Sustainable Agriculture and Food Security

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Food Security for African Smallholder Farmers

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Part I
Agronomy: Soils and Crop Development

Chapter 1
Decades of Cultivar Development: A Reconciliation of Maize and Bean Breeding Projects and Their Impacts on Food, Nutrition Security, and Income of Smallholder Farmers in Sub-Saharan Africa

Aleck Kondwakwenda, Bruce Mutari, Kennedy Simango, Eileen Bogweh Nchanji, Rowland Chirwa, Jean Claude Rubyogo, and Julia Sibiya

Abstract The past decades have seen the implementation of several multi-national maize and common bean cultivar development projects in sub-Saharan Africa (SSA). However, the impacts of these projects on income generation and food and nutrition security have not been adequately interrogated and documented. This chapter provides a synthesis of some of the past and current multinational maize and common bean breeding projects in terms of international distribution, cultivars released, cultivar adoption rates, and impacts on food, nutrition, and income security in SSA. The information used in this chapter is from reliable published journal articles, institutional reports, and authors' knowledge of cultivar development and agricultural systems in SSA. Good progress has been made in the past decades in terms of the number of cultivars released with huge yield advantages over

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unimproved landraces, good tolerance to biotic and abiotic factors. Millions of farmers were moved out of poverty and cushioned from hunger after adopting the improved cultivars. Biofortified maize and bean cultivars with enhanced content of ion, zinc, protein, and provitamin A are proving to be effective solution for malnutrition, which is widespread in SSA. However, more promotional efforts are still needed to increase the adoption of improved cultivars by farmers.

Keywords Cultivar development · Maize · Common bean · Impacts · Food security · Multinational projects

1.1 Introduction

Rapid population growth, agricultural land shortages, poor soils, and biotic and abiotic constraints threaten food and nutrition security in sub-Saharan Africa (SSA). This inefficient system has been further exacerbated by the COVID-19 pandemic (Nchanji et al. 2021). Plant breeding—the science, art, and business of developing improved plant cultivars for human benefit—is an effective strategy to address food and nutrition insecurity (Bernardo 2002). The development of cultivars and their subsequent deployment provides farmers with genetically improved crop cultivars that are high yielding, nutritious, resistant to biotic and abiotic stresses, and preferred by the consumers and value chain actors.

In Africa, cultivar development activities are implemented by public breeding programmes within the National Agriculture Research Systems (NARS), private seed companies, and International Research Centres, under the Consultative Group on International Agricultural Research (CGIAR). The NARS is often under-resourced so it receives financial and technical support mainly from international donors and CGIAR institutions through collaborative projects. The past decades have seen SSA benefiting from several multi-national and regional cultivar development projects implemented either collaboratively or individually by the NARS, CGIAR, and private sectors under different project code names. However, the impacts of these projects on food and nutrition security and income have not been adequately interrogated and reported. The few reports on the achievement of these projects are often disjointed, institutionally biased or too narrow in scope (Eriksson et al. 2018; Masuka et al. 2017). To motivate and attract continuous investments in cultivar development, it is important to present an updated reconciliation report of cultivar development projects and their impacts on food, nutrition, and livelihood security. This chapter focuses on maize (*Zea mays* L.) and common beans (*Phaseolus vulgaris*) cultivar development projects because of their importance to food and nutrition security in SSA and they are widely researched by NARS and CGIAR. Figure 1.1 shows an overview of the distribution of some of the major maize and common bean cultivar development projects across SSA.

Maize is a strategic crop in combating food and nutrition insecurity in SSA due to its widespread production and consumption in the region (Cairns et al. 2012). In the past decades, the International Maize and Wheat Improvement Center (CIMMYT)

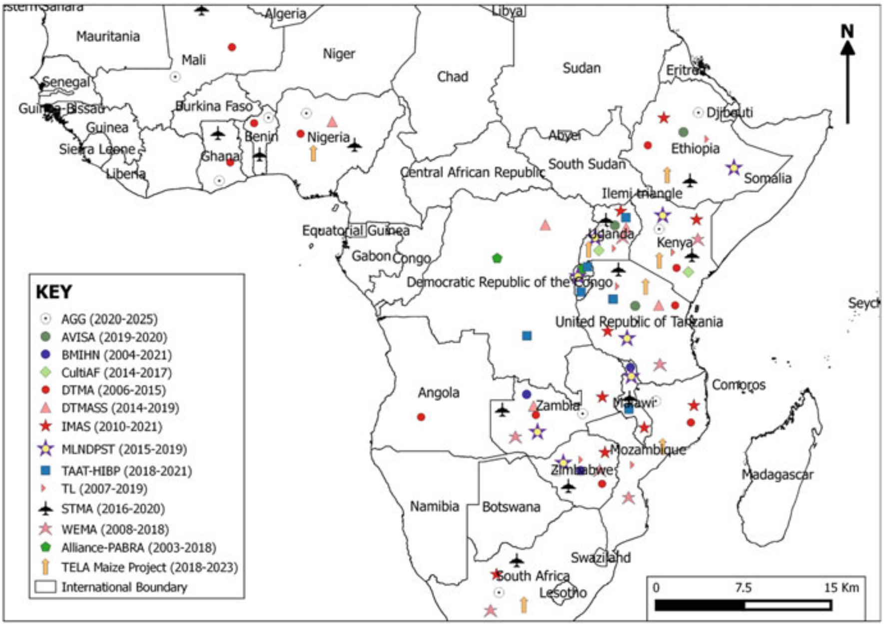

Fig. 1.1 International distribution of some of the major past and current multinational maize and bean cultivar development and deployment projects implemented in SSA. *AGG* accelerating genetic gains in maize and wheat, *AVISA* accelerated varietal improvement and seed delivery of legumes and cereals in Africa, *BMIHN* biofortified maize for improved human nutrition, *CultiAF* the Cultivate Africa's Future Fund on precooked beans for food, nutrition, and income, *DTMA* drought tolerant maize for Africa, IMAS improved maize for African soils, *MLNDPST* maize lethal necrosis diagnostics and prevention of seed transmission, *STMA* stress tolerant maize for Africa, *DTMASS* drought tolerant maize for Africa seed scaling, *TAAT-HIBP* technologies for african agricultural transformation—high iron bean project, *TL* tropical legumes projects, *STMA* stress tolerant maize for Africa, *WEMA* water efficient maize for Africa, *Alliance-PABRA* the alliance for bioversity international and the international center for tropical agriculture through the Pan-Africa Bean Research Alliance

and International Institute of Tropical Agriculture (IITA) and partners from the NARS and private sector have spearheaded the development and delivery of maize cultivars in SSA. Common beans are also a staple in many African countries. Once considered meat for the poor, the rich consume it now due to its nutrient-dense nature. The International Center for Tropical Agriculture (CIAT) is responsible for bean cultivar development with private and public sector partners across 31 countries in Africa. The above institutions also work collaboratively with HarvestPlus spearheading crop biofortification, mainstreaming the three micronutrients recognized by WHO as limiting (Iron, Zinc, and vitamin A). So far, full-fledged biofortification programs for major staple crops, including maize and beans, have been established (Pfeiffer and McClafferty 2007). Several maize and bean cultivars with high levels of provitamin A, Iron, and Zinc have been developed and delivered to different end-users as seed, grains, or value-added products in Africa (Andersson et al. 2017).

The objective of this chapter is to bring visibility to some of the multinational maize and bean cultivar development projects implemented across SSA and their impacts on food and nutrition security. The number and performance of cultivars released and quantifiable economic benefits to smallholder farmers are highlighted. The information reported in this chapter can influence agricultural policies across Africa, as it provides information on the type and availability of different cultivars for farmers and communicates research outcomes to funding agencies, farmers, other researchers, and plant breeding students on possible gaps and opportunities. The subsequent sections provide the projects and impact of maize and common bean breeding on food security and income of smallholder farmers. Testimonies by some of the farmers and value chain actors are also highlighted. We conclude by recommending some of the maize and bean cultivars for production in Southern Africa and providing the policy implications of our findings. It is important for readers to note that in this chapter the words *cultivar* and *variety* are used interchangeably.

1.2 Maize Cultivar Development and Impacts

1.2.1 Maize Breeding Projects

Maize is the most researched crop in SSA due to its importance to food security and wide production in this region. Over 1700 maize cultivars have been released across SSA consisting of 68% hybrids and 32% OPVs (Abate et al. 2017). Table 1.1 shows some of the maize cultivars released over the last 15 years under some of the multinational project. Some of the breeding objectives include breeding for common and menacing abiotic and biotic factors such as drought, poor soil fertility, diseases, and insects. The following sections describe some of the major maize cultivar development and deployment projects undertaken in SSA.

1.2.1.1 Drought Tolerant Maize and Water Efficient Maize for Africa Projects

The Drought Tolerant Maize for Africa (DTMA) project was implemented across 13 African countries (Fig. 1.1) between 2006 and 2015 by CIMMYT and IITA in close collaboration with NARS and few private companies with the main objective of developing drought tolerant maize cultivars (CIMMYT 2015). Breeding for drought tolerance is one of the efficient ways of cushioning farmers from the devastating effects of drought. The DTMA project aimed at increasing maize yields by at least one t/ha under moderate drought conditions. Over 160 drought tolerant hybrids and OPVs were released through the DTMA project (Fisher et al. 2015).

Table 1.1 Examples of maize cultivars released during some of the multinational maize breeding projects in SSA

Release name	Key attributes	Country and year of release	Potential yield (t/ha) and provitamin A content	Project
Gibe-2	OPV, DT, early-intermediate maturity	Ethiopia, 2011	4.5–5.0	DTMA
BH547	Hybrid, intermediate maturity,	Ethiopia, 2013	6.5–7.5	DTMA
BH661	Hybrid, late maturity	Ethiopia, 2011	6.5–8.5	DTMA
ZM523	OPV, DT, early maturity	Malawi and Southern Africa, 2009	5.0–7.0	DTMA
MH38	Hybrid, DT, intermediate maturity	Malawi, 2013	5.0–7.0	DTMA
VumiliaH1	Hybrid, DT, late maturity	Tanzania, 2009	6.0–8.0	DTMA
Meru HB60	Hybrid, MLN-tolerant	Tanzania, 2014	–	MLN
Longe 10H	Hybrid, DT, intermediate maturity	Uganda, 2009	<8.0	DTMA
Bazooka	Hybrid, MLN-tolerant	Uganda, 2014	–	MLN
ZMS606	Hybrid, DT, intermediate maturity	Zambia, 2010	5.0–7.0	DTM
ZM423	OPV, DT, early maturity	Zambia, 2007	55.0–7.0	DTMA
PAN 53	Hybrid, DT, medium maturity	Southern Africa	5.0–9	DTMA
SC403	Hybrid, DT, very early maturity	Southern Africa	5.0–12.0	DTMA
SC719	Hybrid, DT, late maturity	Southern Africa	14	DTMA
ZS500	Hybrid, provitamin A	Zimbabwe and Southern Africa	≤12.0 and 14 μg g^{-1}	BMIHN
ZS244A	Hybrid, provitamin A	Zimbabwe and Southern Africa	7–10 and 12 μg g^{-1}	BMIHN
H6506	Hybrid, MLN-tolerant	Kenya and East Africa, 2014	–	MLN
MH401	Hybrid, DT, medium maturity	Kenya and East Africa	–	STMA
WE3127	Hybrid, DT, transgenic	South Africa, 2014	–	WEMA
WE3128	Hybrid, DT, transgenic	South Africa, 2014	–	WEMA

(continued)

Table 1.1 (continued)

Release name	Key attributes	Country and year of release	Potential yield (t/ha) and provitamin A content	Project
TZEEIOR 202	Hybrid, provitamin A, stress tolerant	Nigeria	23.98 μg g^{-1}	BMIHN and STMA

OPV open pollinated variety, *DT* drought tolerant, *DTMA* drought tolerant maize for Africa, *MLN* maize lethal necrosis, *BMIHN* biofortified maize for improved human nutrition. Very early maturity: 105–125 days; early maturity: 110–130 days; medium maturity: 120–136 days; and late maturity: 140–148. Sources: Fisher et al. (2015) for DTMA, Boddupalli et al. (2020) for MLN, Agricultural Research Council (ARC) reports for WEMA and CIMMYT (2020b) for BMIHN cultivars

The Water Efficient Maize for Africa (WEMA) project was implemented between 2008 and 2018 in seven countries to complement the DTMA by developing and deploying maize varieties that yield 24–35% more than currently available varieties and resistant to stem borers. The varieties were developed using a combination of conventional breeding, marker-assisted breeding, and genetic modification in some countries such as South Africa. The seeds from these projects were sold royalty-free to smallholder farmers in sub-Saharan Africa through African seed companies (CIMMYT 2021).

1.2.1.2 Improved Maize for African Soils

The Improved Maize for African Soils (IMAS) project was implemented to address the challenge of poor soil fertility by developing maize cultivars that are efficient at utilizing the small amount of fertilizer that poor resourced sub-Saharan farmers can afford, especially nitrogen. Cultivars developed under the IMAS projects were sold to farmers at a subsidised price because they were made available royalty-free to seed companies (CIMMYT 2021).

1.2.1.3 Stress Tolerant Maize for Africa

The objective of the Stress Tolerant Maize for Africa (STMA) project was to perpetuate the success achieved by DTMA and IMAS projects. It was aimed at developing maize cultivars that are tolerant and resistant to multiple stresses including drought, low soil fertility, heat, diseases, and pests affecting maize production areas in SSA. The Stress Tolerant Maize for Africa project was implemented across 12 countries (Fig. 1.1), which constitute about 72% of the total maize production area in SSA and home to 176 million people whose livelihoods and food security are largely maize dependent (CIMMYT 2020a). The key milestones of the STMA project across project countries include 40 million farmers benefiting from stress tolerant varieties, 97,000 metric tonnes of certified seed produced, and 3.8 million hectares planted.

1.2.1.4 Biofortified Maize for Improved Human Nutrition and TELA Projects

The Biofortified Maize for Improved Human Nutrition (BMIHN) project was started in 2004 by HarvestPlus in collaboration with its partners from CIMMYT, IITA, and NARs, with the objective of breeding provitamin A- and zinc-enhanced maize for Africa and Latin America. The African project countries are Zambia, Nigeria, Zimbabwe, DRC, Ghana, Malawi, Mali, Nigeria, Rwanda, and Tanzania. So far, more than 50 provitamin A- and zinc-enhanced maize cultivars have been released across African project countries in the form of OPVs, single-cross hybrids, and three-way hybrids (Andersson et al. 2017). A majority of the released biofortified cultivars combine consumer preferred traits such as high yield and high provitamin A or zinc content. So far provitamin A content ranging from 6 to 23.98 μg g^{-1} (Badu-Apraku et al. 2018; Kondwakwenda 2018) and zinc content ranging from 17 to 42 ppm have been reported among the released maize cultivars in SSA (Andersson et al. 2017). In most cases, high zinc maize cultivars also have high protein content, which is commonly known as Quality Protein Maize (QPM). Zinc- and provitamin A-enhanced maize cultivars have proved to be an effective complementary solution of hidden hunger among maize consumers in SSA. Consumption of provitamin A maize helps to curb vitamin A deficiency (VAD) among rural maize consumers, who hardly afford balanced diet. VAD can cause blindness, poor immune system, increased child, and maternal mortality while zinc deficiency is associated with impaired brain function and delayed physical development among other consequences.

The TELA maize project is still in its infant stages. It is a public-private partnership led by the African Agricultural Technology Foundation (AATF). The project supports the commercialization of transgenic drought-tolerant and insect-protected (TELA®) maize varieties to enhance food security in SSA. It continues the progress made under the WEMA Project. TELA maize offer better grain quality, drought tolerance, and protection against stem borers, which helps farmers save money on insecticides and reduce their exposure to these chemicals (CIMMYT 2021).

1.2.1.5 Maize Lethal Necrosis Projects

Maize Lethal Necrosis (MLN) has been a menace in Africa since 2011, predominantly in east Africa. CIMMYT and its partners responded by implementing projects to introgress MLN resistance in maize germplasm and to reduce its transmission. MLN projects comprise the MLN gene editing project and Maize Lethal Necrosis Diagnostics and Prevention of Seed Transmission (MLNDPST). The MLN gene editing project applies gene editing technology to transform elite maize lines that are susceptible into becoming resistant. Coordinating regional efforts to strengthen the control of MLN was the major focus of the MLNDPST project. Marker-assisted selection has also been used to develop MLN tolerant maize cultivars (Boddupalli et al. 2020). Some of the MLN tolerant cultivars that have been so far released in east and southern Africa are presented in Table 1.1.

1.2.1.6 Accelerating Genetic Gains Project

Accelerating Genetic Gains in Maize and Wheat (AGG) is one of the latest projects, which is currently running since 2020. It is spearheaded by CIMMYT in collaboration with partners with the objective to accelerate the development of higher yielding maize and wheat cultivars. The project uses innovative and modern methods that improve breeding efficiency and precision to produce cultivars that are climate-resilient, pest- and disease-resistant, highly nutritious, and market demanded (CIMMYT 2021).

1.2.2 Maize Cultivar Adoption and Economic Impacts

Maize cultivar development is the most successful effort in the history of African agriculture in terms of the number of cultivars released (Gabre-Madhin and Haggblade 2004; Krishna et al. 2021). However, inconsistent and generally low cultivar adoption rates are still a cause for concern. Africa has the lowest average adoption of the improved new crop variety rate of $\leq$35% as compared to Europe, Asia, and America (Walker et al. 2014). There is consensus in literature that the rate of adopting improved maize cultivars in SSA is largely influenced by farmers' ability to access seed and awareness about the cultivar (Danso-Abbeam et al. 2017; Fisher et al. 2015; Houeninvo et al. 2020; Lunduka et al. 2013). The following paragraphs discuss the adoption and impacts of improved maize cultivars released through some of the multinational maize breeding projects implemented in SSA countries.

In their study, Alene et al. (2009) reported an increased adoption of improved maize varieties in west and central Africa from less than 5% in the 1970s to about 60% in 2005. However, a report by Krishna et al. (2021) indicates that such adoption rates were not consistently maintained in the later years. Figure 1.2 shows that average adoption rates of maize cultivars released after 2005 are less than those released before 2005 in most SSA countries.

In southern and eastern Africa, the adoption of drought tolerant maize (DTM) and stress tolerant maize (STM) cultivars varied from country to country and from time to time (Ahmed et al. 2017; Fisher et al. 2015; Krishna et al. 2021). In a study done by Fisher et al. (2015), Malawi had the highest adoption rate of DTM with 61% adoption rate followed by Uganda (26%), Zambia (23%), Ethiopia (15%), Tanzania (21%), and Zimbabwe (9%). They attributed the differences of adoption among study countries to the presence or absence of government to farmer input subsidies or level of farmers' knowledge about DTM owing to awareness campaigns. Thus, at that time Malawi had the highest adoption rate owing to the government-sponsored Farm Input Subsidy Program (FISP), which saw many farmers receiving subsidized

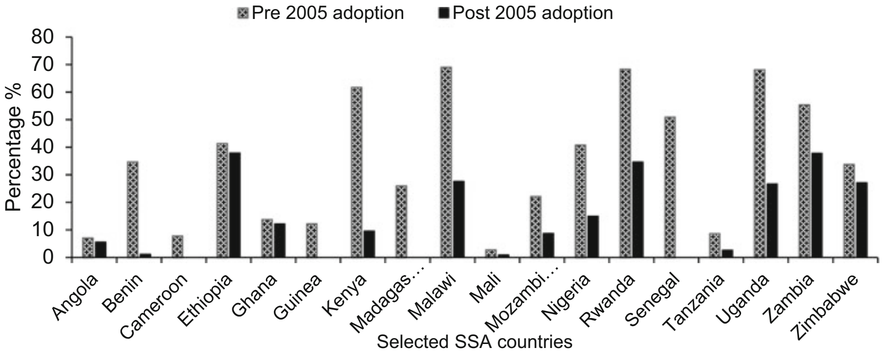

Fig. 1.2 Adoption rates of maize cultivars released by CGIAR and partners before and after 2005. Data Source: Krishna et al. (2021)

farm inputs and free improved seed (Lunduka et al. 2013). Uganda's second highest adoption rate of DTM was attributed to robust knowledge dissemination efforts by the agricultural extension and seed companies.

