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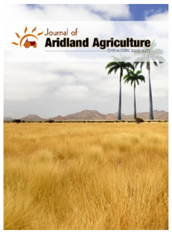

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The role of *Zai* pits and integrated soil fertility management options in improving crop productivity for smallholder farmers in the drylands of Sub-Saharan Africa

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ABSTRACT

The drylands of Africa are experiencing food insecurity due to prolonged drought and water scarcity which has a negative effect on crop production. In the drylands of Sub-Saharan Africa, many small holder farmers are experiencing low crop yields and economic returns as a result of poor soil fertility and water scarcity. This is because of the inappropriate soil and water conservation strategies used in the region. *Zai* pits have been used as a soil and water conservation strategy in the drylands of Africa in combination with integrated soil fertility management (ISFM) options to improve soil fertility, increase the overall crop yields and the economic returns. This review deals on the role of *zai* pits and integrated soil fertility management options in improving productivity for the small holder farmers in the drylands of Sub-Saharan Africa. *Zai* pits have been used to harvest water which ultimately improves soil moisture for crop production with the different fertility inputs applied in the pits for nutrient efficiency. To evaluate productivity and profitability in *zai* tillage system, yield, benefit cost ratio (BCR) and net benefits are used. In this study, different studies by researchers on the use of *zai* pits and integrated soil fertility management options have been discussed and this would be beneficial for other researchers who have interest in this field. Most studies have indicated that the *zai* pit technology is an important soil and water conservation strategy which in combination with the integrated soil fertility management (ISFM) options improves crop productivity in terms of yield and economic returns.

KEYWORDS: *Zai*, ISFM, Small holder farmers, Mineral fertilizers, Sub-Saharan Africa

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INTRODUCTION

In the drylands of Africa, most countries primarily depend on subsistence agriculture as a source of livelihood (Bationo *et al.*, 2003; Morton, 2007; King *et al.*, 2018). These regions are known to experience low and unreliable rainfall which is poorly distributed within the cropping period, high temperatures and soils which have low capacity to retain water and low nutrients (Zougmoré *et al.*, 2014). Agricultural productivity is dwindling in these regions which are evident from the continuous yield decline and economic returns. This is because the farmers majorly rely on rainfall for crop production and their vulnerability to change of climate is relatively high (Adimassu & Kessler, 2016; Kogo *et al.*, 2021).

Soil fertility decline is also a biophysical problem in crop production which is faced by the small holder farmers in Sub-Saharan Africa. This has been associated with higher rates of soil erosion and continuous cultivation without adequate addition of fertility inputs (Njeru *et al.*, 2011; Shah & Wu, 2019). The adoption of suitable technologies and innovative approaches by small holder farmers in this region has addressed the challenge of soil fertility decline and food security problems (Nyang'au *et al.*, 2021). Soil and water conservation strategies have also been used to curb the problem of water scarcity and low yields including irrigation and improved crop seeds as remedies for the changing climate (Gebru *et al.*, 2020; Wawire *et al.*, 2021). These strategies have been used by the small holder farmers to support rainfed agriculture by improving soil fertility, increasing crop yield and economic returns. *Zai* pits have been used as a water harvesting technology to increase water supply for agricultural use in an event of prolonged drought (Liang &van Dijk, 2011; Kiggundu *et al.*, 2018; Kimaru-Muchai *et al.*, 2020; Lutta *et al.*, 2020; Patle *et al.*, 2020). This is because pitting increases the soil moisture content and restores productivity in areas where rainfall is insufficient with prolonged droughts (Kiggundu *et al.*, 2018; Ndeke *et al.*, 2021).

EFFECTS OF DROUGHT ON CROP PRODUCTION

Drought is defined as a phenomenon that occurs naturally with water constraints experienced over a long period (Vicente-Serrano *et al.*, 2012; AghaKouchak *et al.*, 2021). Variables of climate such as temperature and precipitation directly affect crop production since they control their growth, health and yield (Liang *et al.*, 2017). Shortage of rainfall coupled with soil erosion has become a major challenge in crop production to the small holder farmers in the dry lands (Troy *et al.*, 2015). In the world today, food security is hampered by changes in climatic conditions and increased population growth. Heat and drought are greatly affecting crop production leading to food insecurity because they have a huge impact on the growth and productivity of the crops (Fahad *et al.*, 2017; Renard *et al.*, 2023). This is because the sub-optimal water supply and temperatures that are abnormally high physically damages the crops and their biochemical reactions. Prolonged drought conditions also lead to yield reduction because of its adverse effect on plant growth, physiology and reproduction (Iqbal *et al.*, 2020). The potential direct effects of climate change on crop production include; increase in diseases, changes in rainfall and temperature patterns and high weed and pest infestations Hatfield *et al.* (2020) with the shift in rainfall patterns and its unreliability has made the emergence of draught like conditions around the world (Rajsekhar & Gorelick, 2017; Langridge & Reynolds, 2021).

