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Comprehensive Analysis of Agricultural Practices in Adapting Soil, Water and Pest Management to Climate Change in Sub-Saharan Africa

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Abstract

Agriculture constitutes the primary economic sector in Sub-Saharan African (SSA) countries, engaging over 70% of the population, predominantly vulnerable rural communities. For decades, agriculture in SSA has grappled with climatic constraints, intensifying the vulnerability of impoverished communities. In response, communities have developed indigenous practices to adapt to these climatic hazards, warranting greater recognition for potential optimization. This review identifies agricultural practices related to climate change adaptation, specifically focusing on soil management, water, and pests. The operational mechanisms of the most widely utilized practices were scrutinized through a thorough analysis. The study concludes by identifying nine practice categories. Results indicate that water collection practices and the use of organic fertilizers are the most prevalent in soil and water management. Additionally, agricultural and biological control practices dominate pest management. The comprehensive analysis underscores that the most frequently cited practices may not always be the easiest to implement. Nevertheless, these practices are agro-ecologically sustainable, contributing to soil health restoration, efficient water management, and pest control in Sub-Saharan African countries. The findings suggest a need for a research program that concentrates on the simultaneous application of these practices, enabling their optimization for more sustainable agriculture, particularly in the context of climate change adaptation and soil fertility restoration in Sub-Saharan Africa.

Keywords: climate change, soil health, crops protection, irrigation

1. Introduction

Climate change and soil degradation are major stumbling blocks to the development of countries where agriculture is the primary economic sector (IPCC, 2014; Musafuri et al., 2022). Thus, the impact of climate change is more pronounced in developing countries, particularly those in Sub-Saharan Africa (SSA), where more than half of the population is comprised of small farmers (Callaway et al., 2004 in Stringer et al., 2009; Pearce et al., 1996). Climate change is an unavoidable reality in Africa, and rural agricultural populations feel its manifestations in one way or another. Long-term changes in rainfall and temperature are the most visible (Gandure et al., 2009; Laube et al., 2011; Tui et al., 2021). Warming is strong in most of SSA Countries located in tropical and subtropical latitudes. This fact is due to high temperatures throughout the year and its variation from day to night (Nicholson, 2001). A variety of climate models predict median temperature increases in Africa of 3 to 4 ^{o}C by the end of the 21st century (Schlenker & Lobell, 2010). The effects of climate change are not limited only to water deficiency in soils. Indeed, for Sub-Saharan Africa, salinity of water and soil, heat waves as well as floods represent also the direct effects of climate change (Balgah et al., 2023; Akinsemolu et al., 2024; Reed et al., 2022).

Adaptation is a deliberate process of change that occurs in response to multiple pressures and changes in people's lives (Stringer et al., 2009; Laube et al., 2011). Alhassan et al. (2019) define environmental adaptation as actions in soil, water, and pest management practices. Soil management practices have the potential to improve soil chemical and physical fertility (VandenBygaart, 2016; Delonge & Bashe, 2017; Tui et al., 2021; Nyon et al., 2007; Wichelns, 2016). Furthermore, soil organic carbon (SOC) is widely acknowledged as being critical to soil function (Billings et al., 2021; Wiesmeier et al., 2019; Bationo et al., 2007), exerting important controls on soil structure (Yavitt et al., 2021; Kaushal, 2020; Garzon et al., 2020; Meurer et al., 2020) , moisture retention (Lal, 2020; Rawls et al., 2003; Ghezzehei et al., 2019; Dolit et al., 2022; Obour et al., 2018), nutrient cycling (Plante & Parton, 2007; Schroder et al., 2016; Plante, 2014) and biodiversity, which in turn supports a variety of provisioning, supporting, and regulatory ecosystem services (Taylor et al., 2021). Water conservation and irrigation methods are the most widely used for water management techniques (Segno et al., 2021; Kadyampakeni, 2013; Kosmowski, 2015; Wichelns, 2016).

Climate change may have a positive, negative, or no impact on each pest, and determining their global impact requires numerous studies, analyses, and models. Climate change, however, has the potential to alter the incidence of existing vector-borne diseases in humans and crops (FAO, 2007 in Alhassan et al., 2019) as well as the populations of insects and other vectors (Lema & Majule, 2009). Climate change and global warming are particularly favorable to crop-destroying insects and diseases. This could extend their geographical distribution, increase their survival during overwintering, increase the number of generations and modify the synchronization between plants and pests, alter interspecific interaction, increase risk of invasion by migratory pests, increase incidence of insect-transmitted plant diseases, and reduce effectiveness of biological control, particularly natural enemies (DeLucia et al., 2012; Lamichhane et al., 2015; Skendžić et al., 2021). Traditional pest control methods, such as agro-ecological methods and chemical products, are used in the context of climate change (Amare, 2018; Adeagbo et al., 2021; Alhassan et al., 2019).

