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Review Article

Integrated Soil Fertility and Water Management Practices for Enhanced Agricultural Productivity

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Declining agricultural productivity has been a challenge worldwide and especially in Sub-Saharan Africa (SSA). Low agricultural productivity has been attributed to factors such as poor farm management practices, soil moisture stress, soil infertility, and soil degradation, among others. The nations in the SSA are prone to insufficient crop yields due to their inadequate capacity to adapt to good agricultural practices that support crop productivity such as integrated soil fertility and water management (ISFWM) practices. This lowers the farmers' capacity to improve crop productivity, thus contributing in jeopardizing the food and nutritional security in SSA. Past research has shown that ISFWM strategies have not been properly adopted probably due to the lack of adequate awareness among the farmers about them. In addition, there is limited documentation on the importance of ISFWM in enhancement of soil fertility, water use efficiency, and sustainable crop production in SSA. This paper discusses some of the key ISFWM options that have the potential to enhance soil fertility, improve water use efficiency, and consequently increase agricultural productivity. The practices include intercropping, use of tied ridges, minimum tillage, mulching, and combined use of organic and inorganic fertilizers.

1. Introduction

The two interrelated problems that impact all nations are the rising population growth rate and the demand for food. The population of Sub-Saharan Africa (SSA) is projected to reach 2.7 billion people by the year 2060 [1]. Due to the upsurge in population, there is a need to maintain good productivity to be able to curb the insufficient food production [2]. Most of the arable land in SSA countries is utilized for agricultural production [3]. Additionally, in most areas, especially the highland agro ecosystems, land is a scarce resource due to competition in land use systems [3]. Different unmanageable land uses have led to a decline in agricultural productivity due to the loss of soil fertility as a result of increased soil degradation arising from soil erosion and poor farm management practices [4]. One of the strategies that should be embraced by the farmers is the adoption of integrated soil fertility and water management (ISFWM) practices. These practices encompass the adoption of soil conservation, soil fertility enhancement, and water conservation practices. The main aim of ISFWM is to improve soil productivity, improve the efficiency of external inputs, and improve on farm outputs [5]. Therefore, low adoption of ISFWM practices is one of the major contributors to low crop productivity [6].

According to the reports from earlier studies, the main biophysical root causes of decreasing crop output are attributed to persistently low soil fertility and low adoption of ISFWM [7–9]. Soil infertility is mostly caused by soil nutrient erosion. Ideally, conventionally tilled plots' have declining nutrient reserves which causes the soil structure to be destroyed throughout the land preparation [10], thus causing the depletion of nutrient reserves [11]. According to

Kiboi et al. [12], continuous ploughing of lands has also been a key factor in nutrient depletion with farmers adding less or no organic amendments back to the soil. Over the years, most small-scale farmers in SSA, particularly in Kenya, have had a tendency to limit the use of soil amendments and organic fertilizers [5]. This results in the collapse of the soil structure and continuous depletion of available nutrients due to continuous uptake by the plants without adequate replenishment [13]. Lack of sustainable soil management practices has led to immense land degradation and the loss of nutrients through soil erosion [14] and leaching. In order to increase soil fertility, reduce soil depletion rates, and improve agricultural productivity, integrating soil fertility and soil and water conservation practices in the farming systems would be desirable.

Over the years, population growth in Kenya has been on the rise [15] and crop productivity has been on the decline [16, 17]. This underscores the global need to increase agricultural productivity. In SSA, about 30% of the population experiences food insecurity with the majority being resource-poor smallholder farmers in the rural settings who depend on rain-fed farming [18]. In Kenya, a huge number of the population is dependent on agricultural production, with 60% of the population working in the agricultural sector [19]. Poor soil management practices that lack adaptive strategies to climatic uncertainties intensify low agricultural productivity [20]. Such disruptions and incumbent practices result in a significant decline in yields [13]. In addition, unpredictable rainfall that results in extended dry spells and frequent droughts contributes further to the decline in agricultural productivity [21, 22]. Adoption of ISFWM practices by farmers can assist greatly in increasing agricultural productivity in a sustainable manner.

Agricultural production in most smallholder farming systems is mostly rain fed [23]. This therefore means that it is mostly in the rainy seasons when farmers can ultimately utilize the rainfall and produce agricultural crops [24]. In Kenya, it is estimated that 70% of the marketable produce is obtained from rain-fed agriculture [25], indicating that a huge number of farmers do not use irrigated water to grow their crops. According to Akinnifesi et al. [26], continuous variations in rainfall patterns caused by climatic changes are another major problem faced by farmers in rain-fed production systems. This therefore causes either prolonged droughts or floods that result in reduced agricultural production. Failure of farmers to efficiently manage the available rainwater has also contributed to soil moisture stress, thus reducing agricultural productivity [27]. The low availability of soil moisture as a result of scarce and erratic rainfall has also been documented by Kabubo-Mariara and Kabara [24] and Nathan et al. [25]. Additionally, even the drought-tolerant crops such as sorghum are affected by moisture stress during low amounts of rainfall and interseasonal dry spells thus reducing their productivity [28]. It is therefore evident that these changes in rainfall patterns directly impact agricultural productivity. Farmers, therefore, need to take action by adopting soil and water conservation practices to reduce the effects of soil moisture stresses.

Previous research shows that adoption of ISFWM practices has been extremely effective in reducing land degradation, improving soil fertility, increasing productivity, attaining agricultural sustainability, and increasing household income of farming households in Kenya [25, 29]. Unfortunately, even with ISFWM strategies being in existence for decades, the adoption rates are still low [6, 11]. In the central highlands of Kenya, only about 44% of the farmers are able to adopt integrated soil and water management practices [11, 30]. Some of the ISFWM practices that should be promoted for adoption by the farmers include suitable replenishment of soil nutrients using organic and inorganic fertilizers, use of tied ridges, minimum tillage, and mulching among others. This review documents some of the key benefits of these ISFWM options.