Several studies have shown that water shortage and high temperatures are the main factors affecting crop production especially in the dry lands of Africa. Samarah (2005), Boubacar (2010), Huho and Mugalavi (2010), Lobell *et al.* (2011), Boubacar (2012), Fahad *et al.* (2017) and Iqbal *et al.* (2020) noted that water stress resulting from long dry periods affects crop growth and yields. This is because prolonged drought has a direct impact on the growth, physiology and reproduction of the crops (Barnabas *et al.*, 2008; Daryanto *et al.*, 2016; Zhang *et al.*, 2018). Water stress also modifies the biochemical and morphological aspects of crops (Iqbal *et al.*, 2020). Globally, drought patterns have also been associated with losses in crop production. Lesk *et al.* (2017) reported that drought reduced crop production by 10 per cent based on several studies undertaken. Al-Kaisi *et al.* (2013), Zipper *et al.* (2016), Liu *et al.* (2018) and Kim *et al.* (2019) noted that crop production was highly affected by drought. Various water harvesting technologies such as *zai* pits have been used to curb the problem of water scarcity in the soil for improved crop yield.

ZAI PIT SYSTEM AS AN INTERVENTION FOR SOIL AND WATER CONSERVATION

The *zai* pit system is a traditional soil and water conservation strategy that was originally used in Northern Burkina Faso with some literature pointing to Dogon Mali (Sawadogo, 2011; Danjuma & Mohammed, 2015; Partey *et al.*, 2018). *Zai* pits averagely measure 20-30 cm in diameter, a depth of 10-20 cm and a spacing of 60-80 cm between the pits. As described by Motis *et al.* (2013), *zai* pits are best suited in areas receiving annual rainfall ranging from 300-800 m annually and soils with water infiltration problems caused by hardpans and crusted soils. The *zai* pit system has been promoted in most African countries like Zambia, Kenya, Tanzania and Ethiopia among others (Kuyah *et al.*, 2021). This strategy is beneficial in improving rainfall capture, reduce runoff and water evaporation which eventually increases agricultural production (Amede *et al.*, 2011; Dile *et al.*, 2013; Wouterse, 2017).

In Sub-Saharan Africa, soil fertility decline, and low soil moisture have been addressed with the innovation of the *zai* pit system since it allows the concentration of water and nutrients close to the root zone (Fatondji *et al.*, 2009; Biazin *et al.*, 2012; Diop *et al.*, 2022). As a soil and water conservation measure, the *zai* pit technology has promoted water-nutrient synergy as well as increase agricultural production in the drylands of sub-Saharan Africa (Kimaru-Muchai *et al.*, 2021). Danjuma and Mohammed (2015) noted that *zai* pits have more than 500% water holding capacity. This has therefore been used as a strategy to improve fertility in poor soils especially during dry conditions. Pits have also been practiced in some countries in West Africa including Burkina Faso, Mali and Niger with studies indicating that they increase crop yield and improve soil fertility over time (Zougmoré *et al.*, 2003).

Several studies have shown that the use of *zai* pits has been practiced extensively in the drylands of Africa with the studies revealing that they are well suited for these areas. Mati (2006), Kathuli and Itabari (2014), Zougmoré *et al.* (2014) and Muchiri *et al.* (2020) noted that *zai* pits are used for crop production in the arid and semi-arid regions by farmers in dry eroded valley soils and bush fields to increase and retain soil moisture, soil erosion reduction and soil fertility improvement through applying manure in the pits before planting is done (Zougmoré *et al.*, 2014). Some of the crops that have been reported by small holder farmers to do well in the pit technique include; cow peas (*Vigna unguiculata*), sorghum (*Sorghum bicolor*) and millet (*Pennisetum glaucum*) among other crops that are drought resistant in the arid and semi-arid regions hence an improvement in production of the major food crops (Wildemeersch *et al.*, 2015). Digging pits help more rain water infiltration and with the application of both organic and inorganic fertility inputs there is an improvement in soil fertility (Kar *et al.*, 2013; Kugedera *et al.*, 2022).