These practices are mostly traditional in SSA, allowing small farmers to cope with the negative effects of climate change. However, these practices and techniques are numerous, making it difficult to select effective practices for long-term resilience. Furthermore, little is known about the causes and efficacy of various adaptation techniques. Alternatively, it is obvious that further research can be conducted to improve their performance if the mechanism of action of various methods and techniques of action is improved. The goal of this review is to provide an up-to-date synopsis of cultural adaptation practices to climate change in SSA related to soil, water resource management, and pests. The specific goals are to (1) inventory, through a literature review, cultural adaptation practices to climate change in SSA related to soil, water resource management, and pests; (2) understand the causes and mechanisms of action of the most cited cultural adaptation practices.

2. Methodology

This bibliographical review was carried out following three distinct steps. This involved gathering information, their analysis from various sources, their organization and the review writing. The first step involved checking through various scientific search motors such as Google Scholar and Yahoo. The informations were orgnanized in a virtual library using Zotero. The primary sources of information were then chosen based on their relevance to the review's specific topics. The next step consisted of classifying the main soils, water and pest management strategies in SSA into main categories. A bibliographical search was then carried out and the percentage of citations for each of the categories calculated. The last step was the comprehensive analysis of the most cited cultural practices.

3. Results

3.1 Cultural Practices of Soil Adaptation and Water Conservation in Sub-Saharan Africa in Response to Climate Change

The cultural practices relative to soil and water management practices to climate change that have been identified are diverse and vary from one country to another. Several practices such as construction of irrigation structures, the use of manure-compost, frequent ploughing, terracing, bounds, ditches, crop rotation, legume crops, fallowing, the shift to cheaper food items, the planting of multipurpose trees and shrubs on their farmland, are various soil and water conservation management practices inventoried (Tofu et al., 2022; Addis et al., 2021; Amare et al., 2018). Specially, agroforestry is an important option for mitigating the negative effects of climate change (Sheppard et al., 2020; Muthee et al., 2022; Gnonlonfoun et al., 2020; Mbow et al., 2014; Critchley et al., 2023; Zougmoré et al., 2018). Planting and natural regeneration of trees (Anabaraonye et al., 2022; Chomba et al., 2020; Rosenstock et al., 2019; Bayala et al., 2023) as well as planned agroforestry systems (Segnon et al., 2022), directly contribute to improve soil water retention (Debray et al., 2018; Cyamweshi et al., 2023;

Rosenstock et al., 2019). Drainage (Gebrehiwot & Gebrewahid, 2016; Burney et al., 2012; Mguni et al., 2016), growing low-maintenance crops (Balasha et al., 2013), mulch (Mhlanga et al., 2021; Brempong et al., 2023; Boillat et al., 2019), and composts are common adaptation practices (Balasha et al., 2023; Kalele et al., 2021; Ochieng et al., 2016; Toundou et al., 2021). In Ghana, for example, cocoa farmers perform the construction of bunds or drainage channels to conserve water in soils (Kuwornu et al., 2013; Amfo et al., 2021; Apuri et al., 2018; Limantol et al., 2016). Increased weeding, mulching, the use of surface water and changing the timing of farm operations were also identified as the soil-adapted practices most used in Nigeria, Uganda and Tanzania (Ozor et al., 2012; Sadiq et al., 2019; Enete et al., 2012; Kikoyo et al., 2015; Charles et al., 2013; Fadina et al., 2018). In Zimbabwe, adapted strategies include strengthening, improving indigenous land and water management practices using decision support tools such as seasonal weather forecast data, and developing irrigation infrastructure (Mutekwa et al., 2009) (Table 1).