A number of past studies using various economic models have revealed the economic benefits of improved maize cultivars at household, national, and continental levels (Rovere et al. 2014; Wesseler et al. 2017). New improved maize cultivars have consistently demonstrated yield superiority over obsolete and non-improved varieties across SSA under both stressed and optimum growing conditions (Danso-Abbeam et al. 2017; Houeninvo et al. 2020). Studies done by Khonje et al. (2015) in Zambia, Asfaw et al. (2012) in Tanzania, Houeninvo et al. (2020) in Benin and Ahmed et al. (2017) in eastern Ethiopia revealed that the adoption of improved maize cultivars can lead to significant gains in income, consumption expenditure, and food security at a higher net return on investment. The adoption of DTM in northern Ghana increased farm household yield by more than 150% (Martey et al. 2020). In Ethiopia the adoption of improved maize cultivars and supporting agronomic technologies is attributed to an annual national economic gain of US$175.13–195.60 million, increased household income of US$18.82–24.50 per year, and rural poverty reduction headcount ratio of 0.8–1.13% (Walker et al. 2014).

In west and central Africa, the adoption of improved maize cultivars with resistance to maize streak virus (MSV), the parasitic weed Striga, downy mildew, and pests moved more than one million people per year out of poverty between the 1980s to the mid-1990s (Alene et al. 2009). The economic benefits of adopting improved maize varieties for each west African country was estimated to be 27% (Nigeria), 25% (Mali), 20% (Burkina Faso), 20% (Senegal), 19% (Cameroon), 18% (Benin), 17% (Ghana), 15% (Cote d'Ivoire), and 15% (Togo) (Alene et al. 2009). Eriksson et al. (2018) projected the economic benefits of adopting DTM in east Africa to be around US$0.88 billion. In their latest report, Krishna et al. (2021) estimated the aggregate yearly economic benefits of using newer CGIAR improved maize varieties to be between US$0.66 and US$1.05 billion. In a related study to predict the impact of investing in DTM using economic surplus analysis framework, Rovere et al. (2014) projected economic gains between US$0.907 and US$1.535 billion across all 13 DTMA project countries in eastern, southern, and western Africa.

The adoption of biofortified maize cultivars has improved since the inception of BHIHN project. Over 100,000 farming households started growing biofortified maize in Zambia in just 3 years after the release of the first provitamin A biofortified maize cultivar in 2012 (Simpungwe et al. 2017). Adopting provitamin A maize cultivars was estimated to have a huge cost-effectiveness of $24 per Disability Adjusted Life Years (DALYs) saved in Zambia (Lividini and Fiedler 2015). Studies done in Zambia revealed that zinc from biofortified maize meets the requirements of rural young children (Chomba et al. 2015) while provitamin A maize is as efficacious as vitamin A supplements and increased pupillary responsiveness in children (Gannon et al. 2014; Palmer et al. 2016).

1.3 Common Bean Cultivar Development and Impact

1.3.1 Common Bean Breeding Projects

Up until the 1990s, most of the bean research programmes in SSA had focused on improving bean grain yields, but as yields improved, the selection criteria changed to traits such as bean seed size, tolerance to drought and heat stress, cooking time, high iron and zinc content, tolerance to diseases of economic importance, and adaptability to low soil fertility. Sections outlined below summarize the major common bean breeding projects implemented in SSA.

1.3.1.1 Tropical Legumes Projects

The Tropical Legumes (TL) projects were jointly implemented during the period 2007–2019 by three CGIAR centres (IITA, Alliance and ICRISAT) in collaboration with NARS partners with funding support from Bill and Melinda Gates Foundation (BMGF). Even though the TL projects involved five legume crops, namely cowpeas, groundnuts, pigeon pea, chickpea, and common bean, this review only focuses on the latter. The Alliance was responsible for the bean crop and the project was implemented in three phases (TL II Phase I—2007 to 2011, TL II Phase II—2012 to 2014, and TL II Phase III—2015 to 2019). The target countries for Phases I and II were Ethiopia, Kenya, Malawi, Mozambique, Tanzania, Uganda, and Zimbabwe (Varshney et al. 2019). However, Phase III was strategically implemented in three countries only, namely Uganda, Ethiopia, and Tanzania. The project aimed to improve the livelihoods of millions of smallholder farmers in drought-prone areas of SSA through improved production and productivity of common beans (Akpo et al. 2020). Bean research and development activities were the major focus of

Phases I and II, and Phase III focused on strengthening bean seed platforms and building the capacity of CGIAR and NARS breeding programmes to improve their ability to disseminate technology outputs to smallholder farmers.

1.3.1.2 Accelerated Varietal Improvement Seed Delivery of Legume and Cereal Crops Project

The Accelerated Varietal Improvement and Seed Delivery of Legume and Cereal Crops (AVISA) project runs from 2019 to 2022 with funding support from BMGF focusing on five crops (groundnut, common bean, cowpea, millet, and sorghum). However, this review only focuses on common bean, which is being implemented by the Alliance in three target countries (Tanzania, Uganda, and Ethiopia). The project consolidates the gains of TL II Phase III project while refocusing the work to improve the breeding and seed delivery system of CGIARs and NARS. The AVISA project aims to increase productivity, resilience, marketability, and profitability of common bean in Tanzania, Ethiopia, and Uganda. It also focused on developing gender-responsive product profiles through the stage-gate system.

1.3.1.3 Alliance-PABRA Projects

The Alliance for Bioversity International and International Center for Tropical Agriculture (Alliance) through the Pan-Africa Bean Research Alliance (PABRA) employed a partnership approach that engages more than 537 private-public sector partners in developing and disseminating bean technologies across 31 countries in SSA. PABRA implements crop improvement projects in 31 countries spread across west, east, central Africa and southern Africa. The names of the countries participating in the various PABRA projects are shown in Fig. 1.1. In 1985, the Alliance started developing improved cultivars of common beans in the Great Lakes region of central Africa (Rwanda, Burundi and DRC) to enhance food and income security and health of smallholder farmers in SSA (CIAT 2013; Muthoni and Andrade 2015a, b). The project also aimed at reversing the declining trends in bean production observed in the early 1990s by developing the capacity of bean researchers in NARS to increase grain yield (PABRA 2020b). The focus of the regional breeding programme was on breeding for tolerance to insect pests and diseases of economic importance under poor soil fertility conditions (Muthoni and Andrade 2015a, b). The Eastern Africa Bean Research Network (EABREN) and Southern Africa Bean Research Network (SABRN) were created in 1987 to support bean crop improvement programs in the participating countries. As a result, during the 1990s, several improved bean cultivars with high grain yield and tolerance to diseases of economic importance were released in various countries within the SABRN and EABRN networks. It is also during the same period when improved climbing beans were released in the highlands of central Africa. In 1995, the East and Central Africa Bean Research Network (ECABREN) was established to support bean crop improvement activities in east and central Africa. PABRA was launched as an Alliance project in 1996 after ECABREN and SABRN teamed up with the Alliance to support bean crop improvement activities, focusing on high grain yield and disease resistance within the networks (CIAT 2013; Muthoni and Andrade 2015a, b).

In 2000, PABRA developed a new bean breeding strategy with a major focus on cultivars that combine tolerance to multiple constraints (drought, heat, low soil fertility, and diseases) and consumer preferences (CIAT 2013; Muthoni and Andrade 2015a, b). Considering the high prevalence of malnutrition due to nutrient deficiencies in SSA, it was during the 2000s when PABRA started breeding for increased micro-nutrient density beans focusing on iron and zinc. In 2009, the West and Central Africa Bean Research Network (WECABREN) was founded to support bean research for development activities in bean-producing countries in west and central Africa (CIAT 2013). From 2013 to date, the current PABRA breeding strategy focuses on market and climate-resilient bean types to meet the specific demands of various value actors such as farmers, traders, processors, and consumers (Buruchara et al. 2011; CIAT 2013). The grain colours of focus range from red, white, black, red-mottled, cream, cream-mottled, to yellow.

PABRA has implemented a number of projects across the 31 member countries with funding support from Global Affiars Canada, IDRC-ACIAR, Trade and Development, Swiss Agency for Development and Cooperation (SDC), Bill and Melinda Gates Foundation, McKnight Foundation, AGRA, ASARECA and the Governments of PABRA member countries. Some of the major projects implemented by PABRA since the 2000s, excluding the TL and Technologies for African Agricultural Transformation (TAAT) High Iron Bean (HIB) projects, include: (1) improving bean crop production in order to increase the nutrition and food security of rural populations (2009–2013), (2) improving food security, nutrition, incomes, natural resource base, and gender equity for better livelihoods of smallholder households in SSA (2011–2014 and 2015–2020), and (3) improving bean production and marketing in Africa (2016–2022), and (4) the precooked beans for food, nutrition, and income in Kenya and Uganda project (CultiAF project 1 and 2). It is important to highlight that Burundi and Zimbabwe were the flagship countries from 2015 to 2020 under SDC and GAC funding. Most of these PABRA projects aim to improve food security, and nutrition and income security of smallholder farmers by increasing an access to seed of improved, high-yielding, and market-preferred bean cultivars together with complementary good agronomic packages for enhancing bean grain yields and increasing access and consumption of bean grains and bean-based products and equitable access and utilization of project technologies.

PABRA developed the commodity corridor approach that addresses bottlenecks in bean production, distribution, and consumption hubs hindering smallholder farmers' access to markets for grain and seed in the member countries. It uses the demand-led breeding approach, which places its clients at the centre of determining the priority traits and developing suitable varieties.

TAAT High Iron Bean Project

The Alliance has been implementing the TAAT HIB project since February 2018 and the project ends in December 2021. Countries participating in this project for the large-scale deployment of HIB technologies include Uganda, Zimbabwe, Burundi, Malawi, Kenya, DR Congo, Rwanda, and Tanzania. These target countries have released a combined total of 31 HIB cultivars (Mabeya et al. (2020). The focus of the project is to (1) increase HIB productivity from 0.8 to 1.2 t/ha for bush beans and 1.5 to 2.5 t/ha for climbing beans, (2) multiply additional 800,000 tonnes of HIB seed in the above mentioned countries, (3) improve access to HIB seed targeting two million households using the Bean Corridor Approach, and (4) enhance business investment opportunities targeting youths through value addition for HIB grain and improved access to markets (Mabeya et al. 2020). The second phase (TAAT-II) will run from December 2021 to December 2023.

Precooked Beans for Food, Nutrition, and Income

The precooked beans for food, nutrition, and income project (CultiAF project) was implemented in Kenya and Uganda from during October 2014 to March 2017 and later in 2019 to 2021 with funding support from IDRC-ACIAR. The first phase of the project aimed at increasing bean consumption, reducing time spent on cooking beans, creating a more lucrative market for bean farmers, and improving diets. Project activities included pre-screening bean genotypes for their suitability for precooking, industrial processing, seed multiplication of promising genotypes, evaluation of different seed and grain supply models, and formulation of standards for precooked beans. The second phase was meant to scale up the supply of precooked beans leveraging on public-private partnerships in Kenya and Uganda from 2018 to 2020.

1.3.1.4 HarvestPlus Projects (Phases I, II, and III)

Crop development activities on bean biofortification were first initiated in 2003 in Rwanda by the Alliance with funding support from HarvestPlus (Mulambu et al. 2017). The HarvestPlus Phase I project was for the period 2003 to 2008 focusing on pre-breeding for high iron levels, population development in Colombia, trait heritability studies, and fast-tracking the dissemination of biofortified beans which already had high iron levels. The project was also outscaled to Uganda and DRC. On the other hand, the breeding target was to develop bean cultivars with 94 ppm of iron, considering that the non-bio-fortified bean cultivars had a baseline iron content of 50 ppm (Mulambu et al. 2017). As a result of the intervention, the first five biofortified bean cultivars rich in iron (71–81 ppm of Iron) were officially released in Rwanda in 2010. The Phase II (2009–2013) of the HarvestPlus project focused on the delivery of the newly released high iron bean cultivars, developing genotypes with more than 80% of the iron target levels without compromising on other desirable end-use quality and agronomic traits (Mulambu et al. 2017). The target countries were Rwanda and DRC. Studies on nutrient retention, bioavailability, and the stability of grain iron and zinc content across locations were also conducted during Phase II. This led to the release (six cultivars) of the second generation of biofortified cultivars in 2012 with 74–91 ppm iron. From 2015 on (Phase III), the focus in DRC and Rwanda was on marketing, seed multiplication, and delivery of biofortified beans coupled with capacity building on good agricultural practices in collaboration with the private and public partners (seed companies, farmers, and cooperatives).

1.3.2 Common Bean Cultivar Adoption and Impacts

1.3.2.1 Cultivar Releases in Multiple Countries

The common bean research programs in SSA in collaboration with international partners such as the Alliance have released nearly 1000 improved bean cultivars (http://database.pabra-africa.org/). The cultivars have combined tolerance to multiple production constraints and have been officially released in multiple countries (Buruchara et al. 2011). Moreover, most of these cultivars have transformed beans from a subsistence crop to a cash crop. The release of cultivars in multiple PABRA member countries helps to move seed from one country to another, thereby facilitating regional and international trade and ensuring food and nutrition security in many countries. The reason why many bean cultivars have been released in multiple countries is that new bean cultivars developed and released in one country are shared with other countries including those that do not have active breeding programmes. They then assess its stability and adaptability, and release it, thereby enabling a greater impact across SSA. Cultivars which have got the highest number of releases in SSA are NUA45 (eight countries) followed by CAL143 (six countries). NUA45 is highly palatable and widely adapted, cooks fast, early maturing coupled with high grain iron and zinc levels. In countries such as Zimbabwe, farmers charge a premium price when selling NUA45 grain compared to non-biofortified bean cultivars. On the other hand, CAL143 has got a high market demand and grain yield potential in SSA. More examples of cultivars which have been released in multiple countries across SSA are outlined in Table 1.2.

1.3.2.2 Bean Cultivar Adoption and Impacts

As reported by Muthoni and Andrade (2015a, b), by the year 2010, improved bean cultivars adopted by farmers in SSA were relatively old. By the year 2013, improved cultivars of beans had been adopted on approximately 56% of the total bean area in eastern and southern Africa (CIAT 2013). However, these cultivars are being

Table 1.2 Examples of multiple bean cultivar releases across ECABREN and SABRN countries

Cultivar name	ECABREN							SABRN										
	BU	E-CD	ET	KE	RW	TZ	UG	AN	LS	S-CD	MU	MW	MZ	ZA	SW	ZM	ZW
AFR703	–	–	–	–	–	–	–	–	–	–	–	–	2011	–	–	–	2019
Roba 1	–	–	2012	2012	–	2012	2012	–	–	–	–	–	–	–	–	–	
NUA45	–	–	–	–	–	–	–	–	2010	2011	2019	2009	2011	–	2013	2011	2010
PC652-SS3	–	–	–	–	–	–	–	–		–	–	–	–	1999	–	–	2010
KIANGARA	***	–	–	–	2010	–	–	–	–	–	–	–	–	–	–	–	–
RWR719	–	–	–	***	***	–	–	–	–	–	–	–	–	–	–	–	–
LYAMUNGU	–	–	–	***	–	***	–	–	–	–	–	–	–	–	–	–	–
KAT56	***	–	–	***	–	–	–	–	–	–	–	–	–	–	–	–	–
SUG131	–	–	–	–	–	–	1999	–	–	–		2002	2007	–	2007	***	2007
FLOR DE MAYO	1987	–	–	–	1991	2006	–	–	–	–	–	–	–	–	–	–	–
G2333	–	–	–	–	1991	–	1999	–	–	–	–	–	–	–	–	–	–
G685	1993	2004	–	2008	1991	–	1999	–	–	–	–	–	–	–	–	–	–
GASIRIDA	2010	–	–	–	2010	–	–	–	–	–	–	–	–	–	–	–	–
KATB9	–	–	2014	***	–	2017	–	–	–	–	–	–	–	–	–	–	–
KATB1	2008	–	2014	1998	–	2017	–	–	–	–	–	–	–	–	–	–	–
KATX56	2008	–	–	1999	–	–	–	–	–	–	–	–	–	–	–	–	–
KATX69	2008	–	–	1998	–	–	–	–	–	–	–	–	–	–	–	–	–
RWR719	–	–	2003	2008	–	–	–	–	–	–	–	–	–	–	–	–	–
CAL143	–	–	–	–	–	–	–	1998	–	2011	–	1996	2007	–	2007	1997	–
OPS-KW1	–	–	–	–	–	–	–	–	–	–	–	–	–	2001	–	2009	–
AFR708	–	2007	–	2008	–	–	–	–	–	–	–	–	–	–	–	–	–
RWR2154[H]	2010	–	–	–	2010	–	2016	–	–	–	–	–	–	–	–	–	–
RWR2245[H]	–	2011	–	–	2010	–	2016	–	–	–	–	–	–	–	–	–	–
MAC44[H]	–	–	–	–	2010	2017	2016	–	–	–	–	–	–	–	–	–	–

(continued)

Table 1.2 (continued)

Cultivar name		ECABREN						SABRN									
	BU	E-CD	ET	KE	RW	TZ	UG	AN	LS	S-CD	MU	MW	MZ	ZA	SW	ZM	ZW
RWV1129[H]	–	–	–	–	2010	2017	–	–	–	–	–	–	–	–	–	–	–
GLP2	–	–	2012	2010	–	–	2010	–	–	–	–	–	–	–	–	–	–
K132 (CAL96)	–	–	2013	–	–	–	1994	–	–	–	–	2018	–	–	–	–	–
MOORE888002	2016	–	–	–	–	–	2016	–	–	–	–	–	–	–	–	–	–
Awash Melka	–	–	2010	2010	–	–	–	–	–	–	–	–	–	–	–	–	–
AWASH 1	–	–	1989	***	–	–	–	–	–	–	–	–	–	–	–	–	–
RWV3006	–	–	–	–	2012	–	2012	–	–	–	–	–	–	–	–	–	–

NB: *H* indicates that the cultivar was released under HarvestPlus, *BU* Burundi, *E-CD* Eastern Democratic Republic of Congo, *ET* Ethiopia, *KE* Kenya, *RW* Rwanda, *TZ* Tanzania, *UG* Uganda, *AN* Angola, *LS* Lesotho, *S-CD* Southern Democratic Republic of Congo, *MU* Mauritius, *MW* Malawi, *MZ* Mozambique, *ZA* Republic of South Africa, *SW* Swaziland, *ZM* Zambia, *ZW* Zimbabwe

*** Indicate information on the year of official release not found, – Indicate the cultivar was not released in that country replaced by new ones (Letaa et al. 2015). By the year 2015 in Zambia, Burundi, Mozambique, and DR Congo, the adoption of improved cultivars was less than 15% of the total area under beans (Muthoni and Andrade 2015a, b). The reasons for the poor adoption varied from rejection of released cultivars to few cultivar releases. In the late 1990s, 15% of the total bean area in Uganda was covered with PABRA project–related improved cultivars (Johnson et al. 2003).