INTEGRATED SOIL FERTILITY MANAGEMENT OPTIONS FOR IMPROVED AGRICULTURAL PRODUCTIVITY

As defined by Vanlauwe *et al.* (2010), integrated soil fertility management is a means of improving crop production in an environmentally friendly and profitable way. Fairhurst (2012) and Nyagumbo *et al.* (2022) describes it as the use of technologies to improve crop production through the use of organic matter application, use of inorganic fertilizers, improved germplasm and the adaptation to the local conditions by the small holder farmers. This consists of best practices which are commonly used in a combined form for instance, use of fertilizers, organic inputs, and other agronomic practices to address the problem of soil fertility facing the small holder farmers. Proper use of ISFM can improve crop production and reduce soil organic losses (Zhang *et al.*, 2018). The current integrated soil fertility management (ISFM) interventions include dual crop legume-cereal rotations, intercropping and a combined use of organic manure and inorganic fertilizers (Vanlauwe *et al.*, 2015).

Mineral fertilizers are essential concentrated nutrients that are needed by crops that are readily available for plant uptake and used to supplement the nutrients in the soil (Fairhurst, 2012; Elemike *et al.*, 2019). Effectively, balancing the application of inorganic and organic inputs is important in achieving improved crop production in sub-Saharan Africa (Zingore *et al.*, 2008; Smith *et al.*, 2015). The inorganic fertilizers are often classified according to the minerals they have for instance nitrogen fertilizers provide N into the soil. The sources include ammonium and nitrate forms and urea. Ammonium sulphate is widely used and it contains about 21% N and 11% S. Other fertilizers that are known to supply both N and P includes, ammonium phosphate and Diammonium phosphate (DAP) (Muriuki, 2009). The main sources of inorganic nutrients include DAP, CAN, 17.17.0, 23.23.0 and 20.20.0 and in the drylands inorganic fertilizers are used in small quantities due to the high cost and the perception by farmers that they negatively affect soils (Mugwe *et al.*, 2009). These fertilizers are water soluble and can cause damage to seeds especially in soils with high soil pH (Silva and Uchida, 2000). It has been noted that the rate of addition of fertilizer is insufficient in restoring soil fertility and compensating for the nutrients lost and generally, fertilizers are an expensive fertility input and therefore the poor resource farmers cannot be able to buy enough fertilizer to comply with the rates recommended for application (Bedada *et al.*, 2014).

On the other hand, the use of organic resources is an important source of nutrient inputs with manure being the major source of nutrients (Chivenge *et al.*, 2009; Timsina, 2018). Animal manure contains all the micro and macro elements required for the growth of plants. It also contains organic matter this therefore increases soil organic carbon when it is applied (Dunjana *et al.*, 2012). Mugwe *et al.* (2009) noted that manure is widely used in Central Kenya by about 80% of households because it is affordable compared to inorganic fertilizers. Cattle manure is readily obtained by the small holder farmers in high quantities to enhance soil organic matter (Dunjana *et al.*, 2012). The stock of organic carbon present in animal manure generally increases the soil's organic carbon upon its application.

THE INFLUENCE OF *ZAI* PITS AND ISFM OPTIONS ON SOIL NUTRIENTS

Most studies believe that the use of *zai* pits and integrated soil fertility management options has been beneficial to the small holder farmers since they improve soil nutrients. The combined application manure and mineral fertilizers increased total nitrogen in the soil which is an important element in crop production. Bedada *et al.* (2014), Kihara *et al.* (2016), Yegon *et al.* (2016) and Liu *et al.* (2020) noted that the addition of manure and mineral fertilizer increased total nitrogen in the soil. A study by Yegon *et al.* (2016) on the effects of planting pits on soil properties indicated that soil total nitrogen (TN) increased by 0.4 mg kg^{-1}, potassium level by 0.4-0.54 $cmol_c$ kg^{-1} and total organic carbon (OC) by 0.06 mg kg^{-1} in areas where pits were used compared to the control. Conversely, other studies have shown that total nitrogen reduced after the application of the fertility inputs. Omara *et al.* (2019), Pasley *et al.* (2019) and Pal *et al.* (2020) reported a reduction in total nitrogen which could be due to accelerated crop uptake of nitrogen or other losses through erosion, volatilization and leaching.