2. Knowledge Gaps

Food security has been on the decline over the years, and this has been attributed to various causes such as low soil fertility, water scarcity, and poor farm management practices. A majority of farmers, particularly those that operate on a small scale, have limited knowledge of soil and water management techniques that can support sustainable agricultural production. Farmers are more focused on providing subsistence crops when, on the contrary, they can economically upgrade to medium-scale or even large-scale commercial farming through proper adoption of ISFWM technologies. Although various ISFWM technologies have been in existence, their benefits are not well understood by the small-scale farmers, and hence they have not been adequately exploited to curb the low crop productivity especially in the SSA. In addition, most farmers do not understand the interactive benefits of the integrated soil fertility management (ISFM) and soil and water conservation (SWC) practices, and hence they do not apply ISFWM practices in full. Therefore, there is a need to document the pros and cons of ISFWM practices to enable the farmers to make informed adoption decisions for enhanced crop productivity.

3. Methodology

Multiple databases were used as sources of information in this review. The most used platform was Google Scholar, where initial samples of the articles were taken. A number of broad search terms were used in Google Scholar to establish a list of relevant peer-reviewed research articles. The literature search targeted the effects of the following practices in crop production: integrated soil fertility management practices; soil and water conservation; tied ridges; manure and fertilizer impacts; soil organic matter enhancement; and intercropping. From the list obtained from Google Scholar, a predefined list was obtained when using other databases such as research gate and university repositories. In addition, the snowball method was used in identifying articles in line with the purpose of this literature review.

The sources of the literature were analysed using two criteria. The first and the main one was that the source had to be appropriate and relevant to the purpose of this literature review. Secondly, the sources had to be from credible peer-reviewed journals. Information from other credible sources that aligned with this literature review was also included. Where possible, the search targeted mainly recent publications that were not more than 5 years old. In addition, only articles that are well written with proper research procedures, valid and reliable literature, and verifiable methodology were used.

3.1. ISFWM and Their Effects on Agricultural Productivity. Integrated soil fertility and water management may be defined as the integration of organic and inorganic sources of soil nutrients together with other innovative methods of preventing soil degradation and improving the soil structure to facilitate fertilizer and water use efficiency for enhanced crop production [31, 32]. There are numerous strategies that may constitute the ISFWM package. These practices are set to reduce soil erosion, maximize soil water, replenish soil nutrients, reduce nutrient loss, increase soil fertility, and improve crop productivity [5]. This paper addresses some of the key strategies that may be interlinked with the ISFWM paradigm particularly the following:

(i) Intercropping
(ii) Tied ridges
(iii) Combined use of organic and inorganic fertilizers
(iv) Minimum tillage with mulch application

3.1.1. Intercropping. Intercropping refers to the practice of growing many crop varieties in close proximity on the same plot of land so as to maximize resource utilization. Intercropping has been practiced over the years by knowledgeable and unknowledgeable farmers [33]. The utmost importance of intercropping is to boost the crop yields and reduce losses for the farmers. This is achieved when the intercropped crops make use of the available resources in the soils such as nutrients that could not have been utilized by a single crop [25]. Intercropping has many benefits which include improving soil cover and enhancing soil physical properties [34], weed controlling, minimizing pests attack on plants, controlling of diseases, promoting soil water conservation, and increasing water use efficiency among plants [25, 35]. Consequently, intercropping helps in improving soil fertility, decreasing soil nutrients loss and increasing crop yields. For example, the effects of intercropping in Zimbabwe on the smallholder farmer's field depicted significant variation between the pure cereal field and the intercropped field. The statistics showed that pure maize fields productivity was 1 t/ha, while intercropped field productivity was 1.3 t/ha [36]. Intercropping of common bean and maize was found to increase productivity of common bean by up to 2.5 $t \cdot ha^{-1}$ in Tanzania [37].

There have been different types of intercropping systems that farmers have been practicing over the years including mixed intercropping, row intercropping, relay intercropping, and strip intercropping among others. Mixed intercropping has been the most practiced form of intercropping. Most farmers do not even tend to distinguish what crops should be mixed on the same piece of land, and they mix the crops unsystematically in the little spaces available in their farms. There is therefore a need to educate farmers on effective forms of mixed intercropping whereby their preliminary benefits will be realized and help in raising the productivity levels [6]. Row intercropping is the type of intercropping whereby two or more crops are grown simultaneously with each crop type being grown in a discrete row arrangement [38]. Schulz et al. [39] and Mousavi and Eskandari [40] acknowledged some advantages of row intercropping such as increasing the crop production levels, reducing crop failure risk, and controlling weeds. Relay intercropping has been the latest form of intercropping practiced by farmers whereby two or more crops are planted on the same piece of land, but with the second crop planted after the first one has reached physiological maturity. The estimates of the yields increment due to implementation of relay intercropping are 17%–45% for cowpea and 12%–80% for pasture, all compared to conventional cowpea and pasture, respectively [41]. Another cropping practice known as strip-intercropping whereby an early-season crop is relay-planted with a late-season crop in strips on the same field has been identified as one of the most effective practices in enhancing water use efficiency [42]. Strip-intercropping was shown to increase water use efficiency by 5.64% and sorghum yield by 0.98 $t \cdot ha^{-1}$ under sorghum-cowpea intercrop [42]. Farmers in SSA have also been practicing temporal intercropping where they intercrop a very fast growing crop with a slow growing crop [43]. In this case, the fast growing crop is harvested before the slow growing crop matures, thus improving yields per unit area [44]. For example, in East Africa, cereals intercropped with pigeon pea increased their yields by 71–282% [45].