Larochelle et al. (2015) reported that the land area (adoption rate) under improved bean cultivars in Uganda was 13.2%. The high frequency of partial adoption and lower overall rate of adoption lower the bean land area planted to improved cultivars in Uganda. During the period from 2003 to 2005, 31% of the total bean area in Uganda was under improved cultivars as revealed by impact studies (Kalyebara et al. 2007). However, during the same period, the improved cultivar K132 (CAL143) that was officially released in Uganda in 1994 was the most widely cultivated cultivar despite the fact that it was highly susceptible to races of bean root rot in Uganda (Muthoni and Andrade 2015a, b). The cultivar K132 was adopted in Uganda due to its market demand and high grain yield potential. By the year 2013, in Uganda, K132 and NABE-4 covered more than 40% of the total area harvested (CIAT 2013; Muthoni and Andrade 2015a, b). The cultivar NABE 15 which was released in Uganda in 2010 under the TL II project has been up-scaled to northern Uganda and South Sudan (Akpo et al. 2020).

In 2007, most of the dry beans traded in the domestic markets in Malawi comprise three improved cultivars, namely, Napilira, Kalima, and Malua (Muthoni et al. 2007). These three cultivars were released in the early 1990s. Chimbamba and Nanyati have also been widely adopted in Malawi (Katungi et al. 2009). However, by the year 2015, 2% or more of the national area planted to dry beans in Malawi was covered with 10 of the 15 officially released improved cultivars (Muthoni and Andrade 2015a, b). In Ethiopia, the percentage of bean area under improved cultivars increased from 8% in the late 1990s to 44% in 2010 (Muthoni and Andrade 2015a, b). Before the 1990s, the white pea bean cultivar Mexican 142 (controlling over 50% of the white canning bean market class) which was released in 1972 was the most widely adopted cultivar in Ethiopia (Teshale et al. 2006). However, during the period 1990–2010, Mexican 142 was now in third place as the improved market-class bean cultivars Awash-1 (canning bean for export) and Nasir accounted for 10% and 12%, respectively, of the total area under improved bean cultivars in Ethiopia (Muthoni and Andrade 2015a, b). Both Awash-1 and Nasir were widely adopted in Ethiopia because they possessed the preferred grain traits (size, colour, and shape) which dominated domestic and export markets.

On the other hand, according to Rubyogo et al. (2007), by the year 2006, about 15% of bean grains exported from Ethiopia were Awash Amelka, a cultivar which was officially released in 1999. The cultivar ‘Red Wolita’ was controlling over 70% of the red cooking bean market class in 2009 in Ethiopia (Varshney et al. 2019). During the period 2008–2009, the area under PABRA projects–related improved cultivars increased from an estimate of 4% (Johnson et al. 2003) to an estimate of 46% (Muthoni and Andrade 2015a, b). Before 2016, the improved cultivar Uyole 96 was cultivated in more than 60% of bean production area in Southern Tanzania

(Varshney et al. 2019). However, by the year 2015, Muthoni and Andrade (2015a, b) reported that Lyamungu 85 (released in 1985) and Lyamungu 90 were the two widely grown cultivars in Tanzania. Both cultivars are bush types and are early maturing. Furthermore, by the year 2016, the TL project–promoted improved cultivars such as Njano Uyole, Wanja, and Uyole 03 were among the widely adopted cultivars in Tanzania (Katungi et al. 2019; Varshney et al. 2019). Njano Uyole has a high grain yield potential, shells easily, cooks fast, fetches a high market price, and is tolerant to insect pests and diseases of economic importance.

Therefore, in terms of area share, the adoption of new improved cultivars in southern Tanzania increased from 21% in 2013 to 25% in 2016 (Katungi et al. 2019). However, Katungi et al. (2019) reported that some farmers in southern Tanzania still grow landraces because they outperform improved cultivars on soils with poor fertility. The other reason why some of the farmers in Tanzania have not yet adopted new improved cultivars is that the estimated increment in average yield if adopters of old improved cultivars such as Kabanima were to shift to new improved cultivars was modest (Katungi et al. 2019). By the year 2015, the Alliance-bred cultivar AND 10 was the first and second most popular cultivar in Burundi and DR Congo, respectively. On the other hand, VCB 813030, an Alliance-bred cultivar, was the top-ranked cultivar in CR Congo (Muthoni and Andrade 2015a, b). An impact study conducted by Mulambu et al. (2017) in Rwanda in 2015 revealed that the iron-biofortified bean cultivar RWR2245 (red-mottled bush bean) was the most widely adopted and disseminated cultivar, being grown by 56% of the farming households. The wide adoption of RWR2245 in Rwanda is attributed to its high grain yield potential of 20–49% over the local landraces (Vaiknoras and Larochelle 2021).

In Kenya, by the year 2009, popular cultivars included Mwatemania, Rosecoco, and GLP2 (Katungi et al. 2009). These cultivars were released in the early 1980s. In Zimbabwe, during the period 2015–2020, the adoption of improved cultivars of dry beans increased from 9% to 47% (PABRA 2020a). On the other hand, the adoption of the biofortified bean cultivar NUA45 in Zimbabwe increased from less than 2% in 2016 to 12% in 2018 (PABRA 2020a). According to a study conducted by Mutari et al. (2021), Ex-Rico (introduced in 1990), locally called Michigan pea bean, is the most widely adopted small white canning bean cultivar in Zimbabwe. The cultivar was grown by 83% of the surveyed households in the South East Lowveld region of Zimbabwe (Mutari et al. 2021). By then (before 2019), farmers adopted Ex-Rico due to lack of improved cultivars in the market. Teabus (a small white canning bean cultivar) was introduced in Zimbabwe from South Africa by bean canning companies, but it was never adopted because of high susceptibility to blight and rust despite having premium canning qualities (Mutari et al. 2021). According to CIAT (2013), around eight million smallholder farmers in SSA now grow improved cultivars of beans developed through the PABRA network. Around 1.6 million hectares in nine countries (Zambia, Malawi, Mozambique, Democratic Republic of Congo, Uganda, Ethiopia, Tanzania, Burundi, and Rwanda) are planted with PABRA-related cultivars (CIAT 2013).

From 1996 to 2013, a US$16 million investment by PABRA in crop management practices and bean cultivar development generated benefits close to US$200 million for more than 5.3 million smallholder rural households in SSA (CIAT 2013). PABRA has developed and released 536 climate-smart, market-demanded bean cultivars along with other complementary technologies reaching close to 22 million farmers; grown on 953,823.7 ha of land to boost bean production. More than 5.028 million metric tonnes of dry beans have been traded on national, regional, and profitable international markets, with 2,260,507 farmers (1,134,386 women) linked to profitable markets. Since introducing the corridor approach in 2017 by PABRA, the number of SMEs directly involved in bean value chains has increased from 52 in 2017 to 238 in 2020. The ABC through the TAAT project is using high iron and zinc bean cultivars in school feeding and nutrition programmes to enhance nutrition and income security of farming communities in Zimbabwe, Uganda, Tanzania, Burundi, and Kenya. In the past 5 years, 10,445,375 men and women consumers are accessing high iron beans. Through the TL projects, several diagnostic molecular markers linked to economic traits of interest were developed (Mukankusi et al. 2019). According to Varshney et al. 2019, these markers were subsequently used in bean breeding programmes for selecting genotypes tolerant to important diseases and insect pests. Most importantly, the use of molecular markers shortens the breeding cycle (period from hybridizations to release) and improves the speed, efficiency, and accuracy of breeding, thus enhancing genetic gains. For example, the TL projects developed and released a total of 104 improved market preferred common bean cultivars (Varshney et al. (2019) with an on-farm grain yield advantage of 10–40% over the standard checks (Mukankusi et al. 2019). These cultivars were also tolerant to insect pests and diseases of economic importance. Furthermore, 96,530 tonnes of certified seed of market preferred, climate resilient, and high yielding cultivars were developed and established on an area of 965,302 ha under the TL projects.

The CultiAF project on precooked beans that was implemented in Uganda and Kenya developed three precooked bean products which included bean flour, a ready-to-eat snack, and precooked beans that cook in 10–15 min (International Development Research Centre (Ugen et al. 2017). These products are already on the market. When households purchase precooked beans for consumption, less wood is used in cooking and less time is spent by women fetching wood. According to (Ugen et al. 2017), precooked beans save consumers associated expenditures on fuel worth US$0.505/kg and over 100 min of cooking time. Furthermore, households who choose to consume precooked beans over dry beans save around US$0.3 per meal of bean prepared (Ugen et al. 2017). In terms of cultivar release, 12 were released under the CultiAF project and four (NABE 4, NABE 14, Rosecoco and Wairimu) of them are now widely cultivated by farmers in Kenya and Uganda (Ugen et al. 2017). These cultivars have a grain yield potential of 1.5–2.0 t/ha, compared to 0.5 t/ha for landraces. The CultiAF project also created employment opportunities and by the year 2017, 13,650 farmers were involved in precooked bean seed production (Ugen et al. 2017). As a result of the cultivation of precooked beans, the average incomes of women from bean sales increased from US$126 in 2014 to US$170 in 2016 (Ugen et al. 2017) in Kenya and Uganda. Furthermore, the volume of beans sold by women increased from 290 kg in 2014 to 314 kg in 2016, thus ensuring food and income security.

1.4 Testimonials by Farmers and Other Value Chain Actors

- 'I grow DTM cultivar PAN53 on about two hectares of land and for the last three years my yields have been impressive, I was a little anxious about my harvest because of poor rains, but I got the highest yield ever in three years', said Miriam Piri, a Zambian farmer who started planting DTM in 2013 under the DTMA project (CIMMYT 2016).
- 'Our family now prefers the new provitamin A maize, as it has great health benefits for my children and granddaughter and the taste is delicious. The *sadza* is better, I was also pleased the variety is drought tolerant. Despite a dry spell in January my maize was able to yield a good harvest.' These are the words of Mr. Musonza Musiiwa of Zimbabwe after growing and eating drought tolerant maize which is also enhanced with provitamin A (CIMMYT 2018).
- 'I would like to grow it for myself and consume it with my family because I heard that it is good for eyesight and skin — and it is also tasty', says Enna Mutasa, a smallholder farmer, referring to the nutritious provitamin A maize cultivars ZS244A and ZS500, which were displayed at a seed fair in Masvingo District, Zimbabwe. The seed fair was organised by CIMMYT through the Biofortified Maize for Improved Human Nutrition (BHIHN) project (CIMMYT 2020b).
- Gomba Seed Producers' Cooperative in Gomba District, Central Uganda grows several improved cultivars of common bean released under the TL projects including NABE 2, 4, 15, 16 and 2 which they sell as a group through NGOs and seed companies (Akpo et al. 2020). According to Akpo et al. (2020), the group which received capacity building on bean production under the TL projects can produce over 200 tonnes of common beans in a season. It is the major supplier of dry beans to schools in Mpigi and Gomba Districts, supplying over 50 tonnes per season. Income generated from bean sales has positively transformed the livelihoods of many farmers in this group. Most of them have now built permanent houses but before venturing into bean production, they lived in grass-thatched houses (Akpo et al. 2020). Additionally, some of the farmers in this group have bought electronics, motorbikes, bicycles, and installed solar panels in their homes.

1.5 Conclusions and Recommendations

We conclude that great strides have been made in maize and bean cultivar development in SSA. Over 1700 maize and nearly 1000 bean cultivars have been released across SSA through several multinational projects, reaching millions of farmers, boosting productivity of these crops, and therefore positively impacting food, nutrition, and income security in the region. The key milestones of maize cultivar projects across project countries include over 300 million farmers benefiting from improved cultivars with 300,000 metric tonnes of certified seed produced and distributed. Over 3.8 million hectares planted with improved maize cultivars. This resulted in several millions of farmers being moved out of poverty, hunger, and malnutrition. Cultivars that can be recommended for production for different purposes and agroecological environments in southern Africa include SC719 for medium-to-high rainfall environments or under irrigation, PAN53 for medium rainfall environments, SC403 for low-to-medium rainfall environments and ZS500 for high provitamin A content combined with high yield (Table 1.1). These cultivars have already been evaluated and released in most of countries in southern Africa, in some cases with different code names. SC719 is a high yielding (14 t/ha), drought tolerant, and long season cultivar with other good agronomic traits. PAN53 is one of the most popular and stable cultivars across southern Africa. It is high yielding, drought tolerant flint-type medium maturity cultivar with good resistance to ear rot, leaf blight, and grey leaf spot while SC403 is a very early maturity cultivar adaptable to many agroecological conditions in southern Africa.

More than 5.028 million metric tonnes of dry beans have been traded on national, regional, and international markets, with 2,260,507 farmers (1,134,386 women) linked to profitable markets. NUA45 (bio-fortified) is the most widely cultivated bean cultivar in southern Africa, mainly because of its palatability, wide adaptation, short cooking time, and earliness (less than 85 days). Thus, this cultivar should be promoted across SSA to improve food, nutrition, and income security considering that farmers in most countries charge a premium price on biofortified bean cultivars. The release of similar cultivars in multiple countries will facilitate regional and international trade among farmers and nations as a whole thereby ensuring food, nutrition, and income security.

Low cultivar adoption by farmers is hampering the expected impact of cultivar development in SSA. Increased awareness by farmers about a new cultivars and sustainable government to farmer input support systems are key to enhanced cultivar adoption by smallholder farmers in SSA. We therefore recommend strategic and robust cultivar promotional systems accompanied by conducive seed policies across SSA. Adoption and impact studies on both maize and bean have been limited to a few countries due to high costs associated with such studies. Therefore, accurate information on adoption rates of maize and bean cultivars for some countries in SSA is not readily available. There is also a need to invest in bioavailability studies to quantify the exact nutritional impact of consuming biofortified maize and bean cultivars in SSA.

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Chapter 2
From Soil to Fork: Can Sustainable Intensification Guarantee Food Security for Smallholder Farmers?

Adornis D. Nciizah, Hupenyu A. Mupambwa, Patrick Nyambo, and Binganidzo Muchara

Abstract Agricultural production on smallholder farms in sub-Saharan Africa (SSA) is hampered by countless challenges, chief among which is soil degradation due to unsustainable farming practices, inadequate technical and financial support, and climate change. Moreover, the ever-increasing African population, which is directly proportional to an increase in the demand for food, makes the situation grimmer. This has consequently resulted in the active search for alternative approaches to agricultural production that do not only ensure that there is enough food at the table but do so sustainably. One such approach that has attracted the interest of researchers, funders and policymakers is sustainable intensification. However, there have been numerous discussions and debates on the usefulness of this concept in increasing crops yields for African farmers, with some opponents going as far as labelling the approach an oxymoron. Therefore, it is important to assess the potential of the concept to not only sustainably feed the rural population but deliver food from the soil to their forks from an African perspective. Therefore, this chapter highlights key sustainable intensification approaches across sub-Saharan Africa that have resulted in significant yield gains across sub-Saharan Africa (SSA) and discusses policy issues required to promote this concept.

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2.1 Introduction

It is estimated that the demand for food will increase by 50% between 2012 and 2050 due to population growth especially in SSA and urbanization, while putting pressure on natural resource base required for agricultural production (FAO 2017a, b). The predicted huge population increase coupled with threats posed by a changing climate will certainly put more pressure on the already strained agricultural land (IPCC 2007). Moreover, there is also a need to overcome several other challenges including soil degradation (soil organic matter depletion, crusting, compaction, erosion and salinization) and persistent droughts if the SSA region is to end hunger and accomplish food security. Water scarcity worsens soil degradation, which further reduces the capacity of the soil to perform one of its most important ecological functions, i.e. feeding an ever-increasing population. Overcoming these challenges and hence achieving the Sustainable Development Goals (SDG), which aim to find solutions to, among others, hunger and poverty and taking action against climate change calls for the adoption of resilient food production methods. This is especially important since meeting the increased food demands with the current agricultural practices is likely to increase land degradation and greenhouse gas emission (FAO 2017a, b).

Over the years, numerous researchers and international research organizations have recommended several interventions and approaches as a sure means of ensuring food sufficiency. However, most of these interventions have many overlaps and only differ in names (Giller et al. 2021). Whilst this may end up confusing farmers, it does highlight the lack of a clear-cut solution to the challenges affecting agricultural production. Consequently, there is sustained interest in finding ways of addressing the mammoth task of increasing food production at minimum damage to the environment.

One of the most recent interventions put forward as a possible solution to the current challenges in agricultural production is sustainable intensification. Sustainable intensification of agricultural production entails feeding a growing population amidst an increasingly degraded environment compounded by climate change without opening up new farmlands (Pretty 2008). Accordingly, sustainable intensification permits farmers to produce more food from the same size of agricultural land. In other words, farmers utilize sustainable technologies to produce more food, while using fewer external inputs, which improves resource efficiency in farming (Pretty 2008). Consequently, sustainable intensification increases crop production per unit area, while minimizing possible environmental impacts (FAO 2017a, b).

Whilst there is a plethora of information on the concept of sustainable intensification, there is little documentation of the tangible success of the concept in Africa. Consequently, there is intense debate on the usefulness of the approach in addressing production challenges in (SSA). Intensification, through increased use of external inputs to increase output without increasing land area, could potentially increase GHG emissions leading to climate change. For instance, Tirado et al. (2010) argued that whilst intensification may increase food production under climate change, it might inadvertently increase the susceptibility of dry lands as the climate changes. To make the concept more appealing, sustainability was identified as one of the key features of intensification, hence sustainable intensification. However, some opponents still argue that the drivers behind the need for this intensification are the key issues that should be addressed. It therefore becomes imperative to review the usefulness of the concept from an African perspective concerning its ability to not only feed the rural population but also achieve this sustainably. It is thus necessary to highlight yield gains on smallholder farms achieved through sustainable intensification as well as highlighting the key practices that drove the yield increase. Consequently, the objectives of this chapter are to

1. Reveal the extent to which sustainable intensification has increased the yield in SSA smallholder agriculture and hence provided food on the table.
2. Determine whether there are any policies that support the sustainable intensification concept for smallholder farmers in (SSA).

2.2 Overview of Current Challenges to Agricultural Food Production in African Smallholder Agriculture

2.2.1 Population Pressure

The continued increase in population and growth in consumption will lead to a rise in the demand for food for at least another 40 years especially in SSA (Godfray et al. 2010). It has been projected that from 2008 and beyond, the world population growth will remain in the 4% range while in SSA and other still developing regions, growth is anticipated to average 6% (Mussa 2007). In SSA alone, the population is projected to increase to two billion by the year 2050 (Bremner 2012). The ever-increasing African population is directly proportional to an increase in the demand for food. However, the same cannot be said about food production. Despite the reports of increases in food production in Africa (Blein et al. 2017), the growth falls far short of the expectations and needs of the African population. As a result, food demand will surpass the domestic food supply. The rise in food demand leads to an increase in the prices of food products at market. In order to increase food production, African farmers tend to expand agricultural lands. Nevertheless, this strategy has its limits and can cause significant environmental degradation (via deforestation).

Increased population has increased urbanization and loss of agricultural lands. As a result, people end up opening up new agricultural lands in peri-urban areas. According to d'Amour et al. (2017), urban expansion takes up agricultural lands that are three times as productive as the average soil in SSA. In addition, the rise in food costs has forced many people in Africa to focus on using any available open spaces in the urban areas for food production. Studies have shown that peri-urban agriculture has resulted in a slight increase in food production in Africa. The growth in food production on the continent is attributed to the intensification and expansion of croplands into previously uncultivated areas. Cropland expansion has adverse effects on biodiversity, mainly through the loss of natural habitat (Chaplin-Kramer et al. 2015). The land plays a dual role as both a source and a sink of greenhouse gases. The land is also pivotal in energy, water and aerosol exchange at the soil surface/atmosphere interface (Arneth et al. 2019). The expansion of cropland disrupts the resilience of social-ecological systems like the carbon cycle, hence increasing global warming. The unsustainable agricultural practices used by most farmers in Africa further disrupt the ecological systems (Nciizah et al. 2021).