Table 1. Main categories of soils adapting practices

Main soils adapting practices categories	Some specific techniques	Author (s)
Water Conservation Practices (construction of micro-and small-scale irrigation structure, rain-fed practices)	Ditches, terracing, stone and soil bund construction, rainwater harvesting and irrigation	Tofu et al., 2022; Partey et al., 2018; Kalele et al., 2021; Addis et al., 2021; Tesfaye et al., 2016; Amfo et al., 2021; Belay et al., 2017; Getie et al., 2020
Organic Fertilizer (manure-compost)	Manure (animal droppings, farmyard, pigs, rabbits, guinea pigs, goats, and poultry), compost (organic materials such as leaves, grass clippings, kitchen scraps and yard wastes; crops residue), zai, half-moon	Amare et al., 2018; Fadina et al., 2018; Amfo et al., 2021; Balasha et al., 2023; Kuwornu et al., 2013; Feliciano et al., 2022
Mulching Practices	Residues from leguminous crops, leaves of retained and shade trees	Fadina et al., 2018; Amfo et al., 2021; Kikoyo et al., 2015; Enete et al., 2012
Agroforestry (leguminous plants, shrubs, shades trees)	*Faidherbia albida*, *Ziziphus spina* and *Z. mauritiaca*, *Bauhinia reticulata*, *Guiera senegalens*	Partey et al., 2018; Debray et al., 2018; Fadina et al., 2018; Apuri et al., 2018; Charles et al., 2013
SMART Practices	Cropping strategies and enhanced adaptive capacity of farmers and seasonal weather forecast data	Mutekwa et al., 2009; Nyang'au et al., 2021

Only seven of the 48 countries in SSA were represented among the sources consulted regarding the adaptation of soils and water systems to climate change. Ethiopia, Ghana, Congo, Nigeria, Kenya, Zimbabwe, and Uganda. Ethiopia, Malawi, Togo, Rwanda and Ghana are the most frequently cited. The cultural practices inventoried are divided into five categories: Water Conservation Practices by Building of micro-and small-scale irrigation structures, Organic Fertilizer Use, Mulching Practices, Agroforestery, and SMART-Practices. If the construction of irrigation structures are the most useful, it is because they require few resources (Figure 1).

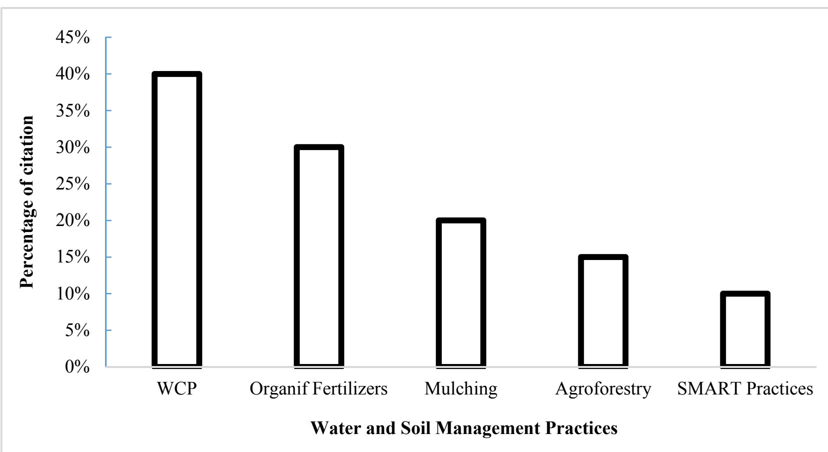

Figure 1. Percentage citation of each categories of adaptation practices (WCP = Water Collection Practices)

The rise in temperature has also long been declared as a manifestation of climate change. There is a relationship between soil temperature, its water content and ability to make nutrients available to crops. High ground temperature is often the cause of evapotranspiration. The effect of residues on soil temperature variation reduces with an increase in percent plant cover and shading of soil (Jarrah et al., 2022). During dry and warm conditions, the energy absorbed by the soil is used to warm it, increasing the release of sensitive heat flux and surface air temperatures happens in the last stage of plant growth (Garcia-Garcia et al., 2023).

Flooding has been proven in several regions of the world in recent years to be a direct consequence of climate change (Alhassan, 2020; McCarthy et al., 2020). The common technic used concerned Building of reservoirs and dams, available weather data and forecasts, restoring vegetation along the rivers, dredging of river channels, early warning system and irrigation systems (Smits et al., 2024; Abass et al., 2022).

3.2 Pest Management Cultural Adaptation Practices

Sustainable agricultural practices have the potential to improve pest management. They could be promoted for mitigating climate change (Murrell, 2017; Amare, 2018). According to these authors, the most promising practices suppressing pests and/or improving biological control are plant species diversification (mixed cropping), cover cropping, tillage practices, application of organic fertilizers (compost and manure), water management practices, biopesticides, synthetic pesticides and insectproof nets (Table 2).