Increased food production, higher household incomes, a broader variety of food crops, and better risk management are just some of the ways in which intercropping can help farmers become more resilient [25]. For instance, soil fertility depletion which is a major contributor to reduced crop productivity worldwide and in Sub-Saharan Africa [46] can be reduced by intercropping with legumes. The legumes are usually helpful in the enhancement of soil fertility since they are capable of forming a mutually beneficial connection with rhizobia and other nitrogen-fixing soil bacteria [47]. Additionally, intercropping promotes nutrient acquisition levels as compared to mono-cropping [48]. Köpke and Nemecek [49] concluded that in phosphorus deficient soils, crops with varying characteristics can explore numerous organic P sources. For instance, higher P uptake can be attained in cereal/legume combinations on such soils compared to similar monocultures in the same type of soils. Barley-legume intercrops show 10–70% P accumulation estimates and an increment in biomass accumulation of 0–40% compared to monocultures [50]. Such systems lead to improved soil fertility while enhancing water use efficiency. A study by Fu et al. [51] showed that intercropping maize and chickpea increased soil organic matter (SOM) by 9.4% as compared to maize monocrop. In the central highlands of

Tharaka-Nithi County, intercropping in combination with manure and fertilizer has shown great performance in increasing the soil water content, increasing infiltration, enhancing water use efficiency, and increasing yields [25, 35, 52]. These empirical evidence confirm that intercropping is effective in promoting soil and water conservation by reducing the amount of soil and water lost through runoff and regulating both water infiltration and retention, thus increasing the usage of available soil water [25].

3.1.2. Tied Ridges. Tied ridges are small rectangular basin-like structures formed within the furrows of cultivated land to help the soil retain more water [6, 53, 54]. Tied ridges have a tendency to improve soil infiltration as well as soil retention since rainwater is stored in the basin like furrows for the plants to utilize [52]. The use of tied ridges helps in increasing soil water in the rhizosphere by 30% compared to nonridge sites [55]. The use of tied ridges led to an increase in rainwater use efficiency and grain yields in Northern Ethiopia of at least 40% compared to nonridged farms [53]. The ridges have been shown to store more water than no-till lands. They reduce soil water erosion thus giving time for the rainwater to infiltrate and also increase moisture retention [53]. The retained soil water in the ridges provides enough moisture to the plants and therefore improves crop productivity by generally improving water use efficiency. It has therefore been established that tied ridges have a higher ability to conserve soil moisture as compared to other water conservation practices [12]. Wolka et al. [56] reported the possibility of increasing maize yields by 7.5 to 87% when ridges are used as compared to the conventional fields.

Erratic rainfall, unreliable, insufficient, and seasonal rainwater are a significant challenge for crop production globally [28, 30]. This has resulted in soil moisture stress, a challenge that has caused about 15% crop losses globally [55]. As it is evident, agricultural production greatly relies on rain-fed agriculture, and thus soil moisture availability to crops is a major factor for increased productivity [19, 23, 57]. Low availability of soil moisture can be a result of scarce and erratic rainfall caused by climatic changes [24, 25]. Rainfall variability, scarcity, and erratic rainfall patterns have a continued effect on rainfall-dependent agriculture in the world at large [58]. Soil moisture provides optimum wet conditions for crop growth. Both drought tolerant and intolerant crops tend to dry and eventually die when faced with a minimal moisture supply [25]. In addition, low amounts of rainfall and interseasonal dry spells subject even the drought tolerant crops such as sorghum to moisture stress, thus declining their potential productivity [28, 59]. In cases when rainfall is sufficient, crop growth may be affected by the inefficient use of the available rainwater [27], hence the need to integrate soil moisture conservation with other ISFWM strategies. According to Zhao et al. [60], an integration of tied ridges and other soil and water conservation practices coupled with soil fertility practices can curb soil moisture stress and improve crop productivity.

3.1.3. Combined Use of Organic and Inorganic Fertilizers. Integration of organic and inorganic fertilizers combined with soil and water conservation measures has resulted in increased soil fertility and improved crop productivity [6]. Organic fertilizers are materials that have a very definite chemical composition and are able to add analytical value and supply nutrients to plants in their available form while inorganic fertilizers are synthetic or mineral chemicals manufactured artificially to provide essential nutrients for improved crop growth [33]. Continuous soil fertility depletion is one of the primary concerns threatening crop output and food security globally [61]. In response to the population growth and increase in food demand, land degradation has been exacerbated by the expansion of agriculture without effective land management or external inputs [62, 63]. There has been a tremendous annual decline in the nutrients in Africa by about 22 kg N ha^{-1}, 2.5 kg P ha^{-1}, and 15 kg K ha^{-1} [64]. This can be attributed to inadequate management and continuous use of nutrients without replenishment as characterized by smallholder farmers in SSA, which is the main cause of soil nutrient depletion. Continuous cropping has also led to nutrient mining [11]. Farmers do not add back to the soil the organic amendments that have been mined through continuous ploughing [65]. Due to soil erosion and nutrients deficiency in the soils, most land in SSA has been degraded [56], thus resulting in low soil fertility. The lack of adoption of integrated soil fertility and water management practices, has caused a loss of 50 $kg{\cdot}ha^{-1}$ of nutrients equivalent to US $4 billion in SSA [66]. Another main cause of low soil fertility is the fact that fertilizer prices have been increasing rapidly in Africa which also discourages its use among smallholder farmers [67].

