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Agroecological techniques: adoption of safe and sustainable agricultural practices among the smallholder farmers in Africa

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Attaining sufficiency in food supply to support a growing population without compromising ecosystem functioning remains a top agenda of researchers and agricultural stakeholders. Agroecological farming approaches are effective techniques that ensure sustainable food production even in adverse situations. Population growth has been forecasted to reach over 9.1 billion by 2050 outpacing food production. However, cereals and grain legumes are strategic to achieving the United Nations Sustainable Development Goal of zero hunger by 2030 (SDG 2), ending extreme poverty (SDG 1), and mitigating the climate change effect (SDG 13). There remains an urgent need to embrace more sustainable measures to increase food production for the growing population. This review explores the role of agroecology which employs a transdisciplinary approach to sustainable agricultural practices to improve the resilience of farming systems by increasing diversification through poly-cropping, agroforestry, use of local varieties, and integrated crop and livestock systems. Furthermore, the agroecological farming approach minimizes water use, lowers pollution levels on the farm, and ensures economic profitability for the farmers. Thus, application of agroecology techniques among the smallholder farmers is strategic to ensuring food security.

KEYWORDS

agroecological farming, sustainable development goals, sustainable food production, small-scale farmers, economic profitability

Introduction

The United Nation's second Sustainable Development Goal (SDGs-2) aims to "end hunger, achieve food security and better nutrition," and promote sustainable agriculture by 2030 (Lartey, 2015). However, the current state of global agricultural and food systems does not guarantee adequate nutrition and food security. There are currently around a billion hungry people globally, which is forecasted to double as the global population reaches 9.1 billion by 2050 (Tripathi et al., 2019; Ikrang et al., 2022). Although over 60% of the population depends on agriculture for food and income, the current population growth rate has outpaced food production (Porkka et al., 2017; Odusola, 2021). Contemporary agricultural practices are characterized by expansive monocultures, the use of high-yielding crop varieties, synthetic fertilizers and agrochemicals including pesticides, fuel-based mechanization, and extensive irrigation operations. Although these practices are able to increase yields, they have failed to eliminate hunger and thereby raise serious concerns regarding the economic, social, and environmental sustainability of the modern farming practices. Industrial agriculture also produces between 25 and 30% of the world's greenhouse gas (GHG) emissions, further aggravating the effects of climate change and jeopardizing the ability of the planet to provide sufficient and nutritious food into the future (Liu et al., 2020).

The current annual usage of pesticides stands at over 2.6 million tons with a market value of more than US$ 25 billion (Rajbhandari, 2017; Abd-Aziz et al., 2022). Such massive use of pesticides often impairs natural regulating systems and contributes towards the loss of biodiversity that would otherwise support food production. The use of high-yielding crop varieties and synthetic fertilizers appears to offer only short-term benefits and have failed to stem declining yields, especially among major cereal and legume production regions (Rajbhandari, 2017; Kuyah et al., 2021). Meanwhile, the current rate of global population's growth has outpaced that of food production, hence, resulting in severe food shortages, chronic hunger and malnutrition especially among the least developed regions of the world (Smith and Glauber, 2020). Many African nations are currently in this category. Despite agriculture being considered as the backbone of the economy and its significant contribution to the livelihood of majority in Africa, most nations in the continent are still challenged by factors which hinders agricultural productivities such as declining soil fertility, climate change effects, water shortages, post-harvest losses, and restricted market access among others (Gashu et al., 2019). This condition has presently resulted in food security challenges, as recently reported in Ethiopia (Yigezu Wendimu, 2021), South Africa (Chakona and Shackleton, 2018), Nigeria (Ayinde et al., 2020), Ghana (Atanga and Tankpa, 2021), Rwanda (Chigbu et al., 2019), and Cameroon (Mbuli et al., 2021) among many others. Hence, the need for a new paradigm for agricultural growth that supports more environmentally friendly, biologically diversified, long-lasting, resilient, and socially acceptable agricultural practices.

The foundation for these new agricultural systems comprise at least 75% of the 1.5 billion smallholder composed largely of family farmers and indigenous people operating 350 million small farms that occupies about 20% of the world's arable land and providing no less than 50% of the world's agricultural production for home consumption (Machovina et al., 2015). Agroecology which has been increasingly recognized for its potential to bring about the transformative changes necessary to meet the SDGs is one such holistic and people-centered farming approach that embraces a long-term vision and has the potential to help successful transitions towards sustainable agriculture and food systems (Anderson et al., 2019a). Agroecology is an applied science that employs ecological concepts and principles to build and manage sustainable agroecosystems with minimal reliance on external inputs but more on natural processes like biological control and natural soil fertility without expanding the agricultural land base (Hathaway, 2016). This ecology-based discipline is characterized by five principles: diversity, efficiency, natural regulation, synergies, and recycling (Anderson et al., 2019a). Agroecological transitions toward more sustainable agriculture and food systems have been categorized into three major categories namely; increasing eco-efficiency, input substitution, and system redesign (Landert et al., 2020).

Agricultural intensification: applications of sustainability in diverse settings

The need for sustainable agriculture came to the limelight in the early 1980s in response to a variety of ecological concerns However, since sustainable agriculture is a normative notion, different fields and affiliations have given it diverse meanings (Mohd Hanafiah et al., 2020). However, the traditional view of sustainable agriculture frequently concentrates on contexts of on-farm and watershed-level sustainability of agriculture with an emphasis on ecological and agronomic dimensions (Martin et al., 2018). Although the commonly practiced conventional approach of agriculture which entails utilization of non-organic fertilizer and pesticides has made considerable strides, but has disregarded some crucial contextual features such as the culture, food tradition, human and social values, and only partially able to identify some broad trends in sustainable agriculture. Since the 1950s, industrialization, and uniformity in the production, transportation, and sale of food and fiber have caused the agricultural systems to become more and more defined by monocultural landscapes. There has therefore been an increase in the consolidation of small farms and the tendency toward economies of scale (Petersen-Rockney et al., 2021). Conventional agriculture in industrialized nations has been negatively linked to excessive energy use, the loss of small farms, and local biodiversity within its framework of massive, heavily financed, automated farms and expanding food networks (Gomiero et al., 2008). These unfavorable consequences have had a significant impact on how the idea of sustainable agriculture has emerged in industrialized nations. In these nations, attempts to reorganize the environmental, sociocultural, geographical, and temporal components of the traditional food system serve as the foundation for ideological concepts of sustainable agriculture (Eakin et al., 2017). This reframes the link between agriculture and the environment by utilizing techniques like organic and biodynamic farming (Muhie, 2023). The nature of the geographical and temporal exchanges that occur in traditional agriculture has also changed as a result of the use of alternative food channels that connect customers and producers directly, such as farmers' markets and community-supported agriculture.

In contrast to industrialized nations, efforts towards sustainable agriculture in poor nations place a greater emphasis on the economic independence, health, and cultural lives of producers than on the esthetics or environmental advantages to the consumers. Agroecological management-based crop and animal diversification reduces the economic risk and uncertainty associated with pest and disease outbreaks and declining prices of agricultural produce (Garrett et al., 2020). Therefore, an integrated farming system with diverse forms of production is characterized by the integration and recycling of various on-farm components to enhance the economic benefits and self-sufficiency in resource utilization (Garrett et al., 2020; Hercher-Pasteur et al., 2021). The intricacies of resource use in sustainable agricultural initiatives in poor nations differ from those in developed countries. Movements for sustainable agriculture in developing nations have emerged as an immediate response to the national economic crises by thriving toward a self-sufficient economy (Lang and Barling, 2012). Therefore, the practices of agroecology have been embraced as approaches that offer resilience for restructuring agricultural development, in spite of the variation in the practice of sustainable agriculture and food security from country to country. The report of Wezel et al. (2014) enumerated a total of 15 the agroecological practices, 9 of which was considered as poorly integrated in agriculture such as the applications of natural pesticides, biofertilizers, crop rotations and crop choice, agroforestry with fruit, nut trees or timber, intercropping and relay intercropping, mulching or direct seeding into living cover crops and integration of semi natural landscape elements at field and farm. However, the agroecological practices that are already well integrated include reduced tillage, organic fertilization, split fertilization, cultivar choice and biological pest control.