Table 2. Main pest management adapting practices categories in Sub-Saharan Africa

Main pest management adapting practices categories	Some specific techniques	Author(s)
Agricultural practices	Mixed cropping (strip cropping, relay cropping, Intercropping, push-pull pest management strategy) crop rotation; cover cropping; resistant varieties	Murrell, 2017;Hassanali et al., 2008; Lang et al., 2022; Ajani et al., n.d.; Bandyopadhyay et al., 2016; De Bon et al., 2014; Edson et al., 2013; Karuri, 2022; Khan et al., 2014 Kuyah et al., 2021; Lamichhane et al., 2015; Lichtfouse, 2015; Ndakidemi et al., 2022; Ratto et al., 2022a; Acevedo-Siaca & Goldsmith, 2020; Ratto et al., 2022aRatto et al., 2022a
Biological control practices	Inert biocides (toxins derived from micro-organisms); autonomous entomophagous microbial biocides (fungi, viruses, bacteria, protozoa); predatory animals and parasitoids; plant-based biopesticides	DeLucia et al., 2012; Ajani et al., n.d.;Bandyopadhyay et al., 2016; De Bon et al., 2014; Edson et al., n.d.; Karuri, 2022; Lamichhane et al., 2015; Lang et al., 2022; Lichtfouse, 2015; Neuenschwander, 2001; Nordey et al., 2020a; Nordey et al., 2020b; Ratto et al., 2022a; Ratto et al., 2022a
Synthetic pesticides using practices	Organophosphates; pyrethroids; phenylpyrazoles; growth regulators	Ajani et al., 2013; De Bon et al., 2014; Edson et al., 2013; Karuri, 2022; Kuyah et al., 2021; Ndakidemi et al., 2022; Ratto et al., 2022a; Lessard, 2011
Physical control practices	Insectproof nets; tillage practices; trapping; mulching; traditional methods (application of livestock urine, application of wood ash, mix of different leaves, Flooding, spraying boiled water, burning of crop residuals, clearing of leaves around farmland, disturb the pests using stick manually, moving affected plants)	De Bon et al., 2014; Martin et al., 2015; Nordey et al., 2020a; Nordey et al., 2020b; Ogero et al., 2019; Karuri, 2022; Kuyah et al., 2021; Neuenschwander, 2001; Ratto et al., 2022a; Amare, 2018; Edson et al., 2013

Table 2 shows the order in which the different crop pest management categories are cited in sub-Saharan Africa. It shows that the top two most cited categories are Agricultural practices and Biological control practices.

Are these practices effective? What is their real impact on the fight against climate change in SSA? Numerous studies exist on the management of insect pests through agricultural practices (DeLucia et al., 2012; Sola et al., 2014; Lamichhane et al., 2015; Skendžić et al., 2021), but few have focused on the ranking of citation of the pest management practice categories (Figure 2). In addition, a focus on SSA could enable decision-makers, scientists and small-scale producers to better understand the impact of agricultural practices on climate change.

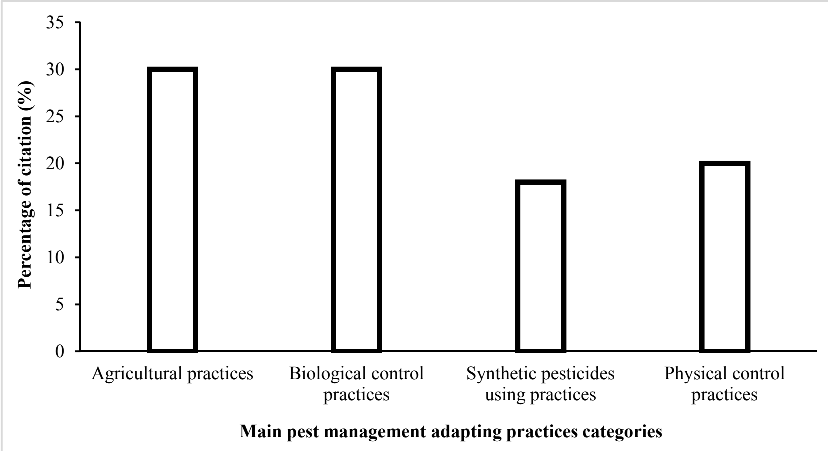

Figure 2. Ranked by order of citation of main pest management adapting practices categories in Sub-Saharan Africa

3.3 Comprehensive Analysis of the Most Widely Used Soil, Cultural and Pest Management Practices

Rainwater harvesting is a simple process or technology used to conserve rainwater by collecting, storing, conveying, and purifying rainwater that runs off of rooftops, parks, roads, and open spaces for later use. Traditional stone bunds, check dam, furrows, rainwater harvesting, ditches, traditional waterways, traditional terracing, traditional waterway, are the most commonly used physical methods for water conservation in agriculture (Tesfaye & Tekalign, 2022; Kato et al., 2009; Sileshi et al., 2019). While Rain Water Harvesting strategies have great biophysical potential as a climate change adaptation strategy, there are still locally specific barriers to their adoption that must be addressed to ensure their successful implementation on a larger scale (Lebel et al., 2015; Karpouzoglou & Barron, 2014; Amede et al., 2023). Terracing is a soil conservation technique used on hills and sloped lands. It was used by the Incas and is still widely practiced today. It entails constructing platforms in the form of step-like structures along a slope. The primary goal of terracing is to break up the slope of the land with flat sections on a regular basis; this reduces the speed of water runoff, significantly reducing soil erosion and surface runoff. Terracing techniques such as graded and level terracing are commonly used in agro-system soil conservation. Stone terraces significantly reduced total runoff by 80% and 73%, respectively, at the arid site, while also maintaining soil moisture content (Al-Seekh & Ayed, 2009). Ditches are narrow channels dug along the side of a road or field to hold or transport water, thereby improving soil conditions. Ditch encourages the growth of plants such as mudbank and reed species (Rasran & Vogt, 2017). They help to regulate water flow and nutrient retention (Herzon & Helenius, 2008; Kozelová et al., 2020) and greatly reduce ridge erosion (Levavasseur et al., 2016). The analysis shows that the terracing method retains more water than ditches and contributes significantly to the improvement of soil chemistry and biological diversity. In fact, erosion occurs when the flow of water is too fast, eroding the soil. As a result of terrace culture, the length of the hills is reduced, and the rate of evaporation of water is slowed. Planed terraces can not only reduce the rate of soil erosion, but also collect and retain rainwater. This allows for the cultivation of water-intensive crops such as rice. Terraces provide flat areas for cultures as well as channels for water flow. The water collected on the terraces can then be absorbed into the soil and used for sustainable cropping. However, terrace culture has some drawbacks, such as soil saturation with rainwater. Terrace construction and maintenance require enormous amounts of labour, and the consequences can be disastrous if they are not properly maintained. No-maintained terraces can cause mudslides, the formation of deep ravines, and soil erosion, particularly in saline soils or on extremely steep land.

Organic agriculture is an important option for adapting agrosystems to climate change (Altieri & Koohafkan, 2008). Because several studies have shown that different types of organic matter could affect soil physics parameters, increasing soil water retention capacity (Amare et al., 2018; Fadina et al., 2017). Indeed, organic matter has a positive effect on soil hydrodynamic parameters such as bulk density, wilting points, hydraulic conductivity, and soil water potential. Once degraded, organic matter provides humic acids and improves soil structure. Indeed, water is connected to earth's elements via two types of forces: osmotically and matricially. The osmotical forces result from the attraction of water to the solution of the soil, whereas the matricial forces forms the connections between the water and the soil structure. Thus, organic materials play a significant role in the strengthening of the soil's matricial forces through structural improvement. The matricial forces are divided into two groups: imbibition forces and capillary forces. Capillary forces are tension forces that allow water to be retained in fine-grained materials. This is true for clay soils, which retain more water in their surface layers than sandy soils with a more complex structure. The concept of bulk density, which provides information about the porosity and ability of the soil to retain water in its interstices, reflects this phenomenon. Organic matter can withstand disaggregation and compaction phenomena due to its ability to form stable organic and mineral complexes that confer plastic properties on the soil. This plastic property ensures proper soil operation by ensuring adequate respiration and the circulation of gases and liquids.

Agricultural intensification has led to a loss of biodiversity in recent decades. Agricultural expansion, leading to the abusive use of chemical pesticides, and the fragmentation of habitats for living creatures are the results of this intensification. The decline of birds and arthropods (insects and arachnids) has been noted (Tscharntke et al., 2005). The use of agricultural practices and methods of biological control of crop pests could reverse this trend.

Agricultural practices are those adopted during the planting of crops. They could have a real impact on production. According to Murrell (2017) and Tscharntke et al. (2005), these practices could mitigate climate change, improve pest management and provide important ecosystem services such as pollination and biological control via complementarity and sampling effects. These practices include mixed cropping (strip cropping, relay cropping, intercropping, push-pull pest management strategy) crop rotation; cover cropping; resistant varieties, etc. Mixed cropping could avoid landscape simplification which could lead to biodiversity losses intensification (Landis, 2017). The Push-Pull strategy for managing insect pests (stemborer moths) is based on crop association. One of the most telling examples in SSA is the combination of maize, *Desmodium* and sudan napier grass (*Sorghum vulgare sudanensis*) or molasses grasses (*Melinis minutiflora*). Desmodium can 'push', or repel, insect pests from maize. These insects, repelled from the maize by Desmodium, are attracted or 'pulled' by the Napier Sudan gasses planted at the edge of the field. Desmodium as cover crop is also very effective in suppressing striga weed while improving soil fertility through nitrogen fixation and improved organic matter content (Hassanali et al., 2008; Lang et al., 2022; Khan et al., 2014; Hasanah, 2014). Some authors classify the push-pull strategy as a biological method of controlling insect pests (Ratto et al., 2022b). The push-pull strategy is very interesting because it allows, through judicious combinations of crops in the fields, to effectively control populations of harmful insects while improving crop yields and respecting the environment. However, there could be concerns about its effectiveness in all countries, as different environmental conditions could influence the insect repellent volatiles (β-ocimene, β-caryophyllene and α-pinene) emitted by the *Desmodium* species used. Furthermore, in an environment where insect pests have experimented an unprecedented outbreak of resistance to broad-spectrum chemical insecticides, the push-pull strategy could prove ineffective in the first few years. The transition could be difficult for low-income farmers to bear. The diversity of insect pests in a given area could also make this strategy difficult to implement. In addition, adopting this strategy will require raising awareness among farmers, who will find it a waste of time to plant species that they do not eat, such as *Desmodium*.

Crop rotation could reduce the damage related to arthropods and microorganisms by limiting the resources available for their population (Dos Santos et al., 2011). However, the decision for planning a crop sequence takes many aspects to consider, such as market opportunities, soil characteristics, and resources (Miranda et al., 2019). Decision-makers should encourage the initiation of agro-environmental programs which encourage farmers to act in favor of the environment because it is important for the future and present agriculture (Tscharntke et al., 2005).

Biological control practices are defined as any practice that utilizes natural enemies of pests for the control of pest populations, could reduce the incidence of pests and enhance yields sustainably (Tembo et al., 2018). Other biological control techniques involve substances of plant origin (Ratto et al., 2022b). Examples of successful biological control exist in SSA. Examples of successful biological control exist in SSA include the management of the cassava mealybug, *Phenacoccus manihoti* (Homoptera: Pseudococcidae) using the neotropical parasitoid *Apoanagyrus* (Epidinocarsis) lopezi (Hymenoptera: Encyrtidae) (Neuenschwander, 2001). There is also the biological control of aflatoxins (Bandyopadhyay et al., 2016). According to Duru et al. (2015), there are two kind of ecological agricultures. The first one try to minimize environmental impacts of modern farming systems and the second one develop ecosystem services provided by biological diversity. The second strategy is the best but it is not easy to implement because of multiplicity of factors to take into account. These two concepts could be improved by the agricultural management which improve biodiversity and ecosystem functions (Barão et al., 2019). This agricultural management must give pride of place to scientific research in SSA. Academics must be involved in all strategies.

Monitoring pest and disease levels in the field could provide an effective and environmentally friendly way to combat plant pests and diseases. This monitoring consists of determining when economic thresholds are reached by an attack of pests or diseases (Ekström & Ekbom, 2011). Pest and disease management strategies could avoid excessive chemical treatments. According to Martin et al. (2008), factors such as number of sample per crops; minimum density of sample per hectare; number of pests per plant; proportion of infested plants; plant size and the weather must be taken into account. According to the same author, the monitoring technique is not fixed and the number of plants visited could be increased if the infestation level is low.

4. Conclusion

The objective of this review was to identify and better understand agricultural practices for adaptation to climate change linked to soil, water and pest management in SSA. Thus, nine categories of practices were identified and the most cited were the subject of a comprehensive analysis. In relation to soil and water management, water collection techniques and the use of organic fertilizers are the most cited. Regarding pest management, cultivation and biological control practices were the most used. This study suggests that research focuses on these four categories of practices for their optimization.

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