Soil fertility can be increased by the application of water-soluble inorganic fertilizers that are easily absorbed by the plants, hence providing almost all the necessary nutrients required for plant growth [68]. The other form of fertilizers is the organic ones which include animal manure, farmyard manure, and compost manure. They are derived mainly from biodegradable organic compounds. Organic fertilizers add nutritional values to the soils by rightfully distributing nutrients to the soil [69]. They also improve the soil structure and contribute to a steady plant growth [44]. Organic fertilizers also contribute to a higher moisture absorption capacity and thus provide a platform for soils to absorb the available water and reduce the soil water erosion [70]. Contrary to inorganic fertilizers, organic fertilizers release their nutrients slowly, making them available to the soil and plants effectively and for the longest period of time, from cultivation to harvesting [71]. Organic fertilizers have the ability to improve the soil structure, soil physiochemical properties, and soil qualities while inorganic fertilizers mainly improve the soil fertility. Organic fertilizers also help reduce the negative impacts on the environment caused by inorganic fertilizers [72].

Combining organic and mineral (inorganic) fertilizers can be utilized to boost crop output and nutrient utilization efficiency [19]. This strategy increases the soil's physiochemical and biological conditions which enhances the environment for crop growth hence high yield productivity [73]. The approximate increase in production under the combination of organic and inorganic fertilizers has been reported to be 7–15% [74] due to provision of all the needed nutrients to the plants [25]. Combined use of organic and mineral fertilizers has also been identified as a water saving strategy since they improve the soil structure thus increasing infiltration and minimizing surface runoff [15]. They also increase the water holding capacity levels resulting in improved water use efficiency [75]. Asmamaw et al. [76] estimated an increase in the water holding capacity by 37 to 64% with the implementation of a combination of manure, lime, and inorganic fertilizers compared to a controlled field under Nitisols in Ethiopia. Integration of organic and inorganic fertilizers have the most sustainable increase in crop yield per unit of water used [31]. They improve the nutrients content in the soil, thus improving soil fertility and contributing largely to agricultural sustainability by increasing the productivity of crops [14]. In addition, the combination has a synergistic effect, which results in the soils improving their nutrient release and the nutrients uptake by the crop [77]. The combined fertilizers also help in improving soil infiltration rate, aggregation, bulk density, hydraulic conductance, and efficient water utilization [14], thus improving the soil status and rebuilding the soil health status [78]. The strategy also helps in reducing nutrient loss in the field as reported by Martínez-Mena et al. [14] who estimated an associated 45% reduction in nutrient losses. Integrated use of organic and inorganic fertilizers is therefore an important strategy to meet the food and feed demands brought about by an increasing population, dwindling land area, and soil infertility [25].

3.1.4. Minimum Tillage with Mulch. Minimum tillage is defined as a soil conservation system where agronomic practices are applied with very minimal soil disturbance [79]. The main goal of minimum tillage is to reduce land manipulation by reducing soil disturbances [80]. In contrast to intensive tillage whereby soil nutrients are being washed off the farming land, minimum tillage retains the bare ground cover that immensely adds to the reservoir of soil organic matter [12]. The soil structure is therefore improved while increasing the aggregate stability [11, 81, 82]. Through minimal land tillage, the undisturbed soil ground cover decreases soil erosion since the soils are less exposed to erosive forces such as runoff water or wind [83]. On the other hand, mulching is the practice of surrounding crops with a protective soil covering made mostly of organic materials such as crop residues, grass, cereal, or legume straw in order to control weeds, retain soil moisture, and lessen soil erosion caused by water or wind processes [14, 84]. Mulching enhances moisture availability through the reduction of moisture evaporation. Integrating minimum tillage with mulching raises soil organic carbon, boosts soil fertility, and lowers soil erosion [79]. As mulch decomposes, beneficial nutrients are added to the soil, hence improving soil fertility [85]. Minimum tillage with mulch has shown to have many benefits including fertilizer usage efficiency, less surface runoff, moderated soil temperatures, and improved moisture retention and infiltration, all of which culminate in increased crop yields [86]. Adoption of minimum tillage revealed an increase in sorghum yields by 11% in Kenya [87]. On the contrary, conventional tillage disturbs the soil causing more indirect soil pores that results in reduction in the infiltration rate and encourages surface runoff losses [25]. Due to soil erosion, there is an estimated annual soil loss of about 22 kg N ha^{-1}, 5 kg P ha^{-1}, and 15 kg N ha^{-1} [88]. This results in soils of poor quality that insufficiently support crop production. Practicing minimum tillage with mulch can reduce these losses by enhancing soil aggregate stability, bulk density, and soil fertility, hence improving the agricultural productivity [89–91].

4. Conclusion

This paper confirms that the decline in soil fertility and soil moisture retention can be significantly improved through the adoption of various types of ISFWM practices, thus resulting in improved crop production. Implementation of minimum tillage with mulch and the use of organic fertilizers contribute to the accumulation of adequate soil organic matter which results in increased water infiltration and improved water holding capacity, thus reducing nutrients loss from the soil through reduction of runoff and leaching. The use of tied ridges helps greatly in water conservation and prevention of soil erosion, thus improving water use efficiency while preventing soil degradation. Intercropping reduces the cost of production significantly by ensuring efficient use of production resources including water, fertilizer, land, labour, and time. Therefore, adoption of ISFWM can potentially transform agricultural production especially in SSA where production resources are scarce. However, the ISFWM technologies have not been widely adopted by the small-scale farmers and hence their benefits have not been properly exploited. There is therefore need to sensitize the small-scale farmers to the interactive benefits of various ISFWM technologies in order to promote their adoption as a package for increased agricultural productivity. The technical capacity of the farmers for the implementation of various ISFWM practices should also be enhanced.

Data Availability

No numerical data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] D. Canning, S. Raja, and A. Yazbeck, *Africa's Demographic Transition: Dividend or Disaster?* The World Bank, Washington, DC, USA, 2015.

[2] W. Fengler, *Demographic Transition and Growth in Kenya*, World Bank, Washington, DC, USA, 2010.

[3] J. Rurinda, P. Mapfumo, M. van Wijk et al., "Managing soil fertility to adapt to rainfall variability in smallholder cropping systems in Zimbabwe," *Field Crops Research*, vol. 154, pp. 211–225, 2013.

[4] C. Chandran, M. Thomas, and E. Unni, *Organic Farming: New Advances towards Sustainable Agricultural Systems*, Springer, New York, NY, USA, 2019.

[5] M. Mucheru-Muna, M. Ada, J. Mugwe et al., "Socio-economic predictors, soil fertility knowledge domains and strategies for sustainable maize intensification in Embu County, Kenya," *Heliyon*, vol. 7, no. 2, Article ID E06345, 2021.

[6] J. Mugwe, F. Ngetich, and E. Otieno, "Integrated soil fertility management in sub-saharan africa: evolving paradigms toward integration," *Zero Hunger*, pp. 1–12, Springer International Publishing, New York, NY, USA, 2019.

[7] D. Bocchiola, A. Soncini, A. Senese, and G. Diolaiuti, "Modelling hydrological components of the Rio Maipo of Chile, and their prospective evolution under climate change," *Climate*, vol. 6, no. 3, p. 57, 2018.

[8] R. Fischer and D. Connor, "Issues for cropping and agricultural science in the next 20 years," *Field Crops Research*, vol. 222, pp. 121–142, 2018.

[9] M. Mucheru-Muna, D. Mugendi, P. Pypers et al., "Enhancing maize productivity and profitability using organic in- puts and mineral fertilizer in Central Kenya small-hold farms," *Experimental Agriculture*, vol. 50, no. 2, pp. 250–269, 2014.

[10] T. Agbede, S. Ojeniyi, and A. Adeyemo, "Effect of poultry manure on soil physical and chemical properties, growth and grain yield of sorghum in southwest, Nigeria," *American-Eurasian Journal of Sustainable Agriculture*, vol. 2, no. 1, pp. 72–77, 2008.

[11] A. Okeyo, M. Mucheru-Muna, J. Mugwe et al., "Effects of selected soil and water conservation technologies on nutrient losses and maize yields in the central highlands of Kenya," *Agricultural Water Management*, vol. 137, pp. 52–58, 2014.

[12] M. Kiboi, K. Ngetich, A. Fliessbach, A. Muriuki, and D. Mugendi, "Soil fertility inputs and tillage influence on maize crop performance and soil water content in the Central Highlands of Kenya," *Agricultural Water Management*, vol. 217, pp. 316–331, 2019.

[13] C. Musafiri, J. Macharia, M. Kiboi et al., "Soil greenhouse gas fluxes from maize cropping system under different soil fertility management technologies in Kenya," *Agriculture, Ecosystems and Environment*, vol. 301, Article ID 107064, 2020.

[14] M. Martínez-Mena, E. Carrillo-López, C. Boix-Fayos et al., "Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems," *Catena*, vol. 187, Article ID 104352, 2020.

[15] M. Ndung'u, L. Ngatia, R. Onwonga et al., "The influence of organic and inorganic nutrient inputs on soil organic carbon functional groups content and maize yields," *Heliyon*, vol. 7, no. 8, Article ID e07881, 2021.

[16] M. Mucheru-Muna, D. Mugendi, J. Kung'u, J. Mugwe, and A. Bationo, "Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya," *Agroforestry Systems*, vol. 69, no. 3, pp. 189–197, 2007.

[17] J. Rockström, P. Kaumbutho, J. Mwalley et al., "Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research," *Soil and Tillage Research*, vol. 103, no. 1, pp. 23–32, 2009.

[18] V. Bjornlund, H. Bjornlund, and A. Van Rooyen, "Why agricultural production in sub-saharan Africa remains low compared to the rest of the world–A historical perspective," *International Journal of Water Resources Development*, vol. 36, no. 1, pp. S20–S53, 2020.

[19] E. Mutuku, D. Roobroeck, B. Vanlauwe, P. Boeckx, and W. Cornelis, "Maize production under combined conservation agriculture and integrated soil fertility management in the sub-humid and semi-arid regions of Kenya," *Field Crops Research*, vol. 254, Article ID 107833, 2020.

[20] B. Moebius-Clune, H. Van Es, O. Idowu et al., "Long term soil quality degradation along a cultivation chronosequence in western Kenya," *Agriculture, Ecosystems and Environment*, vol. 141, no. 1-2, pp. 86–99, 2011.

[21] J. Cobo, G. Dercon, C. Monje et al., "Cropping strategies, soil fertility investment and land management practices by smallholder farmers in communal and resettlement areas in Zimbabwe," *Land Degradation and Development*, vol. 20, no. 5, pp. 492–508, 2009.

[22] A. Belane and F. Dakora, "Symbiotic N_2 fixation in 30 field grown cowpea (*Vigna unguiculata* (L.) Walp.) Genotypes in the upper West region of Ghana measured using 15N natural balance," *Biology and Fertility of Soils*, vol. 46, no. 2, pp. 191–198, 2010.

[23] V. Phogat, M. Skewes, M. McCarthy, J. Cox, J. Šimůnek, and P. Petrie, "Evaluation of crop coefficients, water productivity, and water balance components for wine grapes irrigated at different deficit levels by a sub-surface drip," *Agricultural Water Management*, vol. 180, pp. 22–34, 2017.

[24] J. Kabubo-Mariara and M. Kabara, "Global warming and livestock husbandry in Kenya: impacts and adaptations," *Ecological Economics*, vol. 68, no. 7, pp. 1915–1924, 2009.