Adoption of agroecological techniques among the smallholder farmers: the impact on food sovereignty

Small-scale agriculture has, in recent times, received more global attention. This is a result of the realization of its immense potential contribution to solving food security problem even in the face of energy, economic and climate change challenges (Simon et al., 2020). More so, agroecology principles support the plight of the small-scale farmers for food sovereignty. According to La *Via* Campesina, "Food Sovereignty is the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems" (Huambachano, 2019). In essence, food sovereignty describes how food security could be attained. Thus, the concepts of food sovereignty and agroecological-based production systems have received a lot of attention globally over the past 20 years, due to their prospects of increasing food production and bettering the lives of the poorest. Therefore, if the most effective agricultural methods are to be employed, a radical change toward agroecology must be embraced (Peredo Parada et al., 2020) because ecologically based management strategies in agroecosystems and agricultural landscapes can increase the sustainability of agricultural production while reducing off-site consequences Matson et al. (1997).

Agroecology is one of the most reliable routes of attaining sustainable development in the face of the current and expected future climatic, energy, and economic conditions (Streimikis and Baležentis, 2020). Currently, the global "agrarian revolution" is receiving its scientific, methodological, and technical foundation from agroecology (Kohler and Negrão, 2018). Hence, the agroecology-based production system is the foundation of the food sovereignty approach because they are resilient, efficient, biodiverse, and socially acceptable (Anderson et al., 2019b). It is a system that is characterized by a vast diversity of domesticated plant and animal species that are maintained and improved to ensure the appropriate biodiversity, soil conservation, and water regime management that are supported by intricate traditional knowledge systems (Marchetti et al., 2020). These systems have nourished a vast majority of the population for generations. The practice of small-scale farming employs the principles of recycling, diversity, synergy, and integration as well as social processes that value community involvement and empowerment, is the major means of promoting an agroecological development paradigm set to meet the world's food needs in this era of increasing oil cost and climate change coupled with the socioecological importance of peasant agriculture (Wezel et al., 2020).

The agroecological features of smallholder farming systems have demonstrated an efficient farming techniques without depending on the aid of chemical fertilizers, pesticides, mechanization, or other modern agricultural science technologies (Altieri et al., 2012). Traditional farmers in many developing nations have created complex farming techniques that have been passed down from generation to generation. A successful indigenous agricultural strategy is shown by the continued use of more than 3 million hectares of traditional agriculture in the form of terraces, raised fields, agroforestry systems, and polycultures, among others (Koohafkan and Altieri, 2011). Thus, the majority of traditional agroecosystems share some outstanding characteristics, which entail a stable agroecosystem that is resilient, minimizes the risk of losses, and adapts to adverse conditions caused by human or natural events. The traditional practices as well produce a variety of products that support both food and livelihood security (Quiroz-Guerrero et al., 2020). More so, these systems are supported by farmers' inventions, technology, and traditional knowledge, which results in high levels of biodiversity that are essential for controlling the ecosystem function and for delivering important ecosystem services from local to global levels (Singh M., 2021). The traditional agroecosystems are characterized by innovative landscapes, water and land resource management, and conservation technologies that enhance ecosystem management. Also, socio-cultural practices, such as ingrained institutions for agroecological management, normative agreements for resource access and benefit sharing, value systems, etc., are governed by strong cultural values (Marchi et al., 2018; Tittonell, 2020).

Agricultural systems are dynamic and influenced by population growth, scientific and technological advancements, global market forces, agricultural subsidies, consumer demands, climatic change and variability, and pressure from social movements calling for land reform, food sovereignty, and poverty reduction (Harmanny and Malek, 2019). Agroecologists have therefore redesigned and optimized smallholders' agricultural systems using agroecological concepts and techniques in order to make them more responsive to these factors and potentially viable in a world that is changing rapidly (Barrios et al., 2020). The majority of what could be considered the pillars of sustainable management of agricultural systems are shared by most of the agroecological-based systems that have been successful in terms of productivity and resilience (Sandhu, 2021). These entail (i) raising the production efficiency of all farms, (ii) improving the resilience and ensuring risk reduction, (iii) enhancing biodiversity, ecological services, and resource conservation (iv) supporting social justice, cultural diversity, and economic prosperity, (v) increasing reliance on renewable resources while improving natural cycles, and (vi) preventing damage to the environment and to the land. Agroecological systems obviously place strong emphasis on promoting food sovereignty, which advocates for the right and access of everyone to food that is safe, nourishing, and culturally appropriate for food in sufficient quantity and quality to supports a healthy life while maintaining human dignity. In furtherance of this, the agroecological plan also aims at improving energy and technical sovereignty in light of the anticipated rise in the cost of fuel and inputs (Ramankutty and Dowlatabadi, 2021).

We therefore hypothesize that re-designing of the food systems through agroecological techniques entails consideration of the contributory roles of the biotic and abiotic influences on the ecological services and agroecosystem functions. Mores so, the farmers planned agroecological techniques which aims at attaining improved soil quality and plant health, higher productivity, enhanced socio-ecological resilience, autonomy and food sovereignty are further shaped by innovative approaches and social movements. Thus, achieving these requires an enabling environment for agroecological practices that could be derived through responsible governance. More so, agroecological production and consumption are facilitated by the context and innovative approaches that modulates the social and institutional improvements while the practice of circular and solidarity economy prioritizes the promotion and development of local economies by promoting solutions based on the local needs, resources, and the capabilities to build a fairer and sustainable markets that empowers the smallholders' farmers (Figure 1).

Agroecology and sustainable agricultural practices: the African perspectives

Smallholder farmers reportedly feed about one-third of the 238 million people who live in towns and cities, and the majority of the 712 million hungry people who live in rural and remote areas across the world (Altieri et al., 2012). This implies that small-scale farming supports about half of the world's population, and produces at least 70% of the world's food, this on plots averaging 2 ha (Kihara et al., 2020; Sheppard et al., 2020). More so, millions of smallholders and their family, and indigenous people are engaged in resource-conserving farming, a practice that has greatly contributed to food security and improvement of agricultural systems despite the unfavorable climatic and environmental conditions in many areas (Powlson et al., 2011). The traditional agricultural practices that are still operational in many countries throughout Asia, Latin America, and Africa make up an important and inventive agricultural heritage that reflects the value of the diversity of agricultural practices adapted to different environments. This makes up a significant neolithic heritage, although modern agriculture continuously jeopardizes the viability of this legacy (Koohafkan and Altieri, 2011). More than 1.9 million plant types have been reportedly submitted to the world's gene banks by indigenous farmers and peasants, who have created 5,000 domesticated crop species (Kinfe and Tesfaye, 2018). Also, rather than use commercial hybrid seeds, majority of smallholders cultivate their crops using self-bred seeds. Farmers are protected by such genetic diversity from pests, diseases, droughts, and other pressures as the population of diverse and adaptable landraces, as well as weedy and wild relatives of crops, can be found in traditional agroecosystems (Mercer et al., 2019). They are also able to make use of the whole spectrum of agroecosystems that exist in each location and vary in terms of altitude, slope, water availability, soil quality, etc (Quiroz et al., 2018). The stability of agricultural systems is increased by genetic diversity, which also enables farmers to take advantage of various microclimates and employ genetic variation across species for a variety of nutritional and other purposes (Nonić and Šijačić-Nikolić, 2021; Singh R. P., 2021).