2.2.2 Unsustainable Farming Practices

Food production amongst smallholder farmers can potentially be increased by taking up agricultural intensification. Agricultural intensification is defined as the increase in agricultural production per unit of inputs (Kenmore et al. 2004). Productivity can potentially be increased by using high yielding crop varieties, increasing land under irrigation, increasing fertiliser use, improving access to market, governance, embracing information and communication technology, increasing the use of genetically modified crops and land reform (Jones 2015). However, agricultural intensification must be done sustainably. This presents a challenge for most African smallholder farmers who lack resources, knowledge and the will to follow sustainable farming systems. Instead, agricultural practices commonly used cause low fertility and high erodibility problems that have resulted in a decline in the productivity of field crops (AGIS 2013).

Soil degradation is a result of unsustainable agricultural production practices that cause rapid mineralization of organic matter and nutrient content of the soil, and have contributed intensively to low soil productivity, which creates high crop production risks in SSA (FAO 2016). Mills and Fey (2004) reported that soil degradation was due to unsustainable land use and management practices that deplete the soil organic matter (SOM), which erodes soils' natural fertility and capacity to fulfil its ecological functions. Soil tillage, which represents, arguably, the most influential manipulation of soil physical properties is one of the foremost factors that affect soil properties and crop yield (Nyambo et al. 2020a). Tillage practices, e.g., ploughing, enhances degradation by altering soil structure, which in turn increases runoff and soil erosion (Nciizah et al. 2021; Nyambo et al. 2021). Conventional tillage through ploughing also causes soil compaction (plough pans) and rapid mineralization of SOM (Laker 2004). Consequently, these practices result in the loss of SOM, the destruction of soil structure, and poor soil health and crop productivity (Thierfelder and Wall 2009). Moreover, crop residue mismanagement can lead to direct input of carbon dioxide (CO_2) into the atmosphere, hence aiding greenhouse gas (GHG) emissions (Lal 2010).

Most smallholder farmers in Africa remove crop residues from the fields. At a smallholder farm, crop residues are an important source of fuel, building material and animal feed (Turmel et al. 2015). Other farmers burn the crop residues before tilling their soils while some are left to be grazed in the fields (Nyambo et al. 2020b). Crop residues are vital for the supply of SOM and soil stability. The practice of removing all the crop residues and leaving the soil surface bare reduces soil quality, leading to a decline in crop yield. Furthermore, these practices leave the soil susceptible to erosion, environmental pollution.

2.2.3 Climate Change

Climate change has become a significant challenge to agricultural development in SSA. The escalation in unpredictable and erratic weather systems threatens food security and the livelihoods of most people in rural areas in SSA. Climate change is linked to increases in global temperature and extreme weather conditions such as dry spells, torrential rains, high winds, flooding and cyclones, ultimately affecting the standard ways of life and sustainable food production (IPCC 2001). Prolonged drought periods and flooding demonstrate the extent of a changing climate that destroys homes and farms, thereby leading to food-insecure rural communities (Nciizah et al. 2021). While the climate is changing, the primary concern for agriculturists is the magnitude of crop yield decline, especially amongst SSA farmers. Whilst a steady rise in temperature and carbon dioxide provides conditions that favour an increase in the yield of some crops (Porter et al. 2014), these potential yield gains in some regions are likely to be superseded by extreme events, mostly extreme temperature and water stress during crop flowering. Climate change negatively affects agro-ecological conditions, which directly affects food production and indirectly reduces income and demand for agricultural produce (Schmidhuber and Tubiello 2007).

Climate change has a potential to significantly contribute to food insecurity due to food price increase due to reduced agricultural food production (Mbow et al. 2019). Competition for land may increase because some parts of the land may be climatically unsuitable for food production. In the long run, global warming reduces food availability which causes a rise in commodity prices, thus increasing the vulnerability of the rural population (von Braun 2007).

2.3 Sustainability in Agriculture

In Africa, more than 70% of the farmers are small-scale or smallholders, who practise mainly subsistence farming. Though these farmers mostly produce to feed their families, they are critical in driving food security in SSA. The threat of climate change, intensification pressures to sustain the growing population and resource degradation that the smallholder farmers now face are significant threats to Africa's food security (Mungai et al. 2016). The growing world population has driven the food demand in the past century, and this has seen the need for intensive production systems with a limited ecological approach being used in crop and animal production. This food requirement challenge has also been experienced by African smallholder farmers, who have shifted from their nature-based farming techniques to Green Revolution technologies that make use of industrially produced chemicals in production. However, these technologies have actually seen most smallholder farmers realizing declining productivity and soil degradation. This has seen a recent drive towards sustainable agriculture even under intensive production. In general, there are four main constrains to intensified agricultural production and sustainability, which are soil, water, biodiversity and land (Pretty and Bharucha 2014). These constraints have been identified as the main focal points around which decisions of sustainability in agriculture and changes in production systems will need to be made (Pretty and Bharucha 2014). Figure 2.1 shows the effects of the various constraints under both sustainable and non-sustainable agricultural systems.

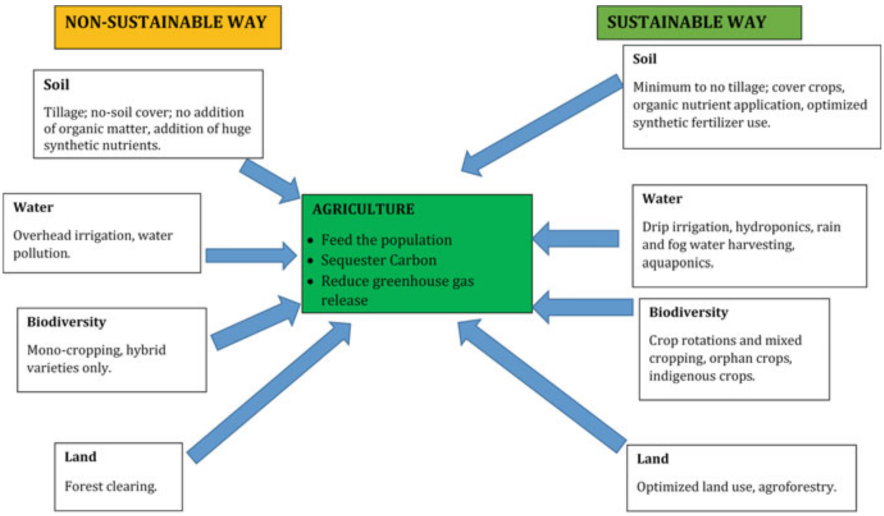

Fig. 2.1 Effects of various constraints to achieving sustainable agriculture under smallholder farming systems

Although sustainability is recommended in agriculture, it important to note that simply adopting the principles indicated in Fig. 2.1 may not be suitable to sustain the projected food requirements of the growing population. There is a need to undertake research on how to optimize the various sustainable technologies that are recommended. For example, in organic soil fertility management, as opposed to the traditional use of composts, improved composts such as vermicomposts need to be promoted and have their application and production optimized. Furthermore, technologies like hydroponics currently require expensive inorganic fertilizers, which most smallholder farmers cannot afford. Research on organic nutrient sources will be important in driving the sustainable utilization of water under hydroponic systems that conserve fresh water utilization in crop production.

2.4 What Is Sustainable Intensification of Agriculture?

As alluded to before, sustainable intensification is not an entirely new concept (Pretty 2008; Pretty et al. 2011), but has seen a lot of renewed interest over the past few years (Cassman and Grassini 2013). Sustainable intensification stems from the need to feed the burgeoning SSA population by increasing food production from the existing agricultural land, which is often over-exploited and used unsustainably. The concept recognizes the need to prevent further environmental damage or opening up new farmlands, hence intensification of agriculture, albeit sustainably (Pretty et al. 2011). Consequently, sustainable intensification addresses whole landscapes and ecosystems in a bid to augment the utilization and management of resources (FAO 2008). This is particularly important since, on one hand, agriculture is the biggest driver of environmental change and, on the other hand, it is the sector most affected by climate change (IPCC 2014). This then underscores the need for sustainability in farming systems, a major characteristic of which is high efficiency of internal resource use through such processes as conservation of soil organic matter and water as well as efficient nutrient cycling.

In simple terms, sustainable intensification enables farmers to grow more food without expanding land area through improved resource efficiency in farming. Sustainable intensification is particularly important in Africa since it provides prospects for boosting crop production per unit area, whilst addressing sustainability features such as social, political, economic and environmental impacts (FAO 2006). According to Pretty et al. (2011), continued population growth erodes improvements made in African agriculture because it stagnates or diminishes the per capita availability of domestically produced food. Given that expanding agricultural land is not feasible, production needs to become both more sustainable and resource use efficient if the natural resource on which agriculture relies is to be conserved. Therefore, sustainable intensification alleviates the potential conflict for land by producing food with a lower land footprint (Mbow et al. 2019).

The ability of sustainable intensification to achieve its goals is often debatable; on the one hand, proponents of the concept argue that it offers a new paradigm to meet food demand and resource scarcity. On the other hand, opponents view it as an oxymoron that sugarcoats intensive farming with sustainability (Cook et al. 2015). Nevertheless, before addressing the usefulness of sustainable intensification, it is perhaps pertinent to have an in-depth look at the practices used in sustainable intensification and how they relate to other models. This is especially important since some authors often contend that there is a lack clarification of the agricultural techniques to use to attain sustainable intensification (Mbow et al. 2019).

2.5 Sustainable Intensification Concepts and Practices

Cook et al. (2015) highlighted three fundamental assumptions about food security and agricultural production that drive the need for sustainable intensifications, i.e. the need to grow more food for the rapidly increasing world population, the need for agriculture to be more sustainable and resource efficient and the undesirability of expanding the arable land base. Consequently, sustainable intensification practices should aim to address all the three assumptions. This is especially true in SSA where there is a rapid population growth (Bello-Schünemann et al. 2017) and high rates of soil degradation (Tully et al. 2015), which are worsened by a changing climate (IPCC 2007).

Sustainable intensification comprises combinations of improved agricultural practices such as conservation agriculture (CA), agroforestry, organic agriculture, integrated pest management and ecosystem services as well as carbon benefits (Mbow et al. 2019). The various practices employed under sustainable intensification can be grouped into up to ten categories or approaches depending on how the technologies are applied (Table 2.1) (Pretty et al. 2018; Mbow et al. 2019; Xie et al. 2019). Several authors have reported significant yield gains following the use of several sustainable intensification approaches across Africa. For instance, smallholder farmers have achieved significant yield gains in several parts of SSA following the adoption of CA (Rusinamhodzi et al. 2011). Thierfelder and Wall (2012) reported between 35 and 56% increase in crop yield under CA compared to conventional tillage, whilst yield increases were up to 27% in Mozambique. These yield increases were attributed to increased soil organic carbon in the soil, which improved soil physical and biological processes. One of the reasons for poor yield under smallholder agriculture is poor pest control because chemicals are usually beyond the reach of many farmers. However, sustainable intensification practices such as integrated pest management often sustainably reduce pest and disease occurrence, hence preventing severe yield losses (Pretty and Bharucha 2015). Moreover, practices such as intercropping and crop rotation with legumes, which increase agricultural system diversity, not only break disease and pest cycles but also have an additional benefit of adding nitrogen to the soil. Intercropping, like any other multiple agroecosystem, has several advantages, which include increased productivity through better use or resources, that is, increased ability to capture light, reduction of weed competition and water loss. In addition, the system ensures a

Table 2.1 Sustainable intensification approaches, adapted from Pretty et al. (2018); Mbow et al. (2019); Xie et al. (2019)

Approach	Intervention
1. Integrated pest management	• Integrated plant and pest management. • Push–pull systems, natural enemies. • Increased pollination.
2. Increased agricultural system diversity and soil management	• Conservation agriculture practices such as zero and minimum tillage. • Soil conservation and soil erosion control. • Improved soil health – increased soil organic matter input. • Cover crops, intercropping, diversified crop rotations. • Compost/green manuring.
3. Integrated crop and biodiversity redesign	• Organic agriculture. • Systems of crop intensification. • Zero-budget natural farming. • Science and technology backyard platforms, farmer wisdom networks. • Landcare and watershed management groups. • Polycultures.
4. Pasture and forage redesign	• Mixed forage–crop systems. • Management intensive rotational grazing systems.
5. Trees in agricultural systems	• Agroforestry. • Joint and collective forest management. • Leguminous fertilizer trees and shrubs.
6. Irrigation water management	• Small-scale intensification. • Integrated aquaculture. • Water user associations. • Participatory irrigation management. • Watershed management. • Micro-irrigation technologies. • Precision agriculture. • Water recycling.
7. Organizational scale-up	• Community farms, allotments, backyard gardens, • Raised beds, vertical farms. • Group purchasing associations and artisanal small producers. • Micro-credit groups for small-scale intensification. • Integrated aquaculture.
8. Genetic improvements	• Genetically modified crops, breeding for drought tolerance. • Livestock breeding.
9. Technological approaches	• Crop and soil monitoring. • Increased fertilizer efficiency. • Greenhouse gas monitoring. • Precision agriculture.
10. Knowledge transfer	• Agro pastoral field schools. • Farmer field schools.

deeper and denser rooting system, which ensures high soil biological activity and nutrient cycling. Some studies have also shown that due to increased plant diversity, intercropping may result in large insect diversity and lower insect damage through decreased plant apparency, increased competition among pest and non-pest insects and improved natural enemy communities (Akbulut et al. 2003). Most importantly, the system has the potential to diversify farm income through the production of more than one type of crop, which leaves the farmer better placed to survive market downturns or crop failure.

Technological interventions such as crop and soil monitoring have increasingly become important since they are enablers of precision agriculture. Frequent soil monitoring allows the detection of soil variability on farms and the subsequent smart irrigation and fertilization, which not only reduces input costs but also protects soil and water bodies from degradation. Other important interventions include the development of improved genotypes that are both drought and disease tolerant. One example of genetic improvement is CIMMYT's Drought Tolerant Maize for Africa (DTMA) project, which was carried out between 2006 and 2015 in several African countries availing 60 drought tolerant hybrids and 57 open-pollinated varieties to smallholder farmers. The project availed seed to over 43 million smallholder farmers and their families. Genetic improvement of seed is thus a very important practice in sustainable intensification, especially if the seed is compatible with other sustainable intensification practices such as intercropping and conservation tillage. Similarly, CIMMYT's Water Efficient Maize for Africa (WEMA) project availed maize varieties that yielded between 24 and 35% more grain under moderate water stress conditions than currently available varieties in Kenya, Mozambique, Tanzania, South Africa, Uganda, Zimbabwe and Zambia. Table 2.1 shows several sustainable intensification approaches and the various interventions in each approach.

2.6 Benefits of Sustainable Intensification of Crop Production in African Smallholder Agriculture

Several field studies, reviews and meta-analyses have highlighted significant yield gains with sustainable intensification practices across Africa (Table 2.2). Whilst sustainable intensification practices can be applied separately or in combination, studies have shown that the adoption of multiple sustainable intensification practices outperforms the use of one practice. For instance, Kotu et al. (2017) analysed both the adoption and impacts of sustainable intensification practices using a dataset from Ghana. The authors used a multivalued semi-parametric treatment effect model to estimate the effects of adopting multiple sustainable intensification practices on the productivity of maize on smallholder farms. The model results showed that a higher number of sustainable intensification practices were significantly related to higher productivity. This was more evident when commercial inputs were combined with cultural practices. Similarly, Lungu (2015) reported maize yield increases of

Table 2.2 Examples of yield increase from the adoption of sustainable intensification practices in Africa

Location	Finding	References
Zambia	Maize yields increased by 45% & 22% for male and female landholders, respectively, between the 2006–2008 and the 2015–2017 (2000 k/ha) growing seasons. Increases in yield were attributed to the uptake of fertiliser and improved seeds and mechanization.	Djurfeldt et al. (2019)
Ethiopia	Direct seeding with a two-wheel tractor resulted in 25% and 13% higher wheat grain and straw yields, respectively, compared with the conventional practice used in the Ethiopian highlands. In the wheat systems, the two-wheel tractor direct seeded system had a 47% higher gross margin than the conventional practice.	ILRI (2020)
Ethiopia	Findings from experiments conducted in southern Ethiopia showed that the adoption of conservation agriculture–based sustainable intensification practices and technologies increased household return on investment in maize (32.6%) and common bean (49%) production, by growing common beans twice a year intercropping and relay cropping with the same maize crop.	Beshir et al. (2021)
Tanzania	Scaling out SIMLESA technologies through innovation platforms increased the number of farmers using improved seeds of maize and legumes from 30–40% to 85% whilst the adoption of a conservation agriculture–based sustainable intensification (CASI) technology package increased yields for maize from 1.5 t ha^{-1} to 4.5 t ha^{-1} and legumes from 0.38 t ha^{-1} to 1.5 t ha^{-1} in Tanzania.	Sariah et al. (2019)
Uganda	Compatible maize–bean intercropping patterns increased labour and land use efficiency and reduced soil degradation due to reduced soil nutrient mining and soil erosion.	Mubiru et al. (2019)
Ghana	A study in Ghana using multivalued semi-parametric treatment effect (MVTE) model to estimate the effects of adopting multiple sustainable intensification practices on maize productivity showed that moving from one of the following sustainable intensification practices—cereal–legume intercropping (IC), cereal–legume rotation (CR), CF, and SWC practices to all of them—increased maize yields by 296 kg/ha.	Kotu et al. (2017)
Zimbabwe	A study on maize production intensification using cattle manure on degraded lands showed that combining 25 t ha^{-1} manure with 100 kg N resulted in the highest yield of 9.3 t ha^{-1} on homefield clay soils, 6.1 t ha^{-1} on clay outfields,	Rusinamhodzi et al. (2013)

(continued)

Table 2.2 (continued)

Location	Finding	References
	7.6 t ha^{-1} in the homefield and 3.4 t ha^{-1} in the eighth season.	
Kenya	Rusinamhodzi et al. (2020) tested the performance of elite maize genotypes under selected sustainable intensification options in Kenya and observed reduced yields after intercropping maize and legumes due to increased competition. They concluded that there is a need to optimize intercropping through improved planting designs and custom mixed fertilizers suitable for intercrops.	Rusinamhodzi et al. (2020)
Tanzania	Mtengeti et al. (2015) Carried out a study to compare farmers' practices (control) and improved practices (the proper use of fertilizer, crop protection inputs and recommended crop seed variety) for maize and rice. The findings showed that maize and rice grain yield ranged between 2.5 and 5.4 t ha^{-1} in farmers' practices and between 6.6 and 8.5 t ha^{-1} under improved practices; moreover, maize and rice stover/straw biomass ranged between 5.33 and 15.4 t ha^{-1} for improved practices and 2.11 and 9.13 t ha^{-1} for farmers' practices.	Mtengeti et al. (2015)
Ethiopia, Kenya, Malawi, Mozambique and Tanzania	Mupangwa et al. (2021) carried out on-farm trials in five countries over a 7-year period to assess the effects conventional practice (Conv_sole) compared with variants of conservation agriculture (CA) such as sole maize (CA_sole), intercropping (CA_intercropping) and rotation (CA_rotation) on maize productivity. The results showed that the CA cropping systems outperformed conventional practices with groundnut and pigeon pea, resulting in the highest relative maize yield advantages, whilst common bean stabilized maize yields under CA than other legumes.	Mupangwa et al. (2021)

30–70% following the use of conservation tillage (deep ripping 15–30 cm), leaving crop residues on the soil surface, and using an appropriate maturity cultivar compared to conventional tillage. However, it is often important to use compatible practices since some practices may cause yield losses. For instance, Rusinamhodzi et al. (2020) carried out a study to determine the contribution of combining different cropping and tillage systems with different genotypes across several cropping seasons towards sustainable intensification. The study assessed the agronomic performance of six maize genotypes under intercropping with conservation tillage (no-till) over six seasons. The results showed that genotypes that yielded highest under sole cropping had lower yields under intercropping with up to 1.1 t ha^{-1} yield penalty. The lower yield under intercropping was attributed to competition. It was concluded that there was a need to use genotypes that reduce risk and maximize yield.

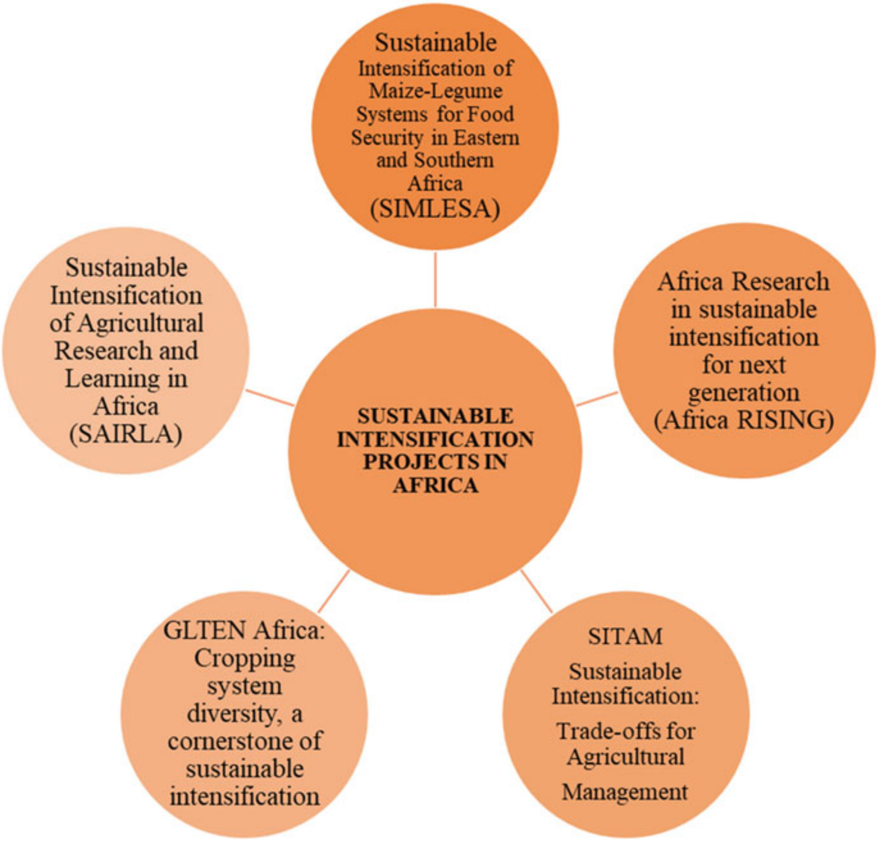

Fig. 2.2 Key projects on sustainable intensification in Africa

One of the recent practices that have been advocated for as part of integrated pest management (IPM) is the push–pull system to control pests. The Montpellier Panel Report (2013) showed that about 25,000 East African smallholder farmers were using the push–pull method to control pests with added benefits such as reduction of pesticide use, which subsequently increased income and increased soil fertility since the method produces a poly-agriculture system. The success of IPM systems hinged on the success of Farmer Field Schools for training and information dissemination. Knowledge transfer through farmer field schools is one of the approaches for sustainable intensification, which plays a crucial role towards the success of the concept. More examples of success stories of sustainable intensification in Africa are shown in Table 2.2.

The examples shown in Table 2.2 are from various funded projects (Fig. 2.2) on sustainable intensification carried out across Africa over the last few years. The high number of sustainable intensification projects in Africa is an indication of the interest the concepts has garnered among global stakeholders. These projects have so far produced insightful findings on the prospects of sustainable intensification as well as entry points of some of the practices in Africa. For instance, the Sustainable Intensification of Maize-Legume Cropping Systems for Food Security in Eastern and Southern Africa (SIMLESA) project was implemented from 2010 to 2018 in Ethiopia, Kenya, Malawi, Mozambique and Tanzania as well as Rwanda and Uganda. The goal of SIMLESA was to improve the food security of African smallholder farmers and increase productivity and income through the integration of sustainable intensification practices, particularly intercropping with legumes and conservation agriculture. The project established experimental trials to test the most promising conservation agriculture–based sustainable intensification (CASI) technologies, such as minimized soil disturbance, soil cover and the use of crop rotations and/or associations. The project also employed other agronomic practices like the use of inorganic and organic fertilizers, herbicides and improved varieties, timely planting, weed control and proper crop management (Wilkus et al. 2021). Findings from the study showed increased maize yield due to the implementation of CASI technologies. In Malawi, maize yield increased by 17 and 38% in the mid-altitude and lowland agro-ecologies, respectively, whilst Ethiopia saw increases between 5 and 18%. Another key project, the Sustainable Intensification of Agricultural Research and Learning in Africa (SAIRLA), was a 5-year project which ended in 2020, which sought to create new evidence and generate tools to enable key stakeholders to establish effective policies and investments in sustainable agricultural intensification (Gebreyes 2017). Some of the findings of the projects included the identification of land use practices that are both socially and environmentally sustainable.

2.7 Policies Supporting Sustainable Intensification of Crop Production in African Smallholder Agriculture

Sustainable agricultural intensification and production by farmers is vital to ensure global food security. The need for intensification is even more critical in SSA, where food production and supply are inherently insufficient. The agricultural support policies in these countries are either weak or poorly coordinated to ensure maximum output at the food production stage of the value chain. Sustainable intensification can be achieved by targeted policy interventions that seek to enhance productivity per unit of land, input supply, mechanization, technology adoption, irrigation, farm management as well as pest and disease control. However, the absence and weak national and regional policies that offer agricultural support often make the agricultural intensification concept unachievable.

As part of ensuring that African governments and policy makers give adequate support to the agricultural sector, a number of policy documents have been produced to guide the agricultural development agenda, including the intensification of the sector. In 2003, African leaders adopted the Comprehensive Africa Agriculture

Development Programme (CAADP), which aimed to promote agricultural growth, reduce poverty and improve food security on the continent (African Union 2003). The CAADP programme was vital because it stipulated how Africa's agricultural policy should be driven at national and continental levels. For instance, the programme made a recommendation that African governments should allocate at least 10% of the total government expenditure to the agriculture sector. It was projected that this level of investment was essential to achieve an average 6% annual agricultural growth rate and attain the Millennium Development Goal (MDG) of eradicating extreme hunger and poverty by 2015 (Matchaya and Chilonda 2012). The CAADP was then followed by the 2014 Malabo Declaration on Accelerated Agricultural Growth and Transformation for Shared Prosperity and Improved Livelihoods adopted at the African Union summit at Malabo, Equatorial Guinea. The end goal of all these programmes was to end hunger and halve poverty in the continent through inclusive agricultural growth by 2025 (African Union 2014). It is important to note that these programmes were coined as an affirmation that:

- African agriculture was not performing according to expectation.
- There is potential for Africa to increase its agricultural output.
- There was increasing hunger and poverty among the population.
- If agricultural budgetary allocations are strengthened at a national level, there is room for turning around the economic fortunes of the continent.

The focus on resource mobilization through budget allocation is a crucial policy imperative that can enhance sustainable intensification of agriculture in Africa. This policy is measureable and monitoring of its implementation is fairly easy and manageable, although misallocation or misuse of the finance meant for the agricultural sector may be a challenge. As governments drive the budget allocation and implementation, it might be important to have a bird's eye view of priority areas that can make sustainable intensification of agriculture possible. These priority areas include the following areas:

- Building sustainable institutions—Weak institutions are Africa's major challenge, hence the need to strengthen them wherever possible. Ideal institutions must be capable of delivering technical and financial services that suit the diversity of the agricultural sector as a whole. Strong institutions are responsible for producing strong policies that can provide subsidies for equipment, fertilizers and seed, which make sustainable intensification a more practical and achievable objective. However, if agricultural institutions are weak or absent, sustainable intensification may remain a pipedream for Africa. All actors within the state are required in order to ensure sustainable intensification, including non-governmental organizations, which play a role in the development of communication networks for sharing access to knowledge and information regarding sustainable land use practices (FAO 2017a, b). Furthermore, informal co-operative arrangements and other types of social capital could provide local frameworks and institutions for risk-sharing that favour private investment in the area of sustainable agricultural intensification.

- Clearly defined incentive structure within the agriculture sector: Sers and Mughal (2018) argued that sustainable intensification can only alleviate poverty when returns to land and labour simultaneously increase. This means that agricultural policies must provide incentives that ensure both farmers' welfare and resource sustainability (Sers and Mughal 2018).
- Agricultural training, education and extension services: Despite enormous evidence that points to the importance of farmer training and extension services, African governments often fail to deliver enough of these services to the farmers. Training improves access to knowledge and information on appropriate technologies and feasible marketing strategies, which are key drivers of sustainable agricultural intensification (SAI). Although participatory technology development (PTD) has become increasingly popular and preferred over the years, formal training on sustainable agricultural practices using experimental research is still critical.
- Increased public infrastructure investment: Farmers face huge transaction costs due to poor road accessibility and distance to both input and output markets (FAO 2015). Although the production levels are low in Africa, the yield potentials are further worsened by poor infrastructure. Besides road network, smallholder farmers must be given access to modern communication and production technologies that keep them connected to the globe. Such technologies also enhance growth aspirations as well as market access.

For a sustained agricultural growth as well as positive spinoffs in the sustainable intensification of the sector, regional and continental institutions must devise joint strategies for promoting collaboration in information sharing, improvements in physical infrastructure, research and agricultural project implementation frameworks. As population increases in Africa, against static natural resources like land and dwindling agricultural water supplies, it means agricultural intensification must adopt a culture and not an optional approach.

2.8 Conclusions

Sustainable intensification of agriculture is not a new concept; however, the last decade has seen a rapid increase in funded projects, discussions and debates on the concept. There is sufficient evidence from key projects carried out by both regional and international research organizations on the effectiveness of sustainable intensification in increasing crop yields in SSA. Studies showed varying levels of yield benefits especially for maize production across Africa, showing that proper application of sustainable intensification practices can improve agricultural production and hence guarantee food security for smallholder farmers. However, some studies have shown yield losses for some maize genotypes when used in intercropping and conservation tillage. There is therefore a need for extensive research on the interaction of the various sustainable intensification practices of yield of various crops.

Some of the practices are knowledge intensive, which calls for the capacitation of smallholder farmers to ensure success of the concept. This may also encourage the uptake of multiple sustainable intensification practices. This is particularly important since some studies have shown farmers will get more benefit by combining up to four practices compared to just one. There is also a need for policy that supports smallholder farmers since agricultural support policies in most SSA countries are either weak or poorly coordinated to ensure maximum output at the food production stage of the value chain. Consequently, targeted policy interventions that seek to enhance productivity per unit of land, input supply, mechanization, technology adoption, irrigation, farm management as well as pest and disease control can assist in achieving sustainable intensification of agriculture and ensure.

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Chapter 3
Sub-Saharan Africa Smallholder Farmers Agricultural Productivity: Risks and Challenges

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Abstract Smallholder farmers are important in the fight against hunger and undernutrition in rural communities in Sub-Saharan Africa (SSA). Even though agriculture contributes close to 23 percent of sub-Saharan Africa's GDP, the continent has remained a net food importer for the past three decades. Furthermore, sub-Saharan Africa loses billions of dollars annually through food imports because it fails to exploit its vast agricultural production potential. While African governments have provided resources to catalyse agricultural productivity, smallholder farmers continue to face barriers that affect their profitability and production capacities. The chapter highlights challenges that sub-Saharan Africa smallholder farmers face and suggests possible interventions to increase agricultural productivity. Gender imbalances, lack of climate change mitigation and adaptation tools, inadequate government support, lack of and unequal access to inputs/extension services, inadequate finance systems (credit and insurance services), public health issues, and infrastructure bottlenecks, among others, possess severe constraints for agricultural productivity for smallholder farmers. Increasing the rates of agricultural mechanisation, promoting climate-smart agricultural practices, better focused public and private sector support for smallholder farmers, and capacity support to strengthen

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agricultural value chains are some measures to enhance and sustain agricultural productivity amongst smallholder farmers.

Keywords Smallholder farmer · Agricultural productivity · Sub-Saharan Africa

3.1 Introduction

Smallholder farmers and agriculture generally play a significant role in the economic development and poverty alleviation efforts in rural communities (Rapsomanikis 2015). The smallholder farmers typically practice low-input mixed crop-livestock farming on small pieces of land that are less than 2 ha (Nyambo et al. 2020a, b). Sub-Saharan Africa's smallholder farmers have a massive social and economic footprint as they derive income from their farms or land, use part of the produce for family consumption, support livelihoods, and employ intensive family labour for productive purposes (Nciizah et al. 2021; Nyambo et al. 2021). McKinsey and Company (2019) reported that between 60% of the sub-Saharan Africa population are smallholder farmers, whereas Goedde et al. (2019) suggested that close to a quarter of the continent's GDP comes from agriculture. In low-income countries, agriculture accounts for over 61% of the total labour force employed (World Bank 2019).

Despite the potential to contribute to agricultural productivity, SSA smallholder farmers are not entirely food self-sufficient because of a host of intertwined factors. Therefore, the debate in the development circle should focus on whether the smallholder farmers are adequately equipped to produce enough to sustainably supply the nourishment needed at the required volumes while managing risks posed by climate change, lack of financial and technical resources, infrastructure deficits, pests, and diseases, among others. In order to increase productivity, whilst reducing the SSA's net food import bill estimated to be just over the US $43 billion in 2019 (Jayne et al. 2021), and reducing food insecurity in Africa, it is vital to look at the smallholder agricultural production dynamics and come up with ways to bridge the yield gaps. This chapter discusses the risks faced by sub-Saharan Africa's smallholder agricultural productivity and suggests possible ways to increase output.

3.2 Causes of Low Yield in Smallholder African Farms

3.2.1 Climate Change

The adverse effects of climate change on agricultural productivity are well documented. Natural disasters that include droughts, cyclones, wildfires, amplified intensity of tropical storms, and flooding have increased in frequency and intensity in many countries (Nciizah et al. 2021). Woetzel et al. (2020) found that Ethiopia could experience volatile coffee and wheat yields while Mozambique faces corn production unpredictability by 2030. Consequently, sub-Saharan Africa's agricultural development and production capacities will be significantly affected, declining to around 15–35% (Barnard et al. 2015). Climate change impacts on stock productivity and fish migration patterns are also likely to affect the production of fisheries worldwide. In other instances water levels in some dams have receded, threatening both livestock and humans who depend upon the water bodies for domestic and industrial uses such as irrigation and drinking water for example. Although the effects of climate change may be felt worldwide, it is widely acknowledged that they will disproportionately affect Africa more than other continents. In most instances, smallholder farmers are either not well informed or have minimal access to insurance coverage, which worsens the effects of climate change-induced natural disasters, animal and crop diseases outbreaks on agricultural productivity (Manitra et al. 2011).

Climate change–induced disasters that have destroyed crops, livestock, and the rudimentary rural infrastructure such as post-harvest storage and processing facilities and transport networks affect agricultural production, ecosystems, and livelihoods. For example, tropical cyclone Idai left a trail of destruction and a humanitarian crisis in Malawi, Mozambique, and Zimbabwe affected smallholder farmers who predominantly rely on a rain-fed agricultural system. To better manage the effects of climate change, significant investment is required to modernize Africa's agriculture. For example, with irrigation facilities, smallholder farmers can maintain yields even when the weather is unfavourable. Nevertheless, it remains expensive for smallholder farmers to exploit groundwater resources considering the cost of fuel, pumps, and pipes (Barrett et al. 2017).

Climate-smart agriculture could sustainably increase smallholder agricultural productivity and income. It promises to enhance adaptation and resilience-building towards climate change and aids in reducing agricultural greenhouse gas emissions. Smallholder farmers can also be introduced to sustainable agricultural practices, like conservation agriculture, which can play a role in adaptation and mitigation strategies for agricultural production. Conservation agriculture practices enhance soil water retention and increase soil organic matter. That improves resilience to drought and extreme weather events, as well as soil carbon sequestration (Nyambo et al. 2020c).

3.2.2 Pests and Diseases

Pests and diseases are among the significant constraints limiting crop productivity in SSA's smallholder farming sector. The frequency of disease epidemics and pest outbreaks has increased partly due to climate change–induced temperatures and rainfall pattern variations. Several pests and diseases are endemic to most of SSA, particularly for maize, a staple crop for most countries in SSA. These include head smuts (*Sphacelotheca reliana*), maize streak virus (MSV), grey leaf spot (GLS) (*Cercosporazeae-maydi*s Tehon & Daniels), rust (*Puccinia sorghi* Schwein. and *P. polysora* Underw.), northern leaf blight (NLB) (*Exserohilum turcicum* Pass. Leornard & Snuggs), and ear rots (Fusarium and Diplodia and Phaeosphaeria leaf spot (PLS) (Phaeosphaeria maydis). These diseases are difficult to control as their occurrence is less predictable since it depends on climate. Most smallholder farmers cannot prevent the diseases due to limited access and resources to purchase pesticides.

Countries in the SSA continue to struggle against an invasion of Fall Armyworm (*Spodoptera frugiperda*). Driving the rapid spread of the pest is the region's climate—fall armyworm tends to thrive in areas where drought is followed by heavy rains, a pattern that has intensified in recent years in many countries in SSA. The pest has the potential to destroy between 21 and 53% of annual maize production in just 12 of the region's maize-producing countries (Prasanna et al. 2018). Developing cultivars that have enhanced levels of disease resistance and high abiotic stress tolerance can be an effective, sustainable solution to increase smallholder farmers' crop yields.

3.2.3 Gender Inequality

Despite constituting a more significant proportion of the agricultural labour force and contributing to agriculture and rural enterprises, women still face persistent structural constraints. Palacios-Lopez et al. (2015) estimated that crop production's average female labour share stood at 40%. Christiaensen et al. (2015) also argued that women's labour contribution to agriculture productivity varied across countries, with 50% in Uganda, Tanzania and Malawi, which was substantially lower for Nigeria (37%), Ethiopia (29%), and Niger (24%).

However, patriarchal beliefs and family responsibilities that cause unequal and limited access to productive assets, including poorly defined property rights, inputs, extension services, and credit/financial markets between men and women, hamper SSA smallholder farming potential. O'Sullivan et al. 2014, UN Women et al. (2015) and Mukasa and Salami (2016) show that the expected benefits of closing the gender productivity differentials for smallholder agriculture improves yields and increases aggregate agricultural output. Similarly, the Food and Agriculture Organisation (2011) argued that levelling access to productive resources between male and female farmers could increase agricultural output in developing countries by 4%.

3.2.4 HIV/AIDS and Pandemics

According to the World Development Indicators 2012, sub-Saharan Africa women are the hardest hit by the HIV/AIDS epidemic. While antiretroviral treatment has become more accessible, rural women bear the greater risk of contracting HIV because of their perceived social standing and beliefs. The nature of the HIV/AIDS epidemic is that those who survive it must devote much of their time to just try to stay alive. Just as other diseases like malaria and cholera, the effects of HIV/AIDS reduce the productivity of smallholder farmers and subsequently production of agricultural products in many SSA countries.

Similarly, the novel Coronavirus-19 (COVID-19) epidemic that has ravaged the globe will likely further affect smallholder farmers' production capacity. The agricultural value chains may be disrupted because human movement has been restricted to combat the spread of Covid-19 between cities and regions. That may affect smallholder farmers who may find it even more challenging to access agriculture inputs in time for the growing season, extension services, food supply, and fuel, among others. Given that smallholder farmers are the source of labour, enforcement of social distancing, working from home, and restricted transportation are expected to affect labour-dependent operations such as planting, plant management, harvesting, threshing, and storage (Nchanji et al. 2021), therefore further reducing their productivity.

3.2.5 Lack of Infrastructure

The SSA region lags behind other regions with regard to infrastructure performance, which thus limits growth and productivity. There is evidence that two-thirds of Africa's rural population does not have access to good road networks. Good rural road networks increase the prospect of farmers' purchasing inputs by 29–35% and enhance connectivity with the markets (Dercon and Hoddinott 2005). Okoboi and Barungi (2012) suggested that the distance caused by poor rural road networks constrained smallholder farmers' access to input and output markets and credit. That can effectively reduce fertilizer use among the smallholder farmers, leading to lower agricultural productivity. Similarly, Nkonya et al. (2011) showed that better access to quality road networks and markets improved investments in soil erosion prevention methods. Better soil management techniques increase agricultural productivity in the long run.

Likewise, 60% of SAA's population has no reliable electricity. Rural electrification improves agricultural wages and income-generating opportunities for non-farm labour, especially for rural households. Similar trends have been observed in the water and sanitation, information and communications technology sectors, especially for rural SSA. Inadequate storage infrastructure can cause post-harvest losses, which affects agriculture production. For example, Jackson et al. (1997) reported that horticultural produce in Zimbabwe that is regarded as a high grade at the farm is often downgraded to very poor grades by the time it gets to the market primarily because of poor roads and poor post-harvest handling techniques. In addition, poor quality seed, inadequate farming practices, and pest infestation can result in the loss of agricultural products well before the harvest time.

Effective approaches for rural development that include investment in the quality and availability of infrastructure can catalyse human and physical capital productivity and economic growth; improve access to education, health, markets for smallholder farmers; and facilitate integration, private investment, and trade. Nonetheless, the availability and quality of rural infrastructure do not substitute prudent macroeconomic, agriculture-specific policies and the robust implementation of such policies by public institutions (Llanto 2012).

3.2.6 Agriculture Extension Support

Agricultural research and extension expenditures in SSA remain very low notwithstanding that public spending on agricultural extension and research has a high payoff for agriculture development. Agricultural extension and advisory services in SSA have suffered from many years of general negligence that has limited their human resource capacities, funding, leadership, and direction (Christoplos 2010). Such policy-induced failures and the lack of enabling institutional establishment constrain the productivity of smallholder farms. That is supported by Owens et al. (2001) who showed that accessing agricultural extension services increased the value of crop production by about 15% for smallholder farmers. Dercon et al. (2006) also find that receiving at least one extension visit increased consumption growth by 7.1% and reduced poverty incidence by nearly 10%.

3.2.7 Management Practices

Sustainable strengthening of agricultural production is required to improve productivity relative to inputs by smallholder farmers in the African region (Dahlin and Rusinamhodzi 2019). One management practice that limits agricultural productivity in smallholder farmers is labour (Giller et al. 2006). Smallholder farmers use family labour to carry out field operations as well as rear livestock. In crop production, weed management is generally one of the most labour-intensive tasks during the cropping season. Farmers tend to remove weeds using a hand hoe. This operation requires more hands and takes a longer period to complete. Usually, smallholder farmers require two or more weeding cycles per season in addition to undertaking many other operations on the farm. At the end, farmers more often than not end up losing the battle against weeds that can cause low yields.

3.2.8 Mechanization

Unlike the use of wheel and crawler tractors, handheld manual tools limit the amount of land that a smallholder farmer can work on, increase the time spent on operations, and sometimes reduce the effectiveness of weeding or harvesting. All these components of manual labour affect crop yields. Nonetheless, mechanisation can address the operational challenge faced by smallholder farmers, enhance productivity,

Table 3.1 Agricultural machinery, tractors per 100 sq. km of arable land

Country name	1961	1965	1970	1975	1980	1985	1990	1995
India	2	3	6	14	24	37	60	84
Sub-Saharan Africa (excluding high income)	14	15	18	24	27	25		
World	99	113	133	156	181	194		194

Adapted from the Word Bank Development Indicators

increase farm incomes, improve livelihoods for smallholder farmers, and create new employment opportunities.

While mechanisation catalyses agricultural production and efficiency in Asia and Latin America, sub-Sahara Africa remains the only region in the world where agricultural productivity is largely static. Yields of maize and other staple cereals have typically remained at about one tonne per hectare, which translates to approximately a third of the average achieved in Asia and Latin America. Perhaps that partly explains why the continent has been a net food importer for the past three decades.

The use of tractors in SSA has not increased significantly over the past 35 years (see Table 3.1). In comparison to India and the rest of the World, the use of tractors for agriculture production is very low. Between 1961 and 1995 the use of wheel and crawler tractors per 100 sq. km of arable land in India increased by 42-fold while the rest of the world was by about 2-fold. SSA data shows a marginal 1.7-fold increase in the number of tractors per 100 sq.km of arable land, which is very low even by the rest of the world standard.

Agricultural mechanisation programs that are led by the public sector with the support of the private sector and development agencies are key for the success of agriculture development in SAA. For agriculture mechanisation to be a success in Africa, the public sector needs to create a favourable investment climate that attracts investors into the agriculture sector and commercialise agriculture to generate the cash needed for continued and sustainable investment.

On the other hand, land in most of SSA is dead capital because farmers do not hold title to the land in question. In most cases, the land belongs to the state and is leased to the farmers on a long-term lease. However, the security of tenure is important as it allows the farmers to sell or buy land while enjoying complete entitlement of the holding. In cases where there is the absence of security of tenureor ambiguity, financial institutions are not forthcoming to accept such land as a form of collateral. Without acess to credit funds, SSA smallholder farmers will be unable to develop and let alone expand the land, purchase machinery, seeds, fertilizers, or construct harvesting sheds. That altermately has a negative effect on crop productivity.

3.3 Policy Level Changes Required to Drive Smallholder Productivity

3.3.1 Land Tenure

Access to land is often the most important household asset for supporting agricultural production and providing food security and nutrition. Evidence shows that secure land tenure is strongly associated with higher levels of investment and productivity in agriculture—and therefore with higher incomes and greater economic well-being. Gender inequality undermines progress towards sustainable development in agriculture. In most African countries, the land tenure system reflects the oppressive patriarchal system, which marginalizes women and girls, especially in rural areas. In order to increase agricultural productivity, there is a need to improve the right to own and manage land by women. For most women, land rights are often correlated with better outcomes for them and their families, including greater bargaining power at household and community levels, better child nutrition, and lower levels of gender-based violence (FAO 2017).

3.3.2 Farm Labour and Gender Equality

Women are usually left at home tending to the farms while men go to urban areas to look for work. Yet, men retain the right to determine what is produced on the land, when to plant, and what type of inputs to purchase. Women and children provide labour at the homesteads. For example, weeding that in most cases is done using hand hoes may require more weeding cycles within a season or two. However, labour is often not adequate; thus, the smallholder farmers end up losing the battle against weeds, ultimately affecting crop productivity. Improvement in the division of household and agricultural labour is essential to ensuring gender equality in agricultural production. This includes investment and access to labour-saving technologies that can reduce women's labour burden in rural areas. Investing in machinery and herbicides to reduce labour input is essential to achieve high yields and low labour input, particularly for women who constitute the majority of the smallholder farmers (Palacios-Lopez et al. 2017). Eradication of gender discrimination in credit and agricultural services will make it easier for women farmers to acquire labour-saving and innovative production inputs. Additionally, closing literacy and knowledge gaps by improving access to the latest technological advancement in agriculture is critical in addressing gender inequality. The improvement in women's agricultural productive capacity depends on changes in social norms relating to gender relations. There is a need for successful commitment from men to see themselves as collaborating beneficiaries and sharing the means of production (Farnworth and Colverson 2015).

3.3.3 Knowledge Sharing

Sharing knowledge and building human capacity is at the centre of development. Without sharing, the knowledge we generate might as well be locked up for life. Smallholder farmers and professional researchers have different skills and knowledge; thus, when the two entities come together, better results can be achieved through knowledge and skill transfer (Hoffmann et al. 2007). This is partly so because farmers' capabilities and researchers' limitations are disregarded. Subsequently, communication and interaction between both groups remain un-coordinated. According to Šūmane et al. (2018), knowledge should directly reach smallholder farmers, and their knowledge reaches researchers through collaboration with stakeholders working closely with rural communities. Knowledge sharing between farmers and researchers potentially promotes collaborations by merging indigenous and scientific knowledge, which can ultimately provide solutions to challenges experienced by farmers and enhance local innovation development (Hoffmann et al. 2007). Science and research constantly produce promising results, but what is the impact of those results for the community regarding tangible development outcomes' research-for-development. Achieving development outcomes depends on our capacity to generate changes in knowledge, attitudes, skills, and practices of everyone involved (Swaans et al. 2013). Knowledge sharing, capacity strengthening, and learning enhance the use and adaptation of scientific results and insights; and they boost the innovation capacity of smallholder farmers (Kilelu et al. 2011).

3.3.4 Communication

Researchers directly or through extension officers must share information on knowing what to grow, how to grow, and when to sell for maximum profit. They both have to be aware of the changes occurring, the opportunities, and the new farming environment's risks (Khan et al. 2012). Researchers also need to be aware of the changes in the smallholder environment. Usually, reports that are made available by researchers are too comprehensive for smallholder farmers such that they more often than not fail to implement it at their farms. Farmers require relevant localized information in languages they do understand, and in formats they can use. Therefore, communication between farmers and researchers is vital for increasing crop productivity in smallholder agriculture (Raidimi and Kabiti 2019).

One way of simplifying communication is by using participatory farmer approaches in agronomy, breeding, and biotech crops research. Farmer participatory research and extension is an approach in which farmers are directly involved in technology development and dissemination, including problem diagnosis, planning, experimentation on their fields, selection of best treatments, adaptation, adoption, and dissemination of results to other farmers (Norman and Atta-Krah 2017). When farmers test and promote successful technology in the fields, they will actively share their experiences with neighbours. Also, by being part of the research, farmers gain knowledge, skills, and experience, potentially leading to increased productivity. Information can also be shared through field days and workshops. The farmer-to-farmer exchanges will also help researchers understand whether successful adaptation options in one place are indeed transferable to another.

3.4 Conclusion

Improving agricultural productivity in Sub-Sahara Africa can positively affect poverty reduction, employment creation, enhancing food security and self-sufficiency, and economic development, among others. Even though smallholder farmers can significantly contribute towards SSA agriculture productivity, they continue to face several hurdles. The chief hurdles include issues of unequal access to land, finance, and inputs. Similarly, gender inequalities, human development, and public health concerns include inadequate schooling, lack of primary health care to manage HIV/AIDS and malaria, access to family planning contraception, and the coronavirus (COVID-19) epidemic negatively hamstrung smallholder farmers' productive capacities. The elephant in the room perhaps concerns government policies, whether the lack of or inability to cater to the smallholder farmers' concerns and lack of adequate climate change resilience and adaptation measures.

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Chapter 4
Integrated Use of Livestock Manure and Inorganic Fertilizer for Sustainable Agricultural Intensification on Marginal Soils in Sub-Saharan Africa

M. E. Malobane, M. Makwela, P. Nyambo, and A. D. Nciizah

Abstract Sustainable food security is important for social and economic development, particularly in sub-Saharan Africa (SSA), where population growth is at the highest rate and most lands are degraded. Sustainable agricultural intensification techniques such as integrated use of manure and inorganic fertilizer are therefore required as they result in higher crop yields at a minimal negative impact on the environment while improving restoring marginal lands. Integrated use of manure and inorganic fertilizer can potentially enhance yields whilst conserving soils in the marginal lands of SSA. The collected data show that the application of manure treatments enhances soil quality indices. However, before massive implementation of integrated use of manure and inorganic fertilizer practices, further investigation of local level in SSA is required. We conclude that integrated use of manure and inorganic fertilizer remains a promising option to optimize sustainable agricultural intensification in marginal lands, resulting in both improved yields and soil restoration.

Keywords Food security · Soil quality · Soil restoration · Crop yields · Crop nutrients

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4.1 Introduction

Sub-Saharan Africa (SSA) is currently experiencing a rapid population growth rate (Binswanger-Mkhize and Savastano 2017), which is anticipated to exert extreme pressure on natural resources which agriculture depends on for production of food, energy, and fibre (FAO 2017; Frόna et al. 2019). To keep up with the population growth, food production around the world should increase by 70% by 2050 (Bruinsma 2003). However, the expected increase in food production is not feasible because of a loss of suitable arable land in especially SSA due to degradation and competing uses (Frόna et al. 2019). The shrinking of arable land threatens sustainable food production (FAO 2017).

The increase in food demand for the growing population will require additional land to supplement the current available arable agricultural land (Tilman et al. 2011; Zhang et al. 2018). Since opening up new agricultural land is not feasible, the additional production will require the use of marginal lands (Shahid and Al-Shankiti 2013; Van Kernebeek et al. 2016). However, marginal lands have inadequate capacity to produce most food/fibre/energy crops due to their deteriorated soil properties (Shahid and Al-Shankiti 2013). Soils in marginal lands are mainly dominated by low soil organic carbon (SOC), fertility status, aggregate stability, infiltration rate, and water holding capacity and are highly erodible (Lal 2012; Shahid and Al-Shankiti 2013; Edrisi and Abhilash 2016; Schröder et al. 2018). Whilst some soils are inherently marginal, anthropogenic activities play a major role in the reduction of soil quality which in turn reduces productivity.

Soil degradation in SSA is severe, with about 65% of the land area estimated to be degraded (Vlek et al. 2008; Nkonya et al. 2016a, 2016b). The fraction of land classified as highly degraded in SSA is very high, accounting for approximately 20–25% of the total land areas (Zingore et al. 2015; Gomiero 2016). It is estimated that SSA loses over 68 billion US dollars per year due to soil degradation (Zingore et al. 2015; Nkonya et al. 2016a, b). Soil degradation also reduces annual agricultural GDP by 3% in SSA (Zingore et al. 2015; Gomiero 2016). Soil degradation is a major factor leading to low crop productivity and high occurrence of malnutrition in SSA (Lal 2009; Obalum et al. 2012). Due to the poor agricultural productivity in marginal lands, developing and implementing soil restoration practices is important for the sustainable increase in food production (Lal 2004, 2015; Schröder et al. 2018). Thus, the projected increased food demand must be met from the current croplands including the marginal lands by intensifying production. However, traditional agricultural intensification has led to acceleration in land degradation and loss of biodiversity in most developing countries, negatively affecting crop yields (Xie et al. 2019). Consequently, any intensification efforts should be done sustainably especially on marginal lands which are highly susceptible to degradation.

The application of sustainable agricultural intensification (SAI) has attracted the attention of researchers as a potential practice to attain higher agricultural yield without expanding crop lands while minimizing the negative impact on agricultural environment (Tilman et al. 2011; Xie et al. 2019). The premise of SAI is that the use of traditional intensification/ 'green revolution' leads to deterioration lands which is expected to surpass the benefits of producing food on new land, and it negatively impacts the environment (Tilman et al. 2011). Thus, the main aim of SAI is to enhance agricultural productivity and resilience by using different measurements that aid in conserving natural resources (Godfray and Garnett 2014; Kassie et al. 2015). According to Dile et al. (2013), the achievement of SAI in SSA remains a challenge. Thus, empirical studies on SAI are still required in SSA.

Sustainable intensification practices include the application of organic fertilizers, conservation tillage, crop rotation, and diversification to promote crop yields at a minimal negative impact on the environment (Xie et al. 2019). The current chapter talks about how integrated fertilizer and animal manure can serve as a component of SAI and build the resilience of marginal lands in SSA for food security under changing climatic conditions and increasing population growth. The chapter also highlight gaps for future research, which can be important in optimising integrated use of animal manure and fertilizer as a component of SAI and may aid in poverty alleviation amongst resource-poor smallholder farmers. Animal manures are easily available to most smallholder famers, making their application as a source of crop nutrients a common practice amongst most smallholder famers (Okorogbona and Adebisi 2012; Scotti et al. 2015; Gómez-Sagasti et al. 2018).

4.2 Marginal Lands in Current and Future Food Security in Sub-Saharan Africa

Agriculture accounts for nearly 40% of the gross domestic product of African countries, with seven out of ten people dependent on it (Masiyawa 2013). Approximately 60% of the African population live in rural areas, where the majority are affected by food insecurity (Nagayets 2005) due to several factors, which include low soil fertility, lack of the farmers adaptive capacity to climate change-induced rainfall variability, temperature fluctuations, and lack of proper agronomic practices. Food security is concerned with the availability and accessibility of food by a given population. Food availability is when the quantity and quality of available food can sufficiently sustain livelihoods in a given population (Dodd and Nyabvudzi 2014). It is intertwined with poverty, another major problem in Africa. The projected 1.3 billion population growth by 2050 (UN 2015) will make the situation even more difficult for most people in Africa. Most countries in SSA import food to meet the demands of their populations. Increased food imports indicate the inability of the domestic food supply to satisfy the rise in demand. Nonetheless, not enough food is imported because of the ever-rising importation costs. Therefore, there is a need to increase crop productivity to cater for rising population and eradicate hunger and poverty on the continent.

One way to reduce food insecurity in SSA is by utilising marginal lands to increase agricultural production. According to Mehmood et al. (2017), marginal lands have low agricultural and economic capacity for food crop production. Generally, lands are classified as marginal due to morphology, unfavourable soil conditions, and harsh climatic conditions (Pancaldi and Trindade 2020). Agronomic practices of most farmers in the SSA region worsen this by using unsustainable farming practices like continuous tilling, maize monoculture, and crop residue removal from the soil surface (FAO 2016; Nyambo et al. 2021). Mills and Fey (2004) reported that soil degradation was due to inappropriate land use and management practices that deplete the soil organic matter (SOM), including the soil's natural fertility to enhance economic values along with ecological issues. Examples of marginal lands are degraded lands, wastelands, and abandoned lands (Pancaldi and Trindade 2020). Shahid and Al-Shankiti (2013) referred to marginal soils as land lacking sufficient food production capability unless significant efforts are made to improve its quality. The same authors, however, highlight the importance of viewing marginal lands in context or specific perspectives. This is because land that is marginal for one agriculture activity can be used for another. For example, some lands in South Africa, Eastern Cape Province, are defined as marginal and can barely support crop production, yet they are used as grazing lands for livestock. In that respect, farmers need to determine what agricultural activity their lands can support and concentrate on that activity. This can help farmers increase income, food access and availability by either producing more specialized crops or farming activity. For example, the use of marginal lands can be used to produce biofuel (Malobane et al. 2020). Biofuel crops like sorghum is a crop that requires little to no nutrient additions; hence it can thrive in marginal soils. Production of such crops can be moved from fertile croplands to marginal. This could help to address the food vs fuel trade-off challenges. Furthermore, both farmers and governments can benefit by saving more on fuel costs and getting more income from selling the biofuels, thus having more money to spend on food imports.

Another way of improving food security is by the use of sustainable agriculture practices that improve soil quality. Some marginal lands have low soil quality, which inputs of soil amendments can improve. Examples: conservation agriculture has been reported to improve soil physical (Thierfelder and Wall 2009; Nyambo et al. 2020a; Nebo et al. 2020), chemical and biological properties of soils (Rusinamhodzi et al. 2011; Malobane et al. 2020). However, improvement in soil quality and crop yield using conservation agriculture requires time (Nyambo et al. 2020b). Therefore, it is essential to look at other alternatives that can increase soil quality faster than conservation agriculture.

4.3 The Application and Importance of Agricultural Intensification in Sub-Saharan Africa

Agricultural intensification is defined as the increase in agricultural production per unit of inputs (Kenmore et al. 2004) and can potentially play a significant role in reducing poverty and food insecurity in SSA. Tiffen et al. (1994) defined agriculture intensification as *increased average inputs of labour or capital on a smallholding, either cultivated land alone, or on cultivated and grazing land, to increase the value of output per hectare*. The various ways of intensifying agricultural production include integrated pest management (IPM), organic farming, diversification, developing high yielding crop varieties, boosting irrigation, increasing fertilizer use, improve market access, regulations and governance, better utilization of information technology, adoption of genetically modified crops, land reforms, and stepping up the integration in Agricultural Value Chains (AVCs) (Jones 2015). Governments in SSA promote agricultural intensification by subsidising inputs like fertilizers and seeds and access to markets (Droppelmann et al. 2017). Smallholder farmers in SSA primarily focus on soil tilling, maize monoculture, while a small percentage who have access to fertilizer apply inorganic fertilizers. These are blamed for further causing soil degradation and reducing productivity in SSA (Nciizah et al. 2020). Yield has been reported to decline over time under agricultural intensification partly due lack of genetic diversity of high yielding cultivars (Carswell 1997). This results in crops with reduced resistance to pests and diseases and not adaptable to the changing climate. Furthermore it more often results in loss of soil fertility, soil organic carbon, and hence increased soil degradation (Nyambo et al. 2020a). Calls are increasing to identify and use technologies that are suitable for sustainable agricultural intensification in SSA (Giller et al. 2015; Nyambo et al. 2021). Such interventions must address the smallholder farmers crop productivity challenges in SSA, including problems with N inputs and their management and the management of water resources (Waddington et al. 2010).

4.4 The Integrated Use of Manure and Inorganic Fertilizer: A Key Strategy for Achieving Sustainable Agricultural Intensification on Marginal Lands in Sub-Saharan Africa

4.4.1 The Integrated Use of Manure and Inorganic Fertilizer to Increase Crop Productivity on Marginal Lands in Sub-Saharan Africa

With increasing food demand and social and economic growth, the amount of agricultural land available will continue to decrease due to anthropogenic impacts, environmental factors, and the fact that many cultivated soils are naturally infertile (Sileshi et al. 2019). This points to the need for effective integrated soil fertility management (ISFM) to enhance crop yields in marginal soils (Vanlauwe et al. 2015). One of the ISFM-promoted strategies is the prolonged use of manure and inorganic fertilizers, which provides a practical solution to soil fertility challenges and a path to SAI. Intergraded use of livestock manure and inorganic fertilizer has a minimal negative impact on the environmental and is the potential economical way to supply enough nutrients to increase crop productivity.

The impact of integrated livestock manure and inorganic fertilizer use on crop productivity is outlined in Table 4.1. Generally, the application of manure plus fertilizer increases yields of different crops compared to both solo fertilizer and manure application (Table 4.1). The increase in crop yields after the application of manure plus fertilizer compared to solo fertilizer might be attributed to the fact that manure contains both macro- and micro-nutrients in addition to organic carbon which improves soil quality, thus increasing soil water content and microbial activities which are important for plant crop (Bedada et al. 2014; Rayne and Aula 2020).

4.4.2 The Combined Use of Livestock Manure and Inorganic Fertilizer to Enhance Soil Physical Properties in Marginal Lands of Sub-Saharan Africa

Soil functions, behaviours and quality depend on its three key functional properties; physical, chemical and biological (Mukherjee and Lal 2013). The influence of combining livestock manure and inorganic fertilizer to enhance soil physical properties in marginal lands of sub-Saharan Africa will be discussed under this section. Soil physical properties dictates air, water, solutes, nutrients and heat movement and storage, and habitat of organisms which are fundamentally important for plant germination, plant, root growth and microbial activities (Thies and Grossman 2006; Almendro-Candel et al. 2018; Jat et al. 2018;). In addition, soil physical properties form the base for numerous chemical and biological processes which are important for soil productivity and erosion processes (Almendro-Candel et al. 2018; Jat et al. 2018; Farooqi et al. 2020).

A study conducted by Ejigu et al. (2021) in Ethiopia found that the application integrated use of manure and inorganic fertilizer significantly reduced soil bulk density (BD) compared to sole mineral fertilizer application. The results were in line with the findings by Mengistu et al. (2017), who also found that bulk density decrease with the application of manure and inorganic fertilizer mixture in Ethiopia. In the study of Ejigu et al. (2021) BD decreased by 12.3% and 9.8% compared to control treatment (no manure/fertilizer) and solo inorganic fertilizer, respectively, while in Mengistu et al. (2017) the BD decreased by 4% compared to control treatment. Both studies were conducted in soils with less than 1.3% soil organic

Table 4.1 The impact of integrating livestock manure and inorganic fertilizer on crop yields under rainfed conditions in sub-Saharan Africa

Country	Crop	Results	Comments	Reference
Zambia	Cassava	The application of chicken manure plus inorganic fertilizer increased cassava by 29% compared to solo fertilizer.	The study was conducted in areas with SOC less than 1.20%, total nitrogen (TN) less than 0.065%, available phosphorus (P) (mg/kg) less than 20 and available potassium (K) less than 0.15 (c mol (+)/kg)	Biratu et al. (2018)
Nigeria	Maize	The application of chicken manure plus inorganic fertilizer had no significant impact on maize yield compared to solo fertilizer. Nonetheless, both chicken manure plus inorganic fertilizer and sole fertilizer significantly increased maize yield compared to no fertilizer and solo manure. Chicken manure plus inorganic fertilizer increased maize yield by 193.31% and 24.56% compared to no fertilizer and solo manure, respectively	The study was conducted in areas with SOC less than 1%, TN of 1%, P less than 7.50 mg/kg and K less than 0.2 c mol (+)/kg	Ayoola and Adeniyan (2006)
Ethiopia	Potato	The application of cattle manures plus inorganic fertilizer increased potato tubers by 39.81% compared to solo inorganic fertilizer	The study was conducted in areas with SOC of 1.5%	Balemi (2012)
Ethiopia	Grain sorghum	Farmyard manure + inorganic fertilizer improved sorghum grain yield by 36% compared to solo manure	The study was conducted in areas with SOC of 1.2%, TN of 0.08%, P of 12.5 mg/kg and K of 2.3 c mol (+)/kg	Bayu et al. (2006)
Ethiopia	Maize	The application of livestock manure compost plus inorganic fertilizer increased maize	The study was conducted in areas with TN less than 0.4% and P less than 15.5 mg/kg	Bedada et al. (2014)

(continued)

Table 4.1 (continued)

Country	Crop	Results	Comments	Reference
		yield 25.14% and 10.76% compared to both solo fertilizer and compos, respectively		
Nigeria	Cucumber	A combination of farmyard manure and inorganic fertilizer increased cucumber yield by 49.89% and 104.48% compared to both solo fertilizer and manure, respectively.	The study was conducted in areas with SOC of 1.4%, TN of 0.13%, P of 10.40 cmol/kg and K of 0.29 c mol (+)/kg	Eifediyi and Remison (2010)
Malawi	Cassava	The application of cattle manures plus inorganic fertilizer increased cassava yields 23.65% compared to solo manure.	The study was conducted in areas with SOC of 1.66%, TN of 0.16% and K of 10.83 c mol (+)/kg	Mathias and Kabambe (2015)
Zimbabwe	Maize	The application of cattle manures plus inorganic fertilizer increased maize yield in sandy soils compared to solo fertilizer. A combination of manure and inorganic fertilizer gave the largest treatment yield of 3.4 to 9.3 t ha^{-1} grain yield which were higher than yield under solo fertilizer application	The study was conducted in areas with SOC less than 0.5%, TN of 0.08%, P less than 12.10 mg/kg and K less than 0.8 c mol (+)/kg	Rusinamhodzi et al. (2013)
Zimbabwe	Maize	The application of cattle manure plus inorganic fertilizer increased maize yield compared to both solo fertilizer and manure. Cattle manure plus inorganic fertilizer was between 189 and 350% compared to no fertilizer across the study areas	The study was conducted in areas with SOC less than 0.65%	Manzeke et al. (2012)
Mozambique	Rice	The application of cattle and chicken manure plus inorganic fertilizer gave the highest rice	The study was conducted in areas with SOC of 2.19%, TN of 0.11%, P of 33.69 mg/	Ismael et al. (2021)

(continued)

Table 4.1 (continued)

Country	Crop	Results	Comments	Reference
		yield by 6% compared no fertilizer application	kg and K of 1.26 c mol (+)/kg	
Kenya	Maize	Farmyard manure + inorganic fertilizer increased maize yield by 52.20% compared to solo manure	The study was conducted in areas with SOC less than 0.3%, P less than 8.8 mg/kg and K of 0.8 c mol (+)/kg	Ademba et al. (2015)
Kenya	Maize	Farmyard manure + inorganic fertilizer had no effect on maize yield compared to solo fertilizer. Nonetheless, the application manure plus inorganic fertilizer increased maize yield by 114.30% compared to farmers practice (inadequate fertilizer)	The study was conducted in areas with SOC of 2.2% and TN of 0.11%	Achieng et al. (2010)
Kenya	Soybean	The application of farmyard manure plus inorganic fertilizer increased soybean grain and biomass yield, and growth compared to both solo fertilizer and manure	The study was conducted in areas with TN of 0.22%, P less than 7.10 mg/kg and K less than 1.10 c mol (+)/kg	Otieno et al. (2018)

carbon (SOC). A study conducted in hardsetting soils with SOC less than 1.5% in South Africa found that the application of manure increased soil aggregate stability and water stable aggregates and reduced soil strength (Nciizah and Wakindiki 2012). Aggregate stability as represented by mean weight diameter was approximately 52% higher under manure treatment compared to control. The increase in aggregate stability leads to reduced soil crusting and erodibility (Le Bissonnais 2016). Adeyemo et al. (2019) conducted a study in south-western Nigeria under soils with SOC of less than 1% and found that the application of manure increased soil water content and infiltration rate. The increase in aggregate stability and infiltration rate is linked to reduced soil erosion (Telak et al. 2021). An increase in a range of soil physical quality indicators under soils with less than 1.3% SOC was reported by Are et al. (2017) in Nigeria after the application of manure. The enhancement in soil physical properties is mainly due to an increase in SOC after the application of manure or manure plus inorganic fertilizer (Are et al. 2017; Chen et al. 2020; Du et al. 2020).

4.4.3 The Integrated Use of Manure and Inorganic Fertilizer Enhance Soil Chemical and Biological Properties in Marginal Lands of Sub-Saharan Africa

Animal manure contains all valuable macro- and micronutrients and thus has significant potential to provide nutrients for smallholder farms in SSA. This is particularly important in marginal soils, which have poor biological and chemical properties. In such soils, the use of animal manure offers multiple benefits such as adding soil organic matter to the soil, which in turn supplies nutrients to crops and modifies important soil physical properties such aggregate stability, bulk density, porosity and water retention (Nciizah and Wakindiki 2012) and improves nutrient cycling and carbon (C) sequestration (Blanco-Canqui and Lal 2004). The improvement in the soil environment provides a conducive environment for soil microbes, improving nutrient cycling in the soil.

A study done by Zhang et al. (2012), in an alluvial paddy soil (Typic Eduoagulpt), concluded that manure enhanced the bacterial and fungal communities whilst chemical fertilizers had an opposite effect. This is because organic manure provides carbon, nitrogen and energy for microbial growth and reproduction (Guo et al. 2016). Likewise, Gong et al. (2009) carried a study to evaluate the soil carbon and nitrogen (N) contents in different soil organic matter (SOM) pools (light and heavy fractions). The study also sought to determine the role of light- and heavy-fraction C in SOC sequestration and culturable microbial counts in the surface (0–20 cm) of afluvo-aquic soil after 18 years of fertilization treatments under a wheat–maize cropping system in the North China Plain. The results indicated that organic manure resulted in the highest total soil culturable microbial counts whilst the unfertilized soil had the lowest value.

Several authors reported similar findings across Africa, although results differed depending on the quality of the manure. For instance, Franke et al. (2008) reported higher soil N, P and exchangeable *K* values, as well as increased N utilization efficiency by maize in an on-farm trial conducted on sandy loam Haplic Lixisol Ferric Lixisol in the northern Guinea savanna of Nigeria over 5 years. Zingore et al. (2008) demonstrated the importance of manure for sustainable soil fertility management on smallholder farms dominated by poorly buffered, sandy soils that are widespread in southern Africa. However, in this 3-year study carried out in Murewa Zimbabwe, a depleted sandy outfield required huge quantities of manure of up to 17 t ha^{-1} $year^{-1}$ to significantly increase soil SOC, pH, available P. Consequently, heavily depleted marginal soils may require a consistently higher amount of manure to raise the SOC and nutrient levels to acceptable levels. However, the manure had a low capacity to replenish N, hence the need to integrate organic and inorganic fertilizers. There have been renewed calls for the adoption of integrated soil fertility management.

4.4.4 The Integrated Use of Manure and Inorganic Fertilizer to Fulfill Criteria for Sustainable Agricultural Intensification in Marginal Lands of Sub-Saharan Africa

The integrated use of manure and inorganic fertilizer as an element to achieve SAI in SSA marginal lands reveals sufficient evidence that implementation of integrated use of manure and inorganic fertilizer results in (1) increased crop yields and (2) enhanced soil productivity and fertility. As defined above, SAI aims to enhance agricultural productivity and resilience by using measurements that aid in conserving natural resources. Therefore, we conclude that the integrated use of manure and inorganic fertilizer could be a key strategy to achieve SAI in SSA at low cost. In addition, the combination of integrated use of manure and inorganic fertilizer and other techniques like water harvesting, no-till, crop rotation and residue management might add more value to achieving SAI and sustainable food security in marginal soils of SSA. Combining above techniques might help define SAI in SSA conditions that are more visible to smallholder farmers. Therefore, there is a need to assess the potential externalities of combining the techniques before implementing SAI in SSA smallholder farmers' lands.

4.5 Conclusion

The use of marginal lands to supplement arable lands is vital for future sustainable food security for the current growing population and their restoration is also vital. Organic amendments have been promoted as a sustainable practice to restore marginal soils. We conclude that there is evidence that integrated use of manure and inorganic fertilizer practices can fulfil the criteria for SAI by (1) improving soil fertility and quality which aid in enhancing productivity even under limited water regimes and drought spells, (2) improving crop yields for sustainable food security, (3) enhancing soil biodiversity, thus improving soil functions, (4) minimizing extensive use of inorganic fertilizers which have negative impacts on the environment and (5) sequestering carbon in agricultural land to help in mitigating climate change. A key question in need of further research is how effectively we can combine different techniques that fit into SAI principles to develop a SAI system that is well used for SSA smallholder farming conditions.

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Chapter 5
In-Field Soil Conservation Practices and Crop Productivity in Marginalized Farming Areas of Zimbabwe

Cosmas Parwada, Justin Chipomho, and Ronald Mandumbu

Abstract There are high rates of soil erosion and low crop productivity in the communal farming areas of Zimbabwe. The communal areas are marginalized as they are characterised by high erosion, inherently infertile soils that are low in organic carbon, low and erratic rainfall leading to very low crop yield per unit; hence, farmers are food insecure. Soil has a direct influence on the growth and productivity of crops; hence, soil conservation is important for food production. However, the high rates of soil erosion in the marginalized areas of Zimbabwe are reducing the soil quality and crop yield. The soil conservation practices are therefore vital for sustainable crop production and food security in these areas. Soil conservation improves crop productivity by enhancing soil fertility and water holding capacity. Nevertheless, farmers in the marginalized areas of Zimbabwe use inappropriate agronomic and soil management practices accelerating the rates of in-field soil loss. In-field soil conservation can modify the soil properties, e.g. increasing the soil organic matter and soil microbial activity and reducing the soil erosivity. Effective soil conservation strategies can reduce the velocity of surface runoff and confers soil resistance to erosion. Various methods of in-field soil conservation can redress the declining soil fertility, soil erosion problem, and land degradation and increase crop productivity in marginalized cropping areas. Agronomic practices such as minimum tillage, crop rotation and mulching can effectively minimize the rates of soil erosion in crop lands, contributing to sustainable crop production in the marginalized areas, thereby achieving food security among the rural poor. This chapter therefore provides a synthesised review of in-field soil conservation strategies that can be applied

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in the marginalized cropping areas of Zimbabwe. The main thrust is to improve crop production in such areas aiming at achieving sustainable food security among the farmers.

Keywords Crop productivity · Dryland (rain-fed) · Erosion · Semi-arid

5.1 Introduction

The largest (approximately 95.34%) of Zimbabwean area is classified as marginalized (Natural farming regions III, IV and V) for crop production (Table 5.1). The areas are marginalized because they are characterised by low and unreliable rainfall during the larger part of the cropping season and are referred to as semi-arid. Besides, these areas are also characterised highly eroded soils with poor structure and low water holding capacity (WHC), leading to moisture stress in crops, thereby reducing yield drastically. Soil erosion in the arable lands of communal farming areas is high due to poor agronomic practices such as high frequency of soil disturbance, mono-cropping and destruction of crop residues after harvesting, causing low soil organic carbon (SOC) build up. Low SOC reduces the soil quality and hence crop productivity in these marginalized areas. Crop productivity is also negatively affected by declining soil fertility and moisture deficit during critical crop growth stages in semi-arid regions of Zimbabwe.

A large number of smallholder farmers in Zimbabwe are situated in these marginalized areas but they lack irrigation infrastructure and rely on the rain-fed agriculture (Rusinamhodzi et al. 2013). The rainfall has been sporadic and unreliable in the past decade and farmers are facing serious starvation. The soils are poorly structured and low water holding capacity that indicates the danger of moisture stress during the growing season causing low yields and ultimately food insecurity among the farmers. However, FAO (2017) observed that few farmers in these dry areas are applying in-field soil conservation regardless of their numerous benefits; this could be due to lack of knowledge on the conservation strategies.

Natural farming region (II and III) may experience heavy rainfall during the rainy season generating high runoff in the fields if the soil is not covered. The soils in these communal areas are highly erodible due to poor aggregation and low SOC content (<2%). Besides the farmers in the marginalized areas remove crop residues for livestock feed and during land preparation exposing the soil to erosive agents. There is high in-field runoff due to poor soil cover as <30% of the crop residues remains. The farmers do not apply any fertilizers or organic matter to the soil but their fields are characterized by high rates of erosion that washes away the fertile topsoil, hence low crop yields per unit area (Nezomba et al. 2015).

Most of the communal farmers in Zimbabwe are densely populated at 33 household per km^2 (FAO 2017). This results in accelerated soil erosion rates in such areas especially cropping and grazing lands. For example, overstocking and conventional tillage greatly reduced soil resistance to erosion by destroying the macroaggregates

Table 5.1 Characteristics of the natural farming regions of Zimbabwe

Region	Soil type	Average rainfall (mm) per year	Rainy season	Number of growing days	Marginalized (−)/ non-marginalized (+)	Total area covered (%)
I	Red clay	>1000	Rain in every month of the year and relatively low temperature	170–200	(+)	–
II	Sandy loams	750–1000	Rainfall is mostly received in summer (October–April)	120–170	(±)	18.68
III	Sandy, acidic, low fertile	650–800	Infrequent heavy fall of rainfall. Subjected to severe seasonal droughts and severe mid-season dry spell. Rainfall is confined to summer with relatively high temperature	60–120	(−)	17.43
IV	Sandy, acidic	450–650	Rainfall is characterised by frequent seasonal droughts and severe dry spells during the rainfall period. Rainfall is confined to summer (October–April)	60–120	(−)	33.03
V	Sandy, acidic and infertile	<450	Very erratic rainfall confined to summer season (October–April). Very high temperatures during the summer	70–100	(−)	26.2

Marginalized area for crop production is determined by quantity and reliability of rainfall during the growing season, soil type and fertility levels, where (−) = marginalized, (+) = non-marginalized and (±) = can be both marginalized and non-marginalized. *Adapted from smallholder Horticulture in Zimbabwe, edited by* Jackson et al. 1997

in the soil. The high rates of erosion in the communal areas are also due to the negative attitude of farmers towards in-field soil conservation strategies like the constructing and maintaining contour ridges. Old farmers (> 40 years) in Zimbabwe viewed the exercise of in-field soil conservation as colonial suppression because the opening of contour ridges was a compulsory exercise once in every two or three seasons in the pre-independence times (Whitlow 1988).

Currently, the Zimbabwe general soil loss is estimated at 3–75 $t^{-1}ha^{-1}year^{-1}$ depending on the soil type, land use and cover with high rates observed in the communal lands. Soil loss from arable lands only ranges from 15–50 $t^{-1}ha^{-1}year^{-1}$ these are by far high rates in comparison with the commercial arable that is estimated at 5–13 $t^{-1}ha^{-1}year^{-1}$. Given that the rates of soil formation in Zimbabwe are very slow (0.4 $t^{-1}ha^{-1}year^{-1}$) whereas rates of soil erosion are much higher, there is a great need to reduce the rates of soil in arable lands. The noted effects of this in-field soil erosion are seen in general declines in crop yield and high rates of siltation of water bodies. Soil nutrient mining and soil degradation are common in the communal areas of Zimbabwe. The farmers lack the knowledge of in-field soil management and crop yield is declining in each year in these marginalized areas. Therefore, this chapter aims to consolidate literature on the in-field soil conservation practices that can enhance crop productivity in the dry areas of Zimbabwe.

Soil conservation techniques are key to sustainable agricultural productivity in the marginalized areas of Zimbabwe. In-field soil conservation involves a set of farming techniques and practices that are aimed at minimising depletion of soil nutrient and improving soil hydro-properties. By taking proper and timely actions, farmers boost the performance of their fields for years to come (Mango et al. 2017). The major objective of soil conservation is maintaining the biodiversity of the inhabiting eco-communities that contribute to its fertility in their own ways. Ecological biodiversity promotes soil organic matter build-up, splits perished organisms to release nutrients particularly nitrogen and improves water infiltration and aeration. Soil organic matter has an essential role in soil biological (provision of substrate and nutrients for microbes), chemical (buffering and pH changes) and physical (stabilization of soil structure) properties (Pan et al. 2009). In general, these properties together with the SOC, N and P are critical indicators for the health and quality of the soil.

Soil conservation techniques are designed to protect the soil by preventing or reducing excessive water runoff, encouraging high infiltration, and protect bare soil surface from the impact of raindrop effect, forms of erosion and soil cracking due to effects of water, wind and excessive. Effective soil conservation in the marginalized dry areas of Zimbabwe can enhance the soil water holding capacity and minimize the irrigation needs of the crops. This is especially important in areas where rainwater and/or groundwater resources for irrigation are scarce or decreasing due to climate change or other causes. Then the objective of this chapter is to review literature on the in-field soil conservation practices and crop productivity with the intention of increasing crop yield in the dry areas of Zimbabwe.

5.2 Soil Conservation Practices

There are a variety of methods that can be used to conserve soil in the field. However, this chapter is going to categorise them into two: (1) soil conservation practices that increase soil resistance to erosion and (2) in-field soil conservation that reduces soil erosivity. Considering that most communal farmers in Zimbabwe are resource constrained relatively low-cost and less complex techniques will be discussed. The soil conservation practices need to primarily rely on the presence of required materials and technical capacity that is locally available.

5.3 Soil Conservation Practices that Increase Soil Resistance to Erosion

Soil erodibility is a measure of the inherent resistance of soil to erosion. A soil with high resistance does not easily detach when exposed to agents of erosion. There are many factors that influence soil erodibility such as the clay content, iron oxides and organic matter (Pan et al. 2009). High content of organic matter is favourable for soil resistance to erosion; however, many soils in the communal areas of Zimbabwe are characterised by very low SOC ($<2\%$) because of poor agronomic practices. The farmers remove the crop residues just after harvesting for livestock feed and other domestic uses besides there is low biomass production in the marginalized areas as there are low rainfall and infertile soils (Nezomba et al. 2015). The soils are therefore highly unstable and susceptible to erosion. In order to increase the SOC in their fields, farmers can apply organic matter (OM), organic mulch and minimum tillage. These practices promote the build-up of SOC ($>2\%$) in the soil and soil aggregation. A good structure confers soil resistance to erosion and this is influenced by both the quality and quantity of OM in the soil (Parwada and van Tol 2018).

5.4 Minimum Tillage

Minimum tillage refers to any tillage and planting system that disturbs the soil only at the planting station. The primary objective is to reduce production costs and the methods do not break many macroaggregates, so a lot of inscribed organic matter will remain protected against microbial decomposition. This builds up the soil organic carbon pools unlike in the convectional tillage, which promotes high mineralisation of soil organic matter. The organic matter promotes the binding of the primary mineral particles which are usually unaggregated in most soils in the Zimbabwe communal farming areas. The minimum tillage can therefore increase the soil resistance to erosion, and if practiced for long periods, the rate of erosion will be very minimal. Minimum tillage also improves soil aggregation and soil hydro-properties, e.g., drainage and moisture holding capacity. Cover cropping extends the continuity of living plant cover on fields that would otherwise be fallow over winter, providing additional inputs of fresh organic matter that can help build SOM stocks (Le Bissonnais 1996). Lastly, implementing crop rotations can improve soil aggregation, build SOM and enhance the indicators of soil fertility.

In most cases the minimum tillage is practiced with the retention of $>30\%$ of crop residues which can act as a physical shield of the soil to erosive agents. Where soil

Table 5.2 Effects of tillage practice on soil erodibility indices in Lixisols in Muzokomba area, Manicaland Province, Zimbabwe

Tillage practices	Soil parameter	2014	2016	2017	2018
Conventional tillage	SOC (%)	1.61	1.40	1.3	1.24
	MWD (mm)	0.40	0.38	0.33	0.26
	WSSI	0.03	0.02	0.01	0.01
Minimum tillage	SOC (%)	1.59	1.90	2.4	2.8
	MWD (mm)	0.50	1.36	1.65	1.81
	WSSI	0.04	0.24	0.51	0.60

MWD mean weight diameter, *WSSI* whole soil stability index
Adapted from Parwada et al. (2019)

erosion by wind is the primary concern, the soil surface should maintain at least 1.13 t ha^{-1} of crop residue in order confers resistance the wind (Gurtner et al. 2011). Crop residues on the surface practically eliminate wind and water erosion, reduce soil moisture loss through the mulch effect, slow spring warm-up (possibly offset by a lower specific heat demand with less water retention in surface soil) and act as a reserve of organically compounded nutrients (as they decompose to humus). There is a build-up of SOM, hence higher available water and nutrient retention, higher biological activity year-round (enhancing biological controls), higher levels of water-stable aggregates and a positive carbon sink in incremental SOM (Parwada and van Tol 2018). One necessary aspect is to carry field operations at the proper time which are mainly determined by the existing soil types. Normally clay soils are better to till after harvesting while other types are better to plough before seeding. In addition, working wet clay soils causes compaction, therefore reducing water infiltration and increase runoff.

Reducing or eliminating tillage maintains healthy soil organic levels which in turn increase the soil's capacity to absorb and retain water. The deep tillage is suited for some areas and soils, deep tillage can help increase porosity and permeability of the soil to increase its water absorption capacity. Minimum tillage coupled with the retention of crop residues on the soil surface greatly increases the soil resistance to erosion (FAO 2017). The crop residues, a renewable resource, play a key role in the soil aggregation. A study by Parwada et al. (2019) showed positive effects of the minimum tillage (MT) on soil erodibility indices with time (Table 5.2). A soil with high (>2%) SOC, mean weight diameter (MWD) > 0.53 and whole soil stability index (WSSI) >0.3 is resistant to erosion (Parwada et al. 2019). The soil had higher values of SOC, MWD and WSSI under the MT than conventional tillage (CT) (Table 5.2).

Greenland et al. (1975) suggested that a critical level of SOC is 2%, below which soil structural stability will suffer a significant decline. The SOC% under conventional tillage was below 2% but was >2% in the third and fourth year of minimum tillage (Table 5.2). This suggested that continuous practice of minimum tillage can confer soil resistance to erosion. The MWD is an index that characterises the structure of the macroaggregate by integrating the aggregate size class distribution into one number. Le Bissonnais (1996) suggested five classes of stability, with a MWD < 0.4 mm classified as very unstable (class 1), 0.4–0.8 mm unstable (class 2), 0.8–1.3 mm medium (class 3), 1.3–2.0 mm stable (class 4) and >2.0 mm very stable (class 5). The class of stability was very unstable under the conventional tillage having very unstable macroaggregates in all the 4 years (Table 5.2). Whole soil stability index ($0 \leq$ WSSI ≥ 1): 0 means all the aggregates are unstable, and 1 means 100% aggregates are stable. The data in Table 5.2 showed that the minimum tillage can effectively stabilise the Lixisols and can reduce erosion.

Farmers can retain the crop residues in order to protect the soil, enhance soil quality, restore degraded soil, improve soil nutrient cycling, increase soil moisture and availability, reduce runoff and leaching of nutrients off-site and sustain and enhance crop productivity and profitability (Mango et al. 2017). The minimum tillage conserves soil and draught power since minimum soil disturbance is required at planting. The minimum tillage promotes the retention of crop residues on the surface which reverses rapid degradation of soil organic matter (SOM) and soil structure at the same time raising the soil biological activity by a factor of 2 to 4 (Mango et al. 2017). The benefits of minimum tillage are many that include reducing soil compaction, enhancing internal drainage through old root holes, reduce the pulverization of soil aggregates and formation of pans and gives shelter, winter food and nesting sites for fauna.

5.5 In-Field Soil Conservation that Reduce Soil Erosivity

Soil erosivity is a measure of the potential ability of the soil to be eroded by rain, wind or surface runoff. Poor in-field crop residue management and cropping systems expose the soil to rain, wind and runoff and increase erosivity. Crop residues in the marginalized communal areas of Zimbabwe are multi-purpose, e.g., used for construction like thatching, livestock feed and fuel for cooking. The farmers usually burn the previous crop residues during land preparation ('mavivi') leading to loss of SOC and volatilization of nitrogen (Pan et al. 2009). These practices reduce the soil cover from the rain and wind and again there is low biomass production in the marginalized areas of Zimbabwe due to poor rains and soil fertility which further reduce the rate of SOC build-up. Marginalized areas are suited for the production of small grain crops like millet and sorghum because these are drought tolerant. The small grains are characteristically narrow leaved so cannot adequately provide enough soil cover especially if monocropped (Nezomba et al. 2015). Generally, (Kassam et al. 2009) observed a higher (>0.95) runoff coefficient in narrow leaved crop species than broad leaved ones. This increases the erosivity of rainfall, wind and surface runoff. There are several methods that can be used by the farmers in the marginalized areas of Zimbabwe, these include the following.

5.6 Contour Farming

Contour farming can be successfully used to reduce runoff velocity on sloppy lands. Cultivation on mountainous areas can cause high soil losses and the contour farming was noted to reduce the runoff coefficient to as low as 0.02 (Pan et al. 2009). The contour farming is efficient in slope territories and suggests planting crop species along the contour has drastically reduced the rainfall runoff (Fig. 5.1a). The velocity of runoff is also reduced by ploughing soil along the contour instead of up- and downward slopes as soil barriers are created and more water is retained in the soils equally across the cropland. This can also significantly increase the soil moisture in the drier natural farming regions of Zimbabwe, thereby increasing crop productivity. Rows up and down the slope provoke soil erosion due to water currents while rows along the contour restrain it.

5.7 Strip Cropping

Strip cropping can also be used to reduce runoff velocity in the same way in the contour farming. In this system, high-growing crops are combined with low-growing ones for the sake of reducing soil erosivity from the wind. e.g., when maize is grown in strips with forage crops (Fig. 5.1b). The practice works even better when high-growing crops are intensified in the sides where winds blow most frequently. The strip cropping and contour farming has been noted to effectively reduce the rates of soil losses in areas that receive heavy downpours in some parts of the year. Besides, these practices have been observed to increase the yield of pearl millet by >40% in the drier regions of Kenya (Kassam et al. 2009).

(a) (b)

Fig. 5.1 (**a**) Contour farming (source: https://www.worldatlas.com/articles/what-is-contour-farming.html) and (**b**) strip cropping (source: https://www.striptillfarmer.com/articles/2529-strip-cropping-experiments-yielding-economic-environmental-advantages)

5.8 Windbreaks

Most parts of the marginalized farming areas in Zimbabwe have rampant deforestation; as a result, they are characterized by accelerated rates of soil erosion. The vast land is bare and strong winds can be a major factor in reducing crop productivity through damaging the established crops and causing flower abortion in fruit trees. The windbreaks can be applied to lower the erosive power of winds on soil in such cases. Trees or bushes are used to shelter crops from winds planted in several rows (Fig. 5.2a). Depending on the number of rows, one can distinguish windbreaks properly (1–5 rows) and shelterbelts (>6 rows). Windbreak vegetation also creates microclimates to the crops that may reduce the rate of evapotranspiration and provides a living environment for wildlife and eliminates soil abrasion on crops due to strong wind blows (Campi et al. 2009). Windbreaks are usually applicable in citrus production where they are useful in reducing the rate of flower abortion, unlike when the citrus is exposed to strong winds (Fig. 5.2a).

5.9 Buffer Strips

These are trees and bushes planted on the banks of water bodies to prevent sedimentation and water wash-off (Fig. 5.2b). The tree roots fix the soil to avoid slumping and erosion, canopies protect from excessive evapotranspiration during hot weathers water and the falling leaves provide organic matter and food of minor aquatic organisms.

Fig. 5.2 (**a**) Windbreak farming (source: http://agronew.vn/windbreaks-for-citrus) and (**b**) buffers strips (source: https://cropwatch.unl.edu/2019/nda-funding-available-install-renew-buffer-strips. accessed in 2021)

5.10 Cropping System

Farmers should include well-planned crop rotations rather than mono-cropping permitting changing agro-species instead of planting one and the same crop for many subsequent seasons (Fig. 5.3a). Growing different types of crops every season helps improve soil structure and thus water holding capacity. Examples include rotating deep-rooted and shallow-rooted crops that make use of previously unused soil moisture, as plants draw water from different depth levels within the soil. Crop rotation may also improve soil fertility and help control pests and diseases. Crop rotation can be used to effectively protect and build up the SOM and soil nutrients. Farmers applying crop rotation reap numerous benefits. It helps to improve the soil structure with diverse root systems, mitigate pest establishments, and add nitrogen to the land with legumes known as nitrogen-fixing plants.

The choice of crops to rotate is specific for each agricultural enterprise and highly depends on historical weather and productivity data. Some crops proved to be efficient in some periods while some have failed. The farmers can access such information from Crop Monitoring alongside daily weather and forecasts up to 2 weeks ahead, including precipitation, min/max temperatures and anticipated risks (Gurtner et al. 2011).

5.11 Mixed Cropping and Inter-Planting

Combining crops of different morphology and length of growth periods can provide soil cover for a long time. Inter-planting the broad leaved and narrow-leaved crop has understory cover and reduces raindrop impact (Mupangwa et al. 2006). Other

(a) (b)

Fig. 5.3 (**a**) Crop rotation of maize and soyabean (source: https://usfarmersandranchers.org/stories/sustainable-food-production/the-benefits-of-crop-rotation-and-diversity/) and (**b**) mixed cropping of maize and soyabean (source: Mehmeti et al. (2009))

soil conservation techniques may include rainwater harvesting to minimize runoff and collect water for use on-site. For more technologies on this, see the technology sheet rainwater harvesting for infiltration.

5.12 Cover Crops

Farmers in the marginalized farming areas of Zimbabwe are forced to grow small grains which are drought tolerant. However, these crops are narrow leaved and cannot provide enough soil cover against the raindrop impact especially when monocropped. To increase the groundcover, farmers can make use of cover crops (Fig. 5.4a). Most farmers in the communal areas rely on natural soil fertility, so sometimes they can practice fallow cropping but a significant amount of soil and moisture is lost during these fallow periods. Cover cropping is the best solution to reduce rates of soil erosion during the fallow periods. These are crops that cover the soil in order to reduce soil erosion during fallow periods in annual cropping systems (FAO 2017). The crops are grown with the sole purpose of adding to the soil for improved organic matter and nutrients. The improved soil quality then also improves water retention capacity. Again the green manure cover crops which are usually legumes are grown to fix N and increase the N content of the following crop. Catch crops are grown during fallow periods in cropping systems in order to utilize nutrients, like N, which could be lost if no plants.

The living mulches are grown both during and after the cash crop growing season and are suppressed to reduce their competition with the cash crop when it is growing. A layer of mulch organic (or inorganic) material is placed on the soil surface to protect the plant root zone. Some of the examples of mulch materials include straw and wood chips. Mulching can also be done using inorganic materials in form of plastic sheeting. Mulching is most suited for low to medium rainfall areas and less suited for areas with very wet conditions. Generally, the cover crops slow the

Fig. 5.4 (**a**) The use of fava bean as a cover crop and (**b**) intercropping of maize and ground nuts [Photo taken in Bikita district, village 30, 2020–2021 cropping season]

velocity of runoff from rainfall reducing soil loss due to sheet and rill erosion. Over time, growing cover crops increase the SOM content in the soil, leading to enhanced soil structure, stability, and increased moisture and nutrient holding capacity for plant growth (FAO 2017). However, Mango et al. (2017) observed that few farmers (<20%) in the drier areas are applying the in-field soil conservation regardless of their numerous benefits.

5.13 Conclusion

Farmers in the marginalized cropping areas of Zimbabwe can reduce production costs by using the minimum tillage system and effective cropping systems in order to minimise soil erosion and increase crop productivity. The in-field soil conservation strategies include two major principles: protecting the soil surface from erosive agents like rainfall, wind and surface runoff (e.g. by use of cover crops) and building soil resistance to erosive agents by adding SOM. Meeting these two principles means improved soil moisture content in the dry and marginalized farming areas, hence increased soil and crop productivity.

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Chapter 6
Can Organic Soil Fertility Management Sustain Farming and Increase Food Security Among African Smallholder Farmers?

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Abstract In Africa, smallholder subsistence farmers contribute up to 70% to the national food basket, making these farmers very important in attaining food security. However, most of these farmers are located in areas characterized by poor-quality soils with limited productivity. Furthermore, around the 1960s, green revolution technologies were advocated for adoption by all farmers, and these involved the intensive use of industrially manufactured chemicals in production, soil tillage and mono-cropping systems. These technologies tended to only feed the crop for increased productivity and ignored to feed the soil, which has resulted in soil degradation in mostly smallholder farming areas. The challenge of soil degradation is now being aggravated by the change in climate, which has seen the productivity of smallholder farmers declining, thus threatening the food security of most African countries. This chapter, therefore