[25] O. O. Nathan, N. K. Felix, K. N. Milka, M. Anne, A. Noah, and M. N. Daniel, "Suitability of different data sources in rainfall pattern characterization in the tropical central highlands of Kenya," *Heliyon*, vol. 6, no. 10, Article ID e05375, 2020.

[26] K. Akinnifesi, C. Ajayi, G. Sileshi, W. Chirwa, and J. Chianu, "Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review," *Agronomy for Sustainable Development*, vol. 30, no. 3, pp. 615–629, 2010.

[27] Fao, *The State of Food Insecurity in the World*, FAO, Rome, Italy, 2015.

[28] M. Kisaka, M. Mucheru-Muna, F. Ngetich, J. Mugwe, D. Mugendi, and F. Mairura, "Rainfall variability, drought characterization, and efficacy of rainfall data reconstruction: case of Eastern Kenya," *Advances in Meteorology*, vol. 2015, Article ID 380404, 16 pages, 2015.

[29] I. Adolwa, S. Schwarze, and A. Buerkert, "Impacts of integrated soil fertility management on yield and household income: the case of Tamale (Ghana) and Kakamega (Kenya)," *Ecological Economics*, vol. 161, pp. 186–192, 2019.

[30] F. Ngetich, C. Shisanya, J. Mugwe, M. Mucheru-Muna, and D. Mugendi, "The potential of organic and inorganic nutrient sources in sub-Saharan African crop farming systems," *Soil fertility improvement and integrated nutrient management–A global perspective*, pp. 135–156, Scitus Academics, Wilmington, DE, USA, 2012.

[31] B. Vanlauwe, J. Kihara, P. Chivenge, P. Pypers, R. Coe, and J. Six, "Agronomic use efficiency of N fertilizer in maize-based systems in Sub-Saharan Africa within the context of integrated soil fertility management," *Plant and Soil*, vol. 339, no. 1-2, pp. 35–50, 2010.

[32] E. Otieno, F. Ngetich, M. Kiboi, A. Muriuki, and N. Adamtey, "Tillage system and integrated soil fertility inputs improve smallholder farmers' soil fertility and maize productivity in the Central Highlands of Kenya," *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, vol. 122, no. 2, pp. 159–171, 2021.

[33] P. Bolo, J. Kihara, M. Mucheru-Muna, E. Njeru, M. Kinyua, and R. Sommer, "Application of residue, inorganic fertilizer and lime affect phosphorus solubilizing microorganisms and microbial biomass under different tillage and cropping systems in a Ferralsol," *Geoderma*, vol. 390, Article ID 114962, 2021.

[34] M. Almagro, J. de Vente, C. Boix-Fayos et al., "Sustainable land management practices as providers of several ecosystem services under rainfed Mediterranean agroecosystems," *Mitigation and Adaptation Strategies for Global Change*, vol. 21, pp. 1029–1043, 2016.

[35] M. Mucheru-Muna, P. Pypers, D. Mugendi et al., "A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya," *Field Crops Research*, vol. 115, no. 2, pp. 132–139, 2010.

[36] F. Baudron, P. Tittonell, M. Corbeels, P. Letourmy, and K. Giller, "Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe," *Field Crops Research*, vol. 132, pp. 117–128, 2012.

[37] E. Nassary, F. Baijukya, and P. Ndakidemi, "Productivity of intercropping with maize and common bean over five cropping seasons on smallholder farms of Tanzania," *European Journal of Agronomy*, vol. 113, Article ID 125964, 2020.

[38] Y. Zhang, J. Liu, J. Zhang et al., "Row ratios of intercropping maize and soybean can affect agronomic efficiency of the system and subsequent wheat," *PLoS One*, vol. 10, Article ID e0129245, 2015.

[39] V. Schulz, C. Schumann, S. Weisenburger, M. Müller-Lindenlauf, K. Stolzenburg, and K. Möller, "Row-Intercropping Maize (Zea mays L.) with biodiversity-enhancing flowering-partners—effect on plant growth, silage yield, and composition of harvest material," *Agriculture*, vol. 10, no. 11, pp. 524–2020, 2020.

[40] S. Mousavi and H. Eskandari, "A general overview on intercropping and its advantages in sustainable agriculture," *Journal of Applied Environmental and Biological Sciences*, vol. 1, no. 11, pp. 482–486, 2011.

[41] R. Orford, "A study of pasture cropping as an alternative cropping system for sub-saharan africa," Doctoral Thesis, 2020, http://opus.uni-hohenheim.de/volltexte/2020/1771/.

[42] V. Chimonyo, A. Modi, and T. Mabhaudhi, "Water use and productivity of a sorghum–cowpea–bottle gourd intercrop system," *Agricultural Water Management*, vol. 165, pp. 82–96, 2016.

[43] M. Sileshi, R. Kadigi, K. Mutabazi, and S. Sieber, "Determinants for adoption of physical soil and water conservation measures by smallholder farmers in Ethiopia," *International soil and water conservation research*, vol. 7, no. 4, pp. 354–361, 2019.

[44] A. Ano and J. Agwu, "Effect of animal manures on selected soil chemical properties (1)," *Nigerian Journal of Soil Science*, vol. 15, pp. 14–19, 2005.

[45] A. Kiwia, D. Kimani, R. Harawa, B. Jama, and G. Sileshi, "Sustainable intensification with cereal-legume intercropping in eastern and southern Africa," *Sustainability*, vol. 11, no. 10, p. 2891, 2019.

[46] S. Zingore, J. Mutegi, B. Agesa, L. Tamene, and J. Kihara, "Soil degradation in sub-Saharan Africa and crop production options for soil rehabilitation," *Better Crops with Plant Food*, vol. 99, pp. 65–67, 2015.

[47] H. Xia, Z. Wang, J. Zhao et al., "Contribution of interspecific interactions and phosphorus application to sustainable and productive intercropping systems," *Field Crops Research*, vol. 154, pp. 53–64, 2013.

[48] Z. Wang, X. Jin, X. Bao et al., "Intercropping enhances productivity and maintains the most soil fertility properties relative to sole cropping," *PLoS One*, vol. 9, no. 12, Article ID e113984, 2014.

[49] U. Köpke and T. Nemecek, "Ecological services of faba bean," *Field Crops Research*, vol. 115, no. 3, pp. 217–233, 2010.

[50] T. Darch, C. Giles, M. Blackwell et al., "Inter-and intra-species intercropping of barley cultivars and legume species, as affected by soil phosphorus availability," *Plant and Soil*, vol. 427, no. 1-2, pp. 125–138, 2018.

[51] Z. Fu, L. Zhou, P. Chen et al., "Effects of maize-soybean relay intercropping on crop nutrient uptake and soil bacterial community," *Journal of Integrative Agriculture*, vol. 18, no. 9, pp. 2006–2018, 2019.

[52] J. Matusso, J. Mugwe, and M. Mucheru-Muna, "Potential role of cereal-legume intercropping systems in integrated soil fertility management in smallholder farming systems of Sub-Saharan Africa," *Research Journal of Agriculture and Environmental Management*, vol. 3, no. 3, pp. 162–174, 2014.

[53] A. Araya and L. Stroosnijder, "Effects of tied ridges and mulch on barley (Hordeum vulgare) rainwater use efficiency and production in Northern Ethiopia," *Agricultural Water Management*, vol. 97, no. 6, pp. 841–847, 2010.

[54] P. Tittonell, B. Vanlauwe, N. de Ridder, and K. Giller, "Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients?" *Agricultural Systems*, vol. 94, no. 2, pp. 376–390, 2007.

[55] G. Edmeades, *Progress in Achieving and Delivering Drought Tolerance in maize – an Update*, ISAAA, Ithaca, NY, USA, 2013.

[56] K. Wolka, J. Mulder, and B. Biazin, "Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: a review," *Agricultural Water Management*, vol. 207, pp. 67–79, 2018.

[57] P. Mafongoya, L. Rusinamhodzi, S. Siziba et al., "Maize productivity and profitability in conservation agriculture systems across agro-ecological regions in Zimbabwe: a review of knowledge and practice," *Agriculture, Ecosystems and Environment*, vol. 220, pp. 211–225, 2016.

[58] W. Mupangwa, S. Twomlow, and S. Walker, "Reduced tillage, mulching and rotational effects on maize (Zea mays L.): cowpea (Vigna unguiculata (Walp) L.) and sorghum (Sorghum bicolour L.) (Moench) yields under semi-arid conditions," *Field Crops Research*, vol. 132, pp. 139–148, 2012.

[59] D. Lobell, W. Schlenker, and J. Costa-Roberts, "Climate trends and global crop production since 1980," *Science*, vol. 333, no. 6042, pp. 616–620, 2011.

[60] Y. Zhao, X. Zhai, Z. Wang et al., "Simulation of soil water and heat flow in ridge cultivation with plastic film mulching system on the Chinese Loess Plateau," *Agricultural Water Management*, vol. 202, pp. 99–112, 2018.

[61] J. Ojeda, K. Pembleton, O. Caviglia, M. Islam, M. Agnusdei, and S. Garcia, "Modelling forage yield and water productivity of continuous crop sequences in the Argentinian Pampas," *European Journal of Agronomy*, vol. 92, pp. 84–96, 2018.

[62] J. Mugwe, D. Mugendi, M. Mucheru-Muna, R. Merckx, J. Chianu, and B. Vanlauwe, "Determinants of the decision to adopt integrated soil fertility management practices by smallholder farmers in the central highlands of Kenya," *Experimental Agriculture*, vol. 45, no. 1, pp. 61–75, 2009.

[63] I. Wilson, "The importance of plant health as a key to sustainable crop production in South Africa," *South African Journal of Science*, vol. 116, no. 11/12, 2020.

[64] M. Bekunda, N. Sanginga, and L. Woomer, "Restoring soil fertility in sub-sahara Africa," *Advances in Agronomy*, vol. 108, pp. 183–236, 2010.

[65] B. Vanlauwe, K. Descheemaeker, K. Giller et al., "Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation," *Soils*, vol. 1, no. 1, pp. 491–508, 2015.

[66] C. Masso, G. Nziguheba, J. Mutegi et al., "Soil fertility management in sub-saharan africa," *Sustainable Agriculture Reviews*, vol. 25, pp. 205–231, 2017.

[67] R. Sitienei, R. Onwonga, J. Lelei, and P. Kamoni, "Use of dolichos (lablab purpureus L.) and combined fertilizers enhance soil nutrient availability, and maize (zea mays L.) yield in farming systems of kabete sub-county, Kenya," *Agricultural Science Research Journal*, vol. 7, pp. 47–61, 2017.

[68] F. Triana, N. Nassi o Di Nasso, G. Ragaglini, N. Roncucci, E. Bonari, and E. Bonari, "Evapotranspiration, crop coefficient and water use efficiency of giant reed (Arundo donax L.) and miscanthus (Miscanthus× giganteus Greef et Deu.) in a Mediterranean environment," *GCB Bioenergy*, vol. 7, no. 4, pp. 811–819, 2015.

[69] C. Gao, A. El-Sawah, D. Ali, Y. Alhaj Hamoud, H. Shaghaleh, and M. Sheteiwy, "The integration of bio and organic fertilizers improve plant growth, grain yield, quality and metabolism of hybrid maize (Zea mays L.)," *Agronomy*, vol. 10, no. 3, pp. 319–2020, 2020.

[70] T. Singh, A. Ali, M. Prasad et al., "Role of organic fertilizers in improving soil fertility," in *Contaminants in Agriculture*, pp. 61–77, Springer Berlin, Germany, 2020.

[71] H. Shaji, V. Chandran, and L. Mathew, "Organic fertilizers as a route to controlled release of nutrients," in *Controlled Release Fertilizers for Sustainable Agriculture*, pp. 231–245, Academic Press Cambridge, MA, USA, 2021.

[72] T. Abedi, A. Alemzadeh, and S. Kazemeini, "Effect of organic and inorganic fertilizers on grain yield and protein banding pattern of wheat," *Australian Journal of Crop Science*, vol. 4, no. 6, pp. 384–389, 2010.

[73] B. Vanlauwe, J. Kihara, P. Chivenge, P. Pypers, R. Coe, and J. Six, "Agronomic use efficiency of N fertilizer in maize-based systems in sub- Saharan Africa within the context of integrated soil fertility management," *Plant and Soil*, vol. 339, 2011.

[74] Y. Zhang, C. Li, Y. Wang et al., "Maize yield and soil fertility with combined use of compost and inorganic fertilizers on a calcareous soil on the North China Plain," *Soil and Tillage Research*, vol. 155, pp. 85–94, 2016.

[75] R. Zougmoré, S. Partey, M. Ouédraogo, E. Torquebiau, and B. Campbell, "Facing climate variability in sub-Saharan Africa: analysis of climate-smart agriculture opportunities to manage climate-related risks," *Cahiers Agricultures*, vol. 27, no. 3, pp. 34001–34009, 2018.

[76] D. Asmamaw, P. Janssens, M. Dessie et al., "Effect of integrated soil fertility management on hydrophysical soil properties and irrigated wheat production in the upper Blue Nile Basin, Ethiopia," *Soil and Tillage Research*, vol. 221, Article ID 105384, 2022.

[77] L. Pincus, A. Margenot, J. Six, and K. Scow, "On-farm trial assessing combined organic and mineral fertilizer amendments on vegetable yields in central Uganda," *Agriculture, Ecosystems and Environment*, vol. 225, pp. 62–71, 2016.

[78] P. Vejan, R. Abdullah, T. Khadiran, S. Ismail, and A. Nasrulhaq Boyce, "Role of plant growth promoting rhizobacteria in agricultural sustainability—a review," *Molecules*, vol. 21, no. 5, p. 573, 2016.

[79] K. Michael, M. M. Monicah, B. Peter, and K. Job, "Optimizing interaction between crop residues and inorganic N under zero tillage systems in sub-humid region of Kenya," *Heliyon*, vol. 7, no. 9, Article ID e07908, 2021.

[80] R. Enninful, "Physiological characterization of parents of sorghum mapping populations exposed to water-deficit stress," [Doctoral dissertation, Kansas State University], Kansas State University Research Repository, 2019.

[81] P. Sanchez and B. Jama, *Soil Fertility Replenishment Takes off in East and Southern Africa in Integrated Plant Nutrient Management in Sub-saharan Africa: From Concept to Practice*, CAB International, New York, NY, USA, 2002.

[82] R. Derpsch, "No-tillage and conservation agriculture: a progress report," *No-Till Farming Systems*, pp. 7–39, World Association of soil and water conservation, Bangkok, Thailand, 2008.

[83] V. Zuazo and C. Pleguezuelo, "Soil-erosion and runoff prevention by plant covers: a review," *Sustainable agriculture*, vol. 28, pp. 785–811, 2009.

[84] M. Miriti, G. Kironchi, A. Esilaba, C. Gachene, L. Heng, and D. Mwangi, "The effects of tillage systems on soil physical properties and water conservation in a sandy loam soil in Eastern Kenya," *Journal of Soil Science and Environmental Management*, vol. 4, no. 7, pp. 146–154, 2013.

[85] G. Saiz, F. Wandera, D. Pelster et al., "Long-term assessment of soil and water conservation measures (fanya-juu terraces) on soil organic matter in South Eastern Kenya," *Geoderma*, vol. 274, pp. 1–9, 2016.

[86] C. Johansen, M. Haque, R. Bell, C. Thierfelder, and R. Esdaile, "Conservation agriculture for small holder rainfed farming: opportunities and constraints of new mechanized seeding systems," *Field Crops Research*, vol. 132, pp. 18–32, 2012.

[87] C. Musafiri, M. Kiboi, J. Macharia et al., "Does the adoption of minimum tillage improve sorghum yield among smallholders in Kenya? A counterfactual analysis," *Soil and Tillage Research*, vol. 223, Article ID 105473, 2022.

[88] E. Smaling, S. Nandwa, and B. Hanssen, *Soil Fertility Is at Stake; Replenishing Soil Fertility in Africa*, SSSA Special Publication No 51, Soil Science Society of America, Madison, WI, USA, 1997.

[89] E. Dube, C. Chiduza, and P. Muchaonyerwa, "Conservation agriculture effects on soil organic matter on a Haplic Cambisol after four years of maize–oat and maize–grazing vetch rotations in South Africa," *Soil and Tillage Research*, vol. 123, pp. 21–28, 2012.

[90] M. Biddoccu, S. Ferraris, A. Pitacco, and E. Cavallo, "Temporal variability of soil management effects on soil hydrological properties, runoff and erosion at the field scale in a hillslope vineyard, North-West Italy," *Soil and Tillage Research*, vol. 165, pp. 46–58, 2017.

[91] T. Matsumoto, O. Cifuentes, and T. Masunaga, "Characterization of soil properties in relation to maize productivity in Andosols of the western highland of Guatemala," *Soil Science and Plant Nutrition*, vol. 59, no. 2, pp. 195–207, 2013.