According to recent studies, many smallholder farmers adapt to and even prepare for climate change by using more drought-tolerant local varieties, water collecting techniques, agroforestry, mixed cropping, soil conservation measures, and a variety of other age-old methods to reduce crop failure (Nyang'au et al., 2021). Small-scale farms constitute the majority of farms and farm produce, especially in rural Asia and Africa. For instance, only a few of the farmers cultivate more than 2 hectares of rice out of over 200 million rice farmers that reside throughout Asia, and the majority of the rice produced by Asian small-scale farmers is made up of local cultivars, which are often cultivated in highland environments or under rain-fed circumstances (Altieri et al., 2012). About half of the global small-scale farms are practiced on 193 million ha in China, followed 93 million in India representing 23% of global small-scale farms, then Indonesia, Bangladesh, and Vietnam (Shams et al., 2020). In

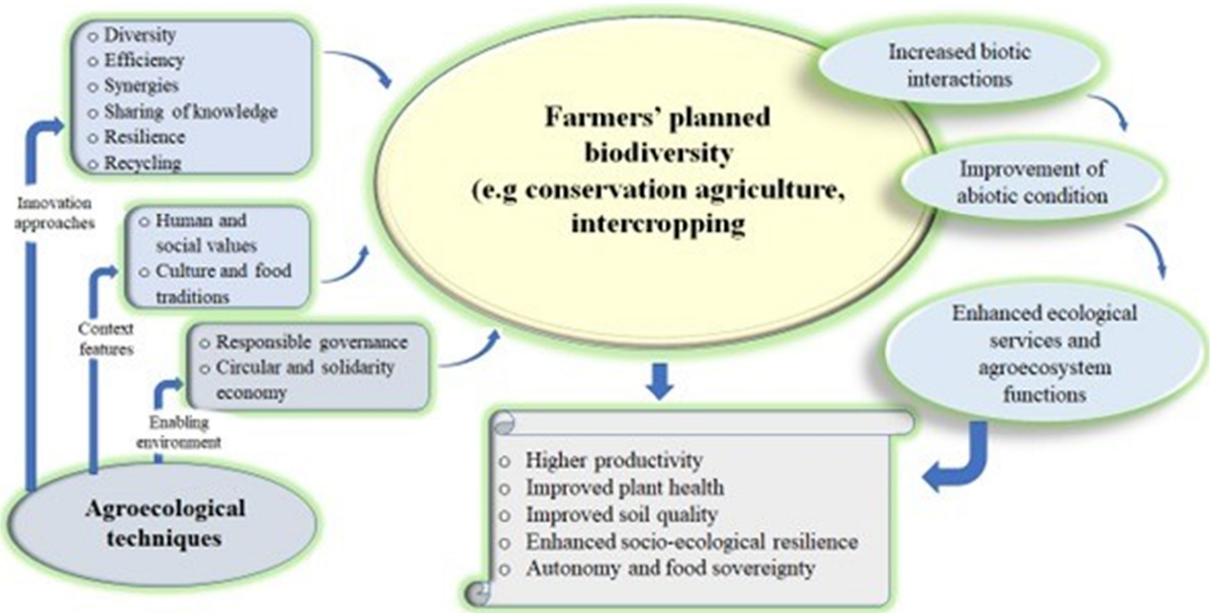

FIGURE 1
The agroecological features of smallholder farming systems.

China alone, there are about 75 million rice farmers who continue to employ techniques dated back to more than a thousand years (Altieri and Nicholls, 2017). In Latin America, smallholder's production units employ 16 million peasant farmers who produce 51 percent of the region's maize, 77 percent of its beans, and 61 percent of its potatoes while providing about 41% of the agricultural output for domestic consumption (McMichael and Schneider, 2011). In Brazil, about 4.8 million family farmers who comprise about 85% of the entire country's farming community work on 30% of Brazil's total agricultural land (Cabral et al., 2016). Similarly, the National Program for Local Innovation in Cuba has successfully spread agroecological innovations that have been shown to improve food security and food sovereignty while coping with and reducing the negative impact of climate change (Fernandez et al., 2018).

Africa presents a peculiar situation as regards the adoption of agroecological practices among the small-scale farmers. A number of farmers, mostly women, were of the opinion that the agroecological models place further pressure on the small-scale farmers by their need to prepare organically acceptable farm additives such as composts, biochar and biopesticides by themselves (Mestmacher and Braun, 2021). More so, the assurance of obtaining better performance as in the case of disease management compared to the conventional farming technique is not guaranteed. Some, therefore, opined that agroecological models are too restrictive to transform the agricultural sector as advocated but rather lure farmers into unproductive farming practices (Mugwanya, 2019). However, this opinion could be a result of the technical know-how, and the limited investigations on agroecology in Africa (Wezel et al., 2014, 2020), especially when the practice of agroecology requires a tailored understanding of plants, biogeochemical and climate relationships (Bezner Kerr et al., 2019), the knowledge that directly impact productivity that may not be readily available to smallholder farmers until they are adequately trained. Consequent to the claims of some that agroecological systems can only provide meager yields, a searchlight on the contribution of Africa to agroecology in the agricultural operations of the smallholder farmers revealed that around 33 million small farms exist in Africa accounting for more than 80% of all the farms on the continent (Hilson et al., 2021). Two-thirds of all African small farms are less than 2 ha, while 90% of all farms are smaller than 10 ha (Conway, 2011).

Largely, smallholder practitioners in Africa are women who engage in "low-resource" agriculture, providing the bulk of the region's grains and nearly all the root and tuber crops, including plantain and most of the legumes consumed (Altieri et al., 2012). Furthermore, smallholder agriculture and rural economic activities have been reported to provide over 60% of the livelihoods in Sub-Saharan African countries, and their effectiveness of operations is influenced by the choice of development strategy, which is hinged on the application of traditional systems (Okoh and Hilson, 2011). This strategy has sped up the pace of change in rural areas, demonstrating an effective and resilient indigenous agricultural strategy and serving as models of sustainability by promoting biodiversity, thriving without agrochemicals, and maintaining year-round yields in the face of societal pressures (Gomiero et al., 2011). Thus, the struggle and goals of rural movements are consistent with agroecology as a science since it upholds rather than undermines peasant logic, optimizes the design of local agricultural systems, and draws on local knowledge and resources. Additionally, agroecology is socially energizing because it depends on community involvement and horizontal techniques of information exchange to function (Levidow et al., 2014). This is evident in the UK government's Foresight Global Food and Farming project, where 40 initiatives and programs were examined in 20 African nations where sustainable crop intensification was pushed from the 1990s to the 2000s (Altieri et al., 2012). Crop enhancements, conservation agriculture, agroforestry, and soil preservation, integrated pest management, horticulture, aquaculture, livestock and fodder crops, and creative policies and collaborations were among the initiatives (Strapasson et al., 2020). The report revealed that by the beginning of 2010, these initiatives have produced improvements on over 12.75 million hectares and demonstrated benefits for 10.39 million farmers and their families. Since the agricultural yields increased by 2.13 times on average as a result of the introduction of new and improved varieties, food outputs from sustainable intensification were considerable (Mondal and Palit, 2021).

Agriculture contributes significantly to Kenya's economy, about 30% of the nation's Gross Domestic Product (GDP), over 60% of exports, 75% of the labor force, and more than 80% of industrial raw materials come from agriculture (Tomich et al., 2018). Although Kenyan smallholder farmers who are mostly engaged in crop production still require more resources to adopt sustainable agriculture and enhance their production efficiency, there is a paucity of empirical evidence and minimal research on the farmers' productivity (Abdulai and Hazell, 1996). Meanwhile, one of the most successful diversification strategies in Africa is agriculture-agroforestry-based practices. Evidence from Tanzania, Malawi, Zambia, Mozambique, and Cameroon revealed that the cultivation of maize alongside quick-growing nitrogen-fixing shrubs such as Tephrosia and Calliandra, increases total maize output of 8 t/ha as opposed to 5 t/ha under monoculture (Altieri et al., 2012). Similarly, the grain yield increase of up to 280 percent was recorded in Malawi when compared to the region outside of the tree canopy (Garrity et al., 2010). Furthermore, in the maize-Faidherbia system in Maradi and Zinder regions of Niger, where about 4.8 million hectares of Faidherbia were cultivated in fields containing up to 150 trees per hectare. The trees shielded maize plants from sweltering breezes, prevented the land from wind and water, while increasing agricultural yields. The success of this program encouraged the launch of such initiatives in other Sahelian countries to support the farmer-managed natural regeneration of Faidherbia and other species (Reij and Smaling, 2008).