Soil organic carbon is beneficial in maintaining soil fertility since it's a sink for nutrients (Bationo *et al.*, 2005; Lahmar *et al.*, 2012; Barnwal *et al.*, 2021). The application of sole organics or in combination increases soil organic carbon in the soil (Mucheru-Muna *et al.*, 2007; Chivenge *et al.*, 2011; Dunjana *et al.*, 2012; Zhou *et al.* 2016). The application of cattle manure has been attributed to the increase of organic carbon in the soil in poor fertility soils. For instance, Dunjana *et al.* (2012) recorded a significant increase in organic carbon and improving aggregate stability in clay soils and soil organic carbon increased significantly in sandy soils. This showed that cattle manure plays a great role in soil organic matter enhancement. Conversely, other studies have shown a reduction of soil organic carbon after planting. Liu *et al.* (2003), Mugwe *et al.* (2009), Blanco-Canqui *et al.* (2013), Corsi *et al.* (2013), Haddaway *et al.* (2015) and Lei *et al.* (2019) all recorded a reduction in the soil organic carbon. This is because mixing of soils with litter favours bacteria and promotes the rapid breakdown process of organic carbon. Tillage induced erosion of soils is also the cause of severe loss of soil organic carbon more especially in upland landscapes.

Cattle manure can restore soil fertility in small holder farms because it increases soil pH (Zingore *et al.*, 2008; Mugwe *et al.*, 2009; Mrunalini *et al.*, 2022). The increase in the rating of soil pH could be associated with the application of cattle manure which has calcium carbonate and bicarbonates as well as the organic anions present in manure which neutralizes the H+ ions (Butterly *et al.*, 2012). Studies have shown that organic manure has a significant effect on soil pH. Mucheru-Muna *et al.* (2014) reported a significant increase in soil pH in the sole application of organic manure from strongly acidic soils to less strongly acidic soils with the complete opposite with the application of sole mineral fertilizer which reduces soil pH. Mugwe *et al.* (2009) and Opala *et al.* (2013) also reported that farmyard manure and cattle manure improved soil fertility by increasing soil pH respectively. Sole mineral fertilizer application reduces the soil pH in comparison with the compost which has an effect of increasing soil pH (Bedada *et al.*, 2014). Similarly, Kimaru (2017) also indicated that soil pH significantly increased with the application of manure under the *zai* pit system. The change of pH was associated with the manure application. Soil electrical conductivity is an important indicator in soil health. Manure application increases soil electrical conductivity because of the dissolved salts in manure. Research has shown that manure application increases soil electrical conductivity (Carmo *et al.*, 2016a, b; Miller *et al.*, 2016).

HOW *ZAI* PITS AND INTEGRATED SOIL FERTILITY MANAGEMENT (ISFM) AFFECTS CROP YIELDS

Various soil and water conservation technologies are being used to improve crop productivity (Banwart, 2011). Several studies have shown that the application of organics or in combination with mineral fertilizer increases the overall yield of the crops compared to where fertility inputs were not used (Mucheru-Muna *et al.*, 2007; Tittonell *et al.*, 2008; Mugwe *et al.*, 2009; Chivenge *et al.*, 2011; Dunjana *et al.*, 2012; Gicheru, 2012; Mucheru-Muna *et al.*, 2014; Bedada *et al.*, 2014; Chen *et al.*, 2018). This is because the fertility inputs can sustain soil health and improve soil fertility (Satyanarayana *et al.*, 2002). Similarly, Dunjana *et al.* (2012) also noted that maize yield significantly increased when combined cattle manure and mineral fertilizer were applied. Chivenge *et al.* (2011) reported higher maize harvest from treatments that combined organic resources and fertilizers with a 114% increase and the sole application of organic inputs at 60% compared to the control.

The use of water harvesting technologies coupled with the use of fertility inputs increases the overall crop yield. Amede *et al.* (2011), Biazin *et al.* (2012), Kar *et al.* (2013) and Wouterse (2017) reported that rain water harvesting in combination with the use of both inorganic and organic inputs increases the nutrients in the soil improving crop productivity. *Zai* pits have been used as an intervention by small holder farmers to improve productivity since they improve precipitation culture and evaporation from the soil. Amede *et al.* (2011) noted that *zai* pits and a combination of fertilizer additions increased the yield of potatoes by 500% to 2000% and bean yield by 250%. Mazvimavi and Twomlow (2008) and Kimaru (2017) also noted that the use of cattle manure and *zai* pit had a higher yield compared to the conventional method of crop production. Tittonel *et al.* (2008), Mugwe *et al.* (2009), Biazin *et al.* (2012), Dunjana *et al.* (2012), Kar *et al.* (2013), Kihara *et al.* (2017) and Mi *et al.* (2018) also attributed the grain yield increase to the combined use of inorganic fertilizer and manure.

ECONOMIC FEASIBILITY OF *ZAI* PITS AND INTEGRATED SOIL FERTILITY MANAGEMENT (ISFM) OPTIONS

Cost benefit analysis is often used to determine the economic benefit of an enterprise because it determines the options that are more profitable. A study by Kalungu *et al.* (2014) and Coulibaly *et al.* (2018) implies that *zai* pits are labour intensive especially during their installation however the benefits are more in the long run. Research has shown that water harvesting techniques in crop production are more profitable. Hatibu *et al.* (2006) reported that economic returns in water harvesting in Tanzania were higher for vegetable and rice production. Similarly, Mazvimavi and Twomlow (2008) noted that higher yields were recorded in the planting pits compared to the conventional practices where manure was broadcasted. Hobbs *et al.* (2011) and Kebede *et al.* (2020) attributed the high net benefits to soil fertility amendments and water conservation techniques used in crop production.

Studies have shown that integrated nutrient management is cost effective since it can improve crop yield. Adamtey *et al.* (2016) noted that the use of ISFM was profitable both in the local and regional markets compared to the conventional method of crop production. This is an economically viable alternative for small holder farmers. The integration of legumes in ISFM often maximizes profitability and cereal-legumes intercropping being a common practice in East Africa (Vanlauwe *et al.*, 2019). Research has shown that a two staggered (MBILI) system of intercropping increases crop production and the net benefits. Mucheru-Muna *et al.* (2010) noted an increase of 40% net benefits in the MBILI system compared to the conventional method. The intercropping of maize and the legumes where N fertilizers were applied yield increased and hence the economic benefits (Kearney *et al.*, 2012; Ojiem *et al.*, 2014).

Studies have shown that the combined application of manure and mineral fertilizer yields higher net benefits compared with the sole application of the fertility inputs (Olarinde *et al.*, 2012; Girma *et al.*, 2020). Kearney *et al.* (2012), Ojiem *et al.* (2014), Matusso *et al.* (2014) and Thimmaiah *et al.* (2016) also noted that greater net benefits were recorded in a combined application of inorganics and fertilizers when compared to the application of sole inorganics and sole fertilizer. Thimmaiah *et al.* (2016) noted that a combination of NPK, vermin-compost and farmyard manure had the highest yield of grain finger millet and the gross benefits. Matusso *et al.* (2014) noted that the intercropping of maize and soybean has a significant effect on the net returns, gross monetary returns and benefit cost ratio (BCR). The use of ISFM technologies can be a feasible alternative available for supplying nutrients compared to the higher cost of purchasing fertilizers (Mucheru-Muna *et al.*, 2007). The combined application of fertilizers and manure can be adopted by the small holder farmers in drylands of Sub-Saharan Africa to supplement nutrients in the soil since they have limited purchasing power.

CONCLUSION

Research on the role of *zai* pits and integrated soil fertility management options in the drylands of Sub-Saharan Africa has shown an improvement in soil fertility, the overall crop yield and the economic returns recorded by the small holder farmers. Most of the studies have shown that the *zai* pit is a beneficial soil and water conservation strategy in the drylands of Africa since it allows the concentration of water and nutrients close to the root zone. Coupled with the combined application of fertilizer and organic resources, the efficiency of fertilizer use is increased as well as crop productivity. ISFM strategies have also been used by the small holder farmers to improve soil fertility and crop production. This is because it supplements nutrients and an alternative to expensive fertilizer.

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