields being recorded under *Zai* with organic amendments either solely or when combined with chemical fertilizer.

The utilization of Zai pits have been found to highly boost crop productivity. Kaboré & Reij (2004) discovered that *Zai* boosted sorghum yields by 310kg/ha compared to the treatments without *Zai* pits. Average yields in *Zai* pits in Niger's Illela area were 310% higher than untreated fields (Kaboré & Reij, 2004). *Zai* pits technology was found to have yielded much better dry matter yields than the traditional method in Western Kenya (Muyekho *et al*., 2000). Bationo *et al*. (2007) discovered that using *Zai* alone did not boost yields as much as using *Zai* in combination with manure and fertilizer in West Africa. In Niger, manure application with *Zai* increased grain yields by 2 to 69 times as opposed to *Zai* with no treatment (Fatondji *et al*., 2009).

In the highlands of Ethiopia, Amede *et al*. (2011) demonstrated the effectiveness of *Zai* pits by reporting a 500 percent to 2000 percent and up to 250 percent increase in potato and bean yields, respectively, when *Zai* pits were used in conjunction with nitrogen inputs compared to the control. Similarly, Sawadogo (2011) reported 100% increased crop yields on farms which employed the use of *Zai* pit technology as compared to the 63–74% increase on farms utilizing rock bunds in the study villages. Similar findings were reported by Zougmoré *et al*. (2004) who found that *Zai* had significantly influenced yields, especially when combined manure and chemical fertilizers are used. Even in the absence of *Zai* pits, several studies have demonstrated the positive influence of integrated soil fertility management options on crop yield. Mucheru-Muna *et al*. (2007) reported that treatments with organic (tithonia) amendments, with or without half recommended rate of mineral fertilizer, gave the highest maize grain yield compared to sole nitrogen treatments while the control treatment consistently gave the lowest yield across all the seasons.

Similarly, Mucheru-Muna *et al*. (2014) also reported that treatments with sole organics and those with combined organics and mineral fertilizers significantly increased maize grain yield compared with treatments with the recommended rate of sole mineral fertilizer (60 kg N ha^{-1})

and the unfertilized control. Kebenei et al. (2021) reported higher sorghum yields in Zai treatments with combined organic and inorganic amendments. Similarly, Oduor *et al*. (2021) reported better yield performance in treatments under *Zai* system which recorded 30.5% and 27.9% higher yields against 18.2% and 22.5% in conventional plots in Machakos and Naivasha, respectively. Several other previous studies have documented higher crop yields in *Zai* treatments whether solely or when utilized with sole organic inputs or integrated organic and inorganic inputs (Getare *et al*., 2021; Mwangi, 2020; Njue *et al*., 2020; Adamtey *et al*., 2016; Kathuli & Itabari, 2015; Recha *et al*., 2014; Fatondji *et al*., 2012; Amede *et al*., 2011; Sawadogo, 2011 Drechsel *et al*., 1999).

VI. FACTORS AFFECTING THE ADOPTION OF ZAI PITS

One of the crucial requirements for agricultural development, particularly in arid and semi-arid regions, is the adaptation and use of water harvesting systems(Danquah et al., 2019). Higher returns to farm production are the main driver of agricultural growth in every nation (Koome, 2017). To raise returns, farmers must embrace agricultural techniques that boost output and manage resources like soil and water more wisely, effectively, and sustainably for the environment (FAO, 2010, 2011).

Despite the technology created and put to the test on farms by various research individuals and institutions, farmers' adoption and implementation levels remain poor, resulting in persistently low productivity (Nyamadzawo et al., 2013). According to a study by (Mango et al., 2014), poor adoption of new technology and ineffective methods for managing soil fertility jeopardize smallholder farmers' ability to produce food sustainably and securely. Due to variations in socio-cultural, economic, and biophysical settings, different factors contribute to zai pits adoption and utilization from place to location and from one household to another (Amsalu & de Graaff, 2007). In their study of the factors influencing the adoption and use of zai and mulching in north Burkina Faso, (Slingerland & Stork, 2000) discovered that farmers who applied zai pits had larger households, more transportation options, and more livestock, which is congruent with their requirement for labor and manure.

Bett (2006) highlighted that a number of factors, including age and educational level, have a favorable or negative impact on the adoption of agricultural technologies. Marenya and Barrett (2007) discovered that greater education has a beneficial impact on adoption decisions because it is linked to the capacity to synthesize more information about the technologies that are available, which enhances the general management of the farm. On the other hand, Mutuku et al. (2016) argued that greater education may open up more career alternatives for a household head, leaving them with less time to devote to farm duties, which would negatively impact the uptake of agricultural-related technologies.

According to (Barry et al., 2009), the Zai Pits need roughly 300 hours of labor per ha.on the other hand, Kaboré and Reij (2004) stated that Zai system is more feasible when carried out by groups of farmers as opposed to individuals because it takes 450 hours/ha to dig the holes and an additional 250 hours/ha to fertilize them. This implies that wealthier farmers may be better placed to gain more from the technology. Several researchers (Gebru et al., 2020; Murgor et al., 2013; Mutuku et al., 2016; Njenga et al., 2021) have indicated that financial concerns, such as the high cost of hired labor, transporting agricultural products, construction materials, and the lack of credit access or lack of capital, are a barrier to farmers embracing contemporary agricultural inputs and technology such as Zai pits. The users' perception of the characteristics of a technology has been found to be an important determinant to its adoption (Koome, 2017).

In Burkina Faso, Sidibé (2005) discovered that factors including education and attitudes toward soil degradation served as the foundation for the utilization of the zai technique. According to (Wildemeersch et al., 2015), the use of zai pit technology in Niger is constrained by a lack of understanding of erosion and other crucial resources including manure, agricultural machinery, and transportation infrastructure. The high potential for zai pit adoption demonstrated by farmers in the most parts could be related to favorable institutional characteristics such an integrated lead farmer strategy and a well-structured extension system (Ndah et al., 2014; Nyanga, 2012).

Even in the presence of all the above researched on and established factors that determine the adoption of proven sustainable agricultural interventions for improvement of crop productivity, there is still low adoption and utilization of agricultural technologies like Zai pits and integrated soil fertility management technologies among farmers in sub-saharan Africa (Danquah et al., 2019). This poor adoption of new technology and effective methods for managing soil fertility has in the long-run jeopardized farmers' ability to produce food sustainably and securely to meet both subsistence and commercial needs.

VII. CONCLUSION

The aim of this study was to review relevant literature on the potential of Zai pit and integrated soil fertility management technologies to enhance agricultural productivity and the factors affecting the adoption and utilization of the Zai farming technique. The reviewed literature has indicated that many past researches and experiments indicated high crop productivity in treatments with Zai pits especially when combined with integrated soil fertility management options. It has also been established that a number of factors, including perception, level of education, age and financial status of a household, has a great influence on its ability and willingness to adopt and utilize sustainable and effective agricultural interventions and technologies such as Zai pits for improved crop productivity. Reviewed literature also indicate that the adoption and utilization rates of Zai pits among farmers in sub-saharan Africa is still low and this could be attributed to other factors such as institutional characteristics and the lack of a well-structured extension system. Based on the findings, this study recommends that intensive education, awareness creation and training should be done among farmers in the sub-saharan Africa region to educate and raise awareness of the advantages of adopting and utilizing Zai and integrated soil fertility management technologies in their farms for improved crop productivity.

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