Agroecological initiatives adopted in African countries also include the combined maize and legume farming, which is followed by rice in the following season as practiced by farmers in Madagascar to sustain soil fertility (Rodenburg et al., 2020). Madagascar farmers similarly employ the association of food crops (groundnut, Bambara bean, etc.) with *Stylosanthes guianensis* cv. CIAT 184 in rotation with rice on the poor soils, as directed by the Groupement Semis Direct de Madagascar (Michellon et al., 2011). Mostly, the presence of *Striga asiatica* in several regions of the nation is one of the main factors that instigated the practice of conservation agriculture, and thus served as a point of entry for the spread of agroecology techniques in the country (Michellon et al., 2011). In addition, the intercropping of maize with cover crops such as pigeon pea and *D. lablab* enables the farmers to produce three harvests even with greater yields in a season instead of the usual two harvests. Hence, the production index under conservation farming increased from 1.25 t/ha in 2004 to 7.0 t/ha in 2009, Thereby leading to significant decrease in the amount of work and time needed to expend on farm operations, and more smallholders embraced this program in the consequent cultivation periods (Owenya et al., 2011; Table 1).

Agroecological practices support biodiversity conservation and promote social justice

Farming practices rooted in agroecological principles are not new in Africa but rather have been the norm for millennia. Intercropping and crop varietal mixtures, crop rotations, weedy margins around gardens, mulches, ridging, bush fallows are common features of historical farming systems of Africa. In Uganda, coffee-banana systems are familiar; bananas provide shade to the coffee (Ssebunya et al., 2019). Similar to this is this cocoa-plantain system in Nigeria and Ghana, where the young cocoa plants benefit from the shade provided by the growing plantain (Dzomeku et al., 2008; Agbongiarhuoyi et al., 2016). In another instance, the system involves coffee and a few tree species like *Markhamia, Ficus* that provide timber, firewood, and fodder. There is no doubt that the root systems of the trees and the resulting litters provide mulch that support a wealth of soil microbes that contribute to a balanced edaphic system (Kalanzi, 2011). Predatory ants are often a constituent of mulched banana gardens and have been proven to constrain the population growth of banana weevils, [*Cosmopolites sordidus* (Germar)] in the plantation (Abera-Kalibata et al., 2006; Okolle et al., 2020). Furthermore, maize is often intercropped with beans or other legumes Intercropping entails the growing of crop varietal mixtures helps to reduce pest and disease incidence (Mulumba et al., 2012) while promoting a component of food security (availability). Soil and soil-water conservation practices like "soil basins", ridging, use of animal manures is widely used in many regions of Africa. The high vegetation diversity associated with agronomic practices based on agroecology sustains a wealth of biodiversity much of which is beneficial (pollinators, natural enemies, "soil engineers") and enables plant vigor.

While ecological farming may lessen many of the disservices associated with conventional farming, it should also be recognized that it is often associated with drudgery and may not be the ultimate solution to Africa's food crises. The current rates of population growth and urbanization may not allow for some techniques and much of the youthful population may opt for alternative forms of income, rather than farming. Declining soil fertility levels and erratic rainfall cannot be ignored; but call for the adoption of technological advancements that can cause significant increases in yield. What is perhaps needed is a well-thought-out mix of the best practices offered by both conventional and ecological farming. For instance, rather small-scale technologies like 'walking tractors' may be preferred over use of oxen; solar-powered water pumps for drip irrigation may be alternatives to rain-fed farming and large-scale irrigation schemes; motor-driven threshers and communal silos may be preferable over manual threshing and traditional homestead granaries. Such technological advancements may have a lower ecological footprint while reducing the labor burden and drudgery of traditional farming systems.

Conclusion and future applications of agroecology in Africa

Agroecology has been described as the cornerstone of sustainable agriculture. Beside its core ecological values in enhancing resource conservation and biodiversity leading to increased production efficiency, other essential features include the creation of an enabling environment for agroecological practices, which is achieved through responsible governance, circular and solidarity economy as shown in Figure 1. Hence, agroecology transcends the science and practice of agriculture to include social movement built on the tenets of ecology, food sovereignty, sustainability, justice, gender equity, farmer networks, resilience, resistance and access to land. It is a system that has been stimulated in response to the food and financial crises of 2008, as opposed to the detrimental effects of capital-intensive methods adopted during the so-called "Green Revolution." Hence, the innovations inherent in agroecological techniques are now gaining prominence due to its participatory approaches, community engagement and local knowledge as a guide. However, unlike the economic and institutional interests and support for agro-industrial based research and development in most African nations, less attention has been paid to research and development for agroecological and sustainable agriculture, which constitute a major arm of agroecology. This needs to be undertaken to overcome the barrier to the acceptance and spread of agroecological practices. Thus, an enabling environment that favors the implementation of agroecological-based farming techniques needs to be created by undertaking significant reforms in the policies, institutions, and the research and development agendas.

The alliances of various actors and organizations involved in the agroecological revolution is essential in enabling adequate coordination of the program. Apart from upscaling the knowledge and application of agroecological innovations, farmers will as well have increased access to government services, seeds, lands, and markets for their produce. Furthermore, the agroecological-based farming technique can be encouraged in African countries through the direct participation of farmers and scientists in the development of the research agenda to promote active engagement in the dissemination of innovative technologies using 'Campesino a Campesino model' where researchers and extension experts could play a pivotal facilitation role. This will enhance the development of sustainable agroecological alternatives that meet the needs of small-scale farmers and the low-income non-farming population, hence restoring the local food systems.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

TABLE 1 The agroecological practices in some African countries.

Country	Crop	Agroecological model	Implications of the intervention	References
Tanzania, Malawi, Zambia, Mozambique, and Cameroon	Maize	Maize cultivation in fast-growing nitrogen-fixing shrubs (e.g., Tephrosia and Caliandra)	increases total maize output of 8 t/ha as opposed to 5 t/ha achieved under monoculture	Altieri et al. (2012)
Niger, Malawi, and the southern highlands of Tanzania	Faidherbia	Faidherbia cultivated with tree crops	Increases yield while trees serve as shield crops from sweltering breezes and prevent wind and water erosion	Reij and Smaling (2008)
Madagascar	Maize, legume, and rice	Maize and legume intercropping, followed by rice cultivation	Sustain the soil fertility	Rodenburg et al. (2020)
	Groundnut, Bambara bean, rice e.t.c	Groundnut, Bambara bean, rice etc. with *Stylosanthes guianensis* cv. CIAT 184 in rotation with rice on the poor soils	Increases crop growth and soil fertility	Michellon et al. (2011), Altieri et al. (2012)
Tanzania	Maize, sorghum and millet	Conservation agricultural practices, organic fertilization	Significantly higher yields were obtained under organic fertilization than under no-fertilizations	Mkonda and He (2023)
	Maize, pigeon pea	Conservation agriculture, intercropping of maize with cover crops such as pigeon pea and *D. lablab.*	Results in greater yields, drought tolerance and produces three harvests instead of two harvests per season	Owenya et al. (2011)
Uganda	Maize	Cultivation of maize with velvet bean (*Mucuna pruriens*),	Generate organic matter and fix soil nitrogen. Increased maize yields. Reduced costs on labor and pesticides were completely removed	Kaizzi et al. (2004)
South Africa	Maize, potatoes, sugarcane	crop diversification, intercropping of maize with food crops, i.e., sugarcane, potatoes, and vegetables.	Enhancing soil fertility and crop yield, mitigating income and production risks	Hitayezu et al. (2016)
	Maize, sunflower	Application of rhizobacteria as soil treatment	Increased growth and yield, mitigation of drought stress	Bundy (1988), Adeleke and Babalola (2021), Agbodjato et al. (2021), Ojuederie et al. (2019)
Rwanda	Maize	Mulching, ridges,	Increase yield, resistance to drought	Uwizeyimana et al. (2018)
	Common bean	Narrow row planting	Increase crop growth and yield	Dusabumuremyi et al. (2014)
	Banana	Disease control through 'complete diseased mat uprooting' and 'single diseased stem removal'	Control of *Xanthomonas* wilt of banana showed that 'single diseased stem removal' was an effective, less labor intensive and less costly method	Blomme et al. (2021)
Nigeria	Maize	Use of endemic atoxigenic strains, biochar, compost, plant extracts	Increase in plant growth and yield, management of fungal diseases of maize	Akanmu et al. (2020, 2021), Dlamini et al. (2022), Donner et al. (2009), Olawuyi et al. (2014)

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TABLE 1 (Continued)

Country	Crop	Agroecological model	Implications of the intervention	References
Zimbabwe	Maize	Conservation agriculture: direct seeding, rip-line seeding, and seeding into planting basins on maize grain yield, soil health and profitability across agroecological regions in Zimbabwe	Reduced soil erosion and bulk density, and increased soil water content. Greater macrofauna abundance and diversity than conventional agriculture	Mafongoya et al. (2016)
Zambia	Maize	Sustainable agricultural practices involve agroforestry, intercropping, and overcrops.	Increased productivity and efficient soil management. Results in the enhanced relationship between land tenure and the use of mulching, tree planting, manure and mineral fertilizers	Nkomoki et al. (2018)
Ghana	Apple, cocoa	Agroecological practices such as organic fertilizers, crop rotation, organic pest and weed control, mulching, cover crops, trees, soil and water conservation	Organic certification increases agroecological practice use. Improvement of soil nutrient	Kleemann and Abdulai (2013), Quaye et al. (2021)
Lesotho	Maize	Crop diversification and livestock integration	High-value intercrops such as pumpkins recorded higher farm economic margin than their monocropping counterparts.	Seko and Jongrungrot (2022)
Senegal	Peanuts	Indigenous agroecosystems through processes of biodiversification	Boosted soil fertility and agricultural productivity	Faye and Braun (2022)
Benin	Bananas and Plantain	Crop association, mechanical destruction of diseased plants, banana plantation in shallows, trap plants, crop rotation, compost use and poultry manure use.	Sustainable production and management of plant diseases caused by Fusarium sp., nematodes and banana bunchy top virus	Dassou et al. (2021)
Burkina Faso	Cereal - legume	(a) Use of organic matter with or without micro-dose mineral fertilization (b) the localized application of organic manure in planting pits dug into hard pan land (zaï), with and without cereal-legume rotation	Enhances soil microbiological activities	Somda et al. (2022)
Mali	Cereal and legumes	Crop residue management, cereal-legume cropping rotations and intercropping, biological pest control through predator rearing, agroforestry, and the use of trees as fences	improved yields due to some better management of agricultural resources.	Paracchini et al. (2020)

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References

Abd-Aziz, S., Gozan, M., Ibrahim, M. F., and Phang, L. Y. (2022). Demand and sustainability of palm oil plantation. *Biorefinery Oil Produc. Plants Value Add. Prod.* 1, 11–28. doi: 10.1002/9783527830756.ch2

Abdulai, A., and Hazell, P. B. (1996). The role of agriculture in sustainable economic development in Africa. *J. Sustain. Agric.* 7, 101–119. doi: 10.1300/J064v07n02_10

Abera-Kalibata, A. M., Hasyim, A., Gold, C. S., and Van Driesche, R. (2006). Field surveys in Indonesia for natural enemies of the banana weevil, *Cosmopolites sordidus* (Germar). *Biol. Control* 37, 16–24. doi: 10.1016/j.biocontrol.2005.11.009

Adeleke, B. S., and Babalola, O. O. (2021). The endosphere microbial communities, a great promise in agriculture. *Int. Microbiol.* 24, 1–17. doi: 10.1007/s10123-020-00140-2

Agbodjato, N. A., Adoko, M. Y., Babalola, O. O., Amogou, O., Badé, F. T., Noumavo, P. A., et al. (2021). Efficacy of biostimulants formulated with Pseudomonas putida and clay, peat, clay-peat binders on maize productivity in a farming environment in Southern Benin. *Fronti. Sustain. Food Sys.* 5:666718. doi: 10.3389/fsufs.2021.666718

Agbongiarhuoyi, A., Ayegboyin, K., Ogunlade, M., and Orisajo, S. (2016). Farmers' use of Banana instead of plantain as shade crop in cocoa establishment: a case of Cross River state, Nigeria. *World Rural Observ.* 8, 14–22. doi: 10.7537/marswro08011604

Akanmu, A. O., Babalola, O. O., Venturi, V., Ayilara, M. S., Adeleke, B. S., Amoo, A. E., et al. (2021). Plant disease management: leveraging on the plant-microbe-soil interface in the biorational use of organic amendments. *Front. Plant Sci.* 1590. doi: 10.3389/fpls.2021.700507

Akanmu, A. O., Sobowale, A. A., Abiala, M. A., Olawuyi, O. J., and Odebode, A. C. (2020). Efficacy of biochar in the management of Fusarium verticillioides Sacc. causing ear rot in Zea mays L. *Biotechnol. Rep.* 26:e00474. doi: 10.1016/j.btre.2020.e00474

Altieri, M. A., Funes-Monzote, F. R., and Petersen, P. (2012). Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. *Agron. Sustain. Dev.* 32, 1–13. doi: 10.1007/s13593-011-0065-6

Altieri, M. A., and Nicholls, C. I. (2017). The adaptation and mitigation potential of traditional agriculture in a changing climate. *Clim. Chang.* 140, 33–45. doi: 10.1007/s10584-013-0909-y

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., and Pimbert, M. P. (2019a). From transition to domains of transformation: getting to sustainable and just food systems through agroecology. *Sustainability* 11:5272. doi: 10.3390/su11195272

Anderson, C. R., Maughan, C., and Pimbert, M. P. (2019b). Transformative agroecology learning in Europe: building consciousness, skills and collective capacity for food sovereignty. *Agric. Hum. Values* 36, 531–547. doi: 10.1007/s10460-018-9894-0

Atanga, R. A., and Tankpa, V. (2021). Climate change, flood disaster risk and food security Nexus in northern Ghana. *Front. Sustain. Food Syst.* 5:706721. doi: 10.3389/fsufs.2021.706721

Ayinde, I. A., Otekunrin, O. A., Akinbode, S. O., and Otekunrin, O. A. (2020). Food security in Nigeria: impetus for growth and development. *J. Agric. Econ. Rural Develop.* 6, 808–820.

Barrios, E., Gemmill-Herren, B., Bicksler, A., Siliprandi, E., Brathwaite, R., Moller, S., et al. (2020). The 10 elements of agroecology: enabling transitions towards sustainable agriculture and food systems through visual narratives. *Ecosyst. People* 16, 230–247. doi: 10.1080/26395916.2020.1808705

Bezner Kerr, R., Young, S. L., Young, C., Santoso, M. V., Magalasi, M., Entz, M., et al. (2019). Farming for change: developing a participatory curriculum on agroecology, nutrition, climate change and social equity in Malawi and Tanzania. *Agric. Hum. Values* 36, 549–566. doi: 10.1007/s10460-018-09906-x

Blomme, G., Dusingizimana, P., Ntamwira, J., Kearsley, E., Gaidashova, S., Rietveld, A., et al. (2021). Comparing effectiveness, cost-and time-efficiency of control options for Xanthomonas wilt of banana under Rwandan agro-ecological conditions. *European Journal of Plant Pathology* 160, 487–501. doi: 10.1007/s10658-021-02258-z

Bundy, C. (1988). *The rise and fall of the South African peasantry (2nd edn.)*. Cape Town, South Africa. 276.

Cabral, L., Favareto, A., Mukwereza, L., and Amanor, K. (2016). Brazil's agricultural politics in Africa: more food international and the disputed meanings of "family farming". *World Dev.* 81, 47–60. doi: 10.1016/j.worlddev.2015.11.010

Chakona, G., and Shackleton, C. M. (2018). Household food insecurity along an agro-ecological gradient influences children's nutritional status in South Africa. *Front. Nutr.* 4:72. doi: 10.3389/fnut.2017.00072

Chigbu, U. E., Ntihinyurwa, P. D., de Vries, W. T., and Ngenzi, E. I. (2019). Why tenure responsive land-use planning matters: insights for land use consolidation for food security in Rwanda. *Int. J. Environ. Res. Public Health* 16:1354. doi: 10.3390/ijerph16081354

Conway, G. (2011). On being a smallholder. In Paper presented at the IFAD Conference on new Directions for Smallholder Agriculture, 25.

Dassou, A. G., Tovignan, S., Vodouhè, F., Vodouhè, G. T., Tokannou, R., Assogba, G.-C., et al. (2021). Constraints, and implications of organic farming in bananas and plantains production sustainability in Benin. *Agric. Sci.* 12, 645–665. doi: 10.4236/as.2021.126042

Dlamini, S. P., Akanmu, A. O., and Babalola, O. O. (2022). Rhizospheric microorganisms: The gateway to a sustainable plant health. *Front. Sustain. Food Sys.* 6:925802. doi: 10.3389/fsufs.2022.925802

Donner, M., Atehnkeng, J., Sikora, R. A., Bandyopadhyay, R., and Cotty, P. J. (2009). Distribution of Aspergillus section Flavi in soils of maize fields in three agroecological zones of Nigeria. *Soil Biol. Biochem.* 41, 37–44. doi: 10.1016/j.soilbio.2008.09.013

Dusabumuremyi, P., Niyibigira, C., and Mashingaidze, A. B. (2014). Narrow row planting increases yield and suppresses weeds in common bean (Phaseolus vulgaris L.) in a semi-arid agro-ecology of Nyagatare, Rwanda. *Crop Protection* 64, 13–18. doi: 10.1016/j.cropro.2014.05.021

Dzomeku, B. M., Staver, C., Aflakpui, G., Sanogo, D., Garming, H., Ankomah, A. A., et al. (2008). Evaluation of the dissemination of new Banana (Musa spp.) Technologies in Central Ghana-the role of technology characteristics. In IV International Symposium on Banana: International Conference on Banana and Plantain in Africa: Harnessing International, pp. 735–740.

Eakin, H., Connors, J. P., Wharton, C., Bertmann, F., Xiong, A., and Stoltzfus, J. (2017). Identifying attributes of food system sustainability: emerging themes and consensus. *Agric. Hum. Values* 34, 757–773. doi: 10.1007/s10460-016-9754-8

Faye, J. B., and Braun, Y. A. (2022). Soil and human health: understanding agricultural and socio-environmental risk and resilience in the age of climate change. *Health Place* 77:102799. doi: 10.1016/j.healthplace.2022.102799

Fernandez, M., Williams, J., Figueroa, G., Graddy-Lovelace, G., Machado, M., Vazquez, L., et al. (2018). New opportunities, new challenges: harnessing Cuba's advances in agroecology and sustainable agriculture in the context of changing relations with the United States. *Elem. Sci. Anth.* 6:76. doi: 10.1525/elementa.337

Garrett, R. D., Ryschawy, J., Bell, L. W., Cortner, O., Ferreira, J., Garik, A. V., et al. (2020). Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. *Ecol. Soc.* 25:24. doi: 10.5751/ES-11412-250124

Garrity, D. P., Akinnifesi, F. K., Ajayi, O. C., Weldesemayat, S. G., Mowo, J. G., Kalinganire, A., et al. (2010). Evergreen agriculture: a robust approach to sustainable food security in Africa. *Food Security* 2, 197–214. doi: 10.1007/s12571-010-0070-7

Gashu, D., Demment, M. W., and Stoecker, B. J. (2019). Challenges and opportunities to the African agriculture and food systems. *Afr. J. Food Agric. Nutr. Dev.* 19, 14190–14217. doi: 10.18697/ajfand.84.BLFB2000

Gomiero, T., Paoletti, M. G., and Pimentel, D. (2008). Energy and environmental issues in organic and conventional agriculture. *Crit. Rev. Plant Sci.* 27, 239–254. doi: 10.1080/07352680802225456

Gomiero, T., Pimentel, D., and Paoletti, M. G. (2011). Environmental impact of different agricultural management practices: conventional vs. organic agriculture. *Crit. Rev. Plant Sci.* 30, 95–124. doi: 10.1080/07352689.2011.554355

Harmanny, K. S., and Malek, Ž. (2019). Adaptations in irrigated agriculture in the Mediterranean region: an overview and spatial analysis of implemented strategies. *Reg. Environ. Chang.* 19, 1401–1416. doi: 10.1007/s10113-019-01494-8

Hathaway, M. D. (2016). Agroecology and permaculture: addressing key ecological problems by rethinking and redesigning agricultural systems. *J. Environ. Stud. Sci.* 6, 239–250. doi: 10.1007/s13412-015-0254-8

Hercher-Pasteur, J., Loiseau, E., Sinfort, C., and Hélias, A. (2021). Identifying the resource use and circularity in farm systems: focus on the energy analysis of agroecosystems. *Resour. Conserv. Recycl.* 169:105502. doi: 10.1016/j.resconrec.2021.105502

Hilson, G., Sauerwein, T., and Cardoso, M. E. (2021). "Small-scale mining, rural resilience and the sustainable development goals in sub-Saharan Africa" in *In Handbook of sustainable politics and economics of natural resources* (Cheltenham: Edward Elgar Publishing).

Hitayezu, P., Zegeye, E. W., and Ortmann, G. F. (2016). Farm-level crop diversification in the Midlands region of Kwazulu-Natal, South Africa: patterns, microeconomic drivers, and policy implications. *Agroecol. Sustain. Food Sys.* 40, 553–582. doi: 10.1080/21683565.2016.1156595

Huambachano, M. A. (2019). Indigenous food sovereignty. *N. Z. J. Ecol.* 43, 1–6. doi: 10.20417/nzjecol.43.39

Ikrang, E. G., Unwana, I. U., and Precious, O. E. (2022). The use of artificial intelligence in tractor field operations: a review. *Poljoprivredna Tehnika* 47, 1–14. doi: 10.5937/PoljTeh2204001G

Kaizzi, C. K., Ssali, H., and Vlek, P. L. (2004). The potential of Velvet bean (Mucuna pruriens) and N fertilizers in maize production on contrasting soils and agro-ecological zones of East Uganda. *Nut. Cycling Agroecosys*. 68, 59–72. doi: 10.1023/B:FRES.0000012233.27360.60

Kalanzi, F. (2011). Farmers' evaluation of agroforestry tree species in Robusta coffee (*Coffea canephora* Pierre ex Froehner) cultivation Systems in Bukomansimbi District, Uganda, MSc thesis. Technische Universität Dresden, Germany.

Kihara, J., Bolo, P., Kinyua, M., Nyawira, S. S., and Sommer, R. (2020). Soil health and ecosystem services: lessons from sub-Sahara Africa (SSA). *Geoderma* 370:114342. doi: 10.1016/j.geoderma.2020.114342

Kinfe, H., and Tesfaye, A. (2018). Yield performance and adoption of released sorghum varieties in Ethiopia Edelweiss. *Appl. Sci. Technol.* 2, 46–55. doi: 10.33805/2576.8484.115

Kleemann, L., and Abdulai, A. (2013). Organic certification, agro-ecological practices and return on investment: Evidence from pineapple producers in Ghana. *Ecol. Econ.* 93, 330–341. doi: 10.1016/j.ecolecon.2013.06.017

Kohler, F., and Negrão, M. (2018). The homeopathy/agroecology nexus: a discourse-centered analysis in a Brazilian agrarian settlement. *Dialect. Anthropol.* 42, 241–255. doi: 10.1007/s10624-018-9499-4

Koohafkan, P., and Altieri, M. A. (2011). *Globally important agricultural heritage systems: a legacy for the future*, Rome: Food and Agriculture Organization of the United Nations Rome.

Kuyah, S., Sileshi, G. W., Nkurunziza, L., Chirinda, N., Ndayisaba, P. C., Dimobe, K., et al. (2021). Innovative agronomic practices for sustainable intensification in sub-Saharan Africa a review. *Agron. Sustain. Dev.* 41, 1–21. doi: 10.1007/s13593-021-00673-4

Landert, J., Pfeifer, C., Carolus, J., Schwarz, G., Albanito, F., Muller, A., et al. (2020). Assessing agro-ecological practices using a combination of three sustainability assessment tools. *Landbauforschung* 70, 129–144. doi: 10.3220/LBF1612794225000

Lang, T., and Barling, D. (2012). Food security and food sustainability: reformulating the debate. *Geogr. J.* 178, 313–326. doi: 10.1111/j.1475-4959.2012.00480.x

Lartey, A. (2015). End hunger, achieve food security and improved nutrition and promote sustainable agriculture. *UN Chron.* 51, 6–8. doi: 10.18356/5940d90a-en

Levidow, L., Pimbert, M., and Vanloqueren, G. (2014). Agroecological research: conforming—or transforming the dominant agro-food regime? *Agroecol. Sustain. Food Syst.* 38, 1127–1155. doi: 10.1080/21683565.2014.951459

Liu, X., Elgowainy, A., and Wang, M. (2020). Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products. *Green Chem.* 22, 5751–5761. doi: 10.1039/D0GC02301A

Machovina, B., Feeley, K. J., and Ripple, W. J. (2015). Biodiversity conservation: the key is reducing meat consumption. *Sci. Total Environ.* 536, 419–431. doi: 10.1016/j.scitotenv.2015.07.022

Mafongoya, P., Rusinamhodzi, L., Siziba, S., Thierfelder, C., Mvumi, B. M., Nhau, B., et al. (2016). Maize productivity and profitability in conservation agriculture systems across agro-ecological regions in Zimbabwe: a review of knowledge and practice. *Agri. Ecosys. Environ.* 220, 211–225. doi: 10.1016/j.agee.2016.01.017

Marchetti, L., Cattivelli, V., Cocozza, C., Salbitano, F., and Marchetti, M. (2020). Beyond sustainability in food systems: perspectives from agroecology and social innovation. *Sustainability* 12:7524. doi: 10.3390/su12187524

Marchi, M., Ferrara, C., Biasi, R., Salvia, R., and Salvati, L. (2018). Agro-forest management and soil degradation in mediterranean environments: towards a strategy for sustainable land use in vineyard and olive cropland. *Sustainability* 10:2565. doi: 10.3390/su10072565

Martin, G., Allain, S., Bergez, J.-E., Burger-Leenhardt, D., Constantin, J., Duru, M., et al. (2018). How to address the sustainability transition of farming systems? A conceptual framework to organize research. *Sustainability* 10:2083. doi: 10.3390/su10062083

Matson, P. A., Parton, W. J., Power, A. G., and Swift, M. J. (1997). Agricultural intensification and ecosystem properties. *Science* 277, 504–509. doi: 10.1126/science.277.5325.504

Mbuli, C. S., Fonjong, L. N., and Fletcher, A. J. (2021). Climate change and small farmers' vulnerability to food insecurity in Cameroon. *Sustainability* 13:1523. doi: 10.3390/su13031523

McMichael, P., and Schneider, M. (2011). Food security politics and the millennium development goals. *Third World Q.* 32, 119–139. doi: 10.1080/01436597.2011.543818

Mercer, K. L., Vigouroux, Y., Castaneda-Alvarez, N., De Haan, S., Hijmans, R. J., Leclerck, C., et al. (2019). "Crop evolutionary agroecology: genetic and functional dimensions of agrobiodiversity and associated knowledge," in *Agrobiodiversity: integrating knowledge for s sustainable future.* eds. K. S. Zimmerer and S. Haan (Cambridge, MA: USA: MIT Press), 21–62.

Mestmacher, J., and Braun, A. (2021). Women, agroecology and the state: new perspectives on scaling-up agroecology based on a field research in Chile. *Agroecol. Sustain. Food Syst.* 45, 981–1006. doi: 10.1080/21683565.2020.1837330

Michellon, R., Husson, O., Moussa, N., Randrianjafizanaka, M. T., Naudin, K., Letourmy, P., et al. (2011). *Striga asiatica*: a driving-force for dissemination of conservation agriculture systems based on *Stylosanthes guianensis* in Madagascar. In Resilient food systems for a changing world/5th World Congress of Conservation Agriculture (WCCA) Incorporating 3rd Farming System Design conference, Brisbane, Australia.

Mkonda, M. Y., and He, X. (2023). The Influence of Soil Organic Carbon and Climate Variability on Crop Yields in Kongwa District, Tanzania. *Environ. Manag.* 71, 170–178. doi: 10.1007/s00267-022-01592-0

Mohd Hanafiah, N., Mispan, M. S., Lim, P. E., Baisakh, N., and Cheng, A. (2020). The 21st century agriculture: when rice research draws attention to climate variability and how weedy rice and underutilized grains come in handy. *Plan. Theory* 9:365. doi: 10.3390/plants9030365

Mondal, S., and Palit, D. (2021). "Ecological intensification for sustainable agriculture and environment in India" in *Ecological intensification of natural resources for sustainable agriculture*. eds. M. K. Jhariya, R. S. and Meena, A. Banerjee (Singapore: Springer), 655.

Mugwanya, N. (2019). Why agroecology is a dead end for Africa. *Outlook Agric.* 48, 113–116. doi: 10.1177/0030727019854761

Muhie, S. H. (2023). Concepts, principles, and application of biodynamic farming: a review. *Circ. Econ. Sustain.* 3, 291–304. doi: 10.1007/s43615-022-00184-8

Mulumba, J., Nankya, R., Adokorach, J., Kiwuka, C., Fadda, C., De Santis, P., et al. (2012). A risk-minimizing argument for traditional crop varietal diversity use to reduce pest and disease damage in agricultural ecosystems of Uganda. *Agric. Ecosyst. Environ.* 157, 70–86. doi: 10.1016/j.agee.2012.02.012

Nkomoki, W., Bavorová, M., and Banout, J. (2018). Adoption of sustainable agricultural practices and food security threats: Effects of land tenure in Zambia. *Land Use Policy* 78, 532–538. doi: 10.1016/j.landusepol.2018.07.021pineapplepr

Nonić, M., and Šijačić-Nikolić, M. (2021). "Genetic Diversity: Sources, Threats, and Conservation," in *Life on Land*. eds. W. Leal Filho, A. M. Azul, L. Brandli, A. Lange Salvia, and T. Wall (Springer International Publishing), 421–435.

Nyang'au, J. O., Mohamed, J. H., Mango, N., Makate, C., and Wangeci, A. N. (2021). Smallholder farmers' perception of climate change and adoption of climate smart agriculture practices in Masaba south sub-county, Kisii. *Kenya. Heliyon* 7:e06789. doi: 10.1016/j.heliyon.2021.e06789

Odusola, A. (2021). "Agriculture as the fulcrum of inclusive development in Africa" in *Africa's agricultural renaissance*. (Cham: Palgrave Macmillan, Cham).

Ojuederie, O. B., Olanrewaju, O. S., and Babalola, O. O. (2019). Plant growth promoting rhizobacterial mitigation of drought stress in crop plants: Implications for sustainable agriculture. *Agronomy* 9:712. doi: 10.3390/agronomy9110712

Okoh, G., and Hilson, G. (2011). Poverty and livelihood diversification: exploring the linkages between smallholder farming and artisanal mining in rural Ghana. *J. Int. Dev.* 23, 1100–1114. doi: 10.1002/jid.1834

Okolle, N., Ngosong, C., Nanganoa, L., and Dopgima, L. (2020). Alternatives to synthetic pesticides for the management of the banana borer weevil (*Cosmopolites sordidus*) Coleoptera Curculioniidae. *CABI Rev.* 2020:26. doi: 10.1079/PAVSNNR202015026

Olawuyi, O. J., Odebode, A. C., Olakojo, S. A., Popoola, O. O., Akanmu, A. O., and Izenegu, J. O. (2014). Host–pathogen interaction of maize (Zea mays L.) and Aspergillus niger as influenced by arbuscular mycorrhizal fungi (Glomus deserticola). *Arch. Agron. Soil Sci.* 60, 1577–1591. doi: 10.1080/03650340.2014.902533

Owenya, M. Z., Mariki, W. L., Kienzle, J., Friedrich, T., and Kassam, A. (2011). Conservation agriculture (CA) in Tanzania: the case of the Mwangaza B CA farmer field school (FFS), Rhotia Village, Karatu District, Arusha. *Int. J. Agric. Sustain.* 9, 145–152. doi: 10.3763/ijas.2010.0557

Paracchini, M., Justes, E., Wezel, A., Zingari, P. C., Kahane, R., Madsen, S., et al. (2020). Agroecological practices supporting food production and reducing food insecurity in developing countries. A study on scientific literature in 17 countries.

Peredo Parada, S., Barrera, C., Burbi, S., and Rocha, D. (2020). Agroforestry in the Andean Araucanía: an experience of agroecological transition with women from Cherquén in southern Chile. *Sustainability* 12:10401. doi: 10.3390/su122410401

Petersen-Rockney, M., Baur, P., Guzman, A., Bender, S. F., Calo, A., Castillo, F., et al. (2021). Narrow and brittle or broad and nimble? Comparing adaptive capacity in simplifying and diversifying farming systems. *Front. Sustain. Food Syst.* 5:564900. doi: 10.3389/fsufs.2021.564900

Porkka, M., Guillaume, J. H., Siebert, S., Schaphoff, S., and Kummu, M. (2017). The use of food imports to overcome local limits to growth. *Earth's Future* 5, 393–407. doi: 10.1002/2016EF000477

Powlson, D. S., Gregory, P. J., Whalley, W. R., Quinton, J. N., Hopkins, D. W., Whitmore, A. P., et al. (2011). Soil management in relation to sustainable agriculture and ecosystem services. *Food Policy* 36, S72–S87. doi: 10.1016/j.foodpol.2010.11.025

Quaye, A. K., Doe, E. K., Attua, E. M., Yiran, G., Arthur, A., Dogbatse, J. A., et al. (2021). Geospatial distribution of soil organic carbon and soil pH within the cocoa agroecological zones of Ghana. *Geoderma* 386:114921. doi: 10.1016/j.geoderma.2020.114921

Quiroz, R., Ramírez, D. A., Kroschel, J., Andrade-Piedra, J., Barreda, C., Condori, B., et al. (2018). Impact of climate change on the potato crop and biodiversity in its center of origin. *Open Agric.* 3, 273–283. doi: 10.1515/opag-2018-0029

Quiroz-Guerrero, I., Pérez-Vazquez, A., Landeros-Sánchez, C., Gallardo-López, F., Velasco-Velasco, J., and Benítez-Badillo, G. (2020). Resilience as an adaptation strategy of agroecosystems in the light of climate change. *AGROProductividad* 13, 61–67. doi: 10.32854/agrop.v13i11.1815

Rajbhandari, B. P. (2017). *Bio-intensive farming system and sustainable livelihoods*. Kathmandu: HICAST Pub., ill. Bibl.

Ramankutty, N., and Dowlatabadi, H. (2021). Beyond productivism versus agroecology: lessons for sustainable food systems from Lovins' soft path energy policies. *Environ. Res. Lett.* 16:91003. doi: 10.1088/1748-9326/ac1e3f

Reij, C. P., and Smaling, E. (2008). Analyzing successes in agriculture and land management in sub-Saharan Africa: is macro-level gloom obscuring positive micro-level change? *Land Use Policy* 25, 410–420. doi: 10.1016/j.landusepol.2007.10.001

Rodenburg, J., Randrianjafizanaka, M. T., Büchi, L., Dieng, I., Andrianaivo, A. P., Ravaomanarivo, L. H. R., et al. (2020). Mixed outcomes from conservation practices on soils and Striga-affected yields of a low-input, rice–maize system in Madagascar. *Agron. Sustain. Dev.* 40, 1–11. doi: 10.1007/s13593-020-0612-0

Sandhu, H. (2021). Bottom-up transformation of agriculture and food systems. *Sustainability* 13:2171. doi: 10.3390/su13042171

Seko, Q. A., and Jongrungrot, V. (2022). Economic modelling and simulation analysis of maize-based smallholder farming systems in the Senqu River valley agroecological zone. *Lesotho. Cogent Food Agric.* 8:2086287. doi: 10.1080/23311932.2022.2086287

Shams, S., Newaz, S., and Karri, R. R. (2020). "Information and Communication Technology for Small-Scale Farmers: Challenges and Opportunities," in *Smart Village Technology. Modeling and Optimization in Science and Technologies, vol 17*. eds. S. Patnaik, S. Sen and M. Mahmoud (Cham: Springer).

Sheppard, J. P., Bohn Reckziegel, R., Borrass, L., Chirwa, P. W., Cuaranhua, C. J., Hassler, S. K., et al. (2020). Agroforestry: an appropriate and sustainable response to a changing climate in southern Africa? *Sustainability* 12:6796. doi: 10.3390/su12176796

Simon, X., Montero, M., and Bermudez, Ó. (2020). Advancing food security through agroecological technologies: the implementation of the biointensive method in the dry corridor of Nicaragua. *Sustainability* 12:844. doi: 10.3390/su12030844

Singh, M. (2021). Organic farming for sustainable agriculture. *Indian J. Organ. Farm.* 1, 1–8. doi: 10.22271/ed.book.1348

Singh, R. P. (2021). Genetically distinct cultivar hybrids for the treatment of insect pests and increased agricultural productivity. *Acad. Int. Multidiscip. Res. J.* 11, 755–764. doi: 10.5958/2249-7137.2021.02587.8

Smith, V. H., and Glauber, J. W. (2020). Trade, policy, and food security. *Agric. Econ.* 51, 159–171. doi: 10.1111/agec.12547

Somda, B. B., Ouattara, B., Zomboudré, G., Gubbels, P., Bourgou, T., and Nacro, H. B. (2022). Effects of agroecological practices on soil microbiological activity in Sudano-Sahelian zone of Burkina Faso. *J. Agric. Sci.Technol.* 12, 73–83. doi: 10.17265/2161-6256/2022.02.004

Ssebunya, B. R., Schader, C., Baumgart, L., Landert, J., Altenbuchner, C., Schmid, E., et al. (2019). Sustainability performance of certified and non-certified smallholder coffee farms in Uganda. *Ecol. Econ.* 156, 35–47. doi: 10.1016/j.ecolecon.2018.09.004

Strapasson, A., Woods, J., Meessen, J., Mwabonje, O., Baudry, G., and Mbuk, K. (2020). EU land use futures: modelling food, bioenergy and carbon dynamics. *Energ. Strat. Rev.* 31:100545. doi: 10.1016/j.esr.2020.100545

Streimikis, J., and Baležentis, T. (2020). Agricultural sustainability assessment framework integrating sustainable development goals and interlinked priorities of environmental, climate and agriculture policies. *Sustain. Dev.* 28, 1702–1712. doi: 10.1002/sd.2118

Tittonell, P. (2020). Assessing resilience and adaptability in agroecological transitions. *Agric. Syst.* 184:102862. doi: 10.1016/j.agsy.2020.102862

Tomich, T. P., Kilby, P., and Johnston, B. F. (2018). *Transforming agrarian economies: Opportunities seized, opportunities missed*, New York: Cornell University Press.

Tripathi, A. D., Mishra, R., Maurya, K. K., Singh, R. B., and Wilson, D. W. (2019). "Estimates for world population and global food availability for global health" in *The role of functional food security in global health*. eds. R. B. Singh, R. R. Watson and T. Takahashi (Academic Press), 3–24.

Uwizeyimana, D., Mureithi, S. M., Karuku, G., and Kironchi, G. (2018). Effect of water conservation measures on soil moisture and maize yield under drought prone agro-ecological zones in Rwanda. *Int. Soil Water Conser. Res*. 6, 214–221. doi: 10.1016/j.iswcr.2018.03.002

Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., and Peigné, J. (2014). Agroecological practices for sustainable agriculture a review. *Agron. Sustain. Dev.* 34, 1–20. doi: 10.1007/s13593-013-0180-7

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., and Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems a review. *Agron. Sustain. Dev.* 40, 1–13. doi: 10.1007/s13593-020-00646-z

Yigezu Wendimu, G. (2021). The challenges and prospects of Ethiopian agriculture. *Cogent Food Agric.* 7:1923619. doi: 10.1080/23311932.2021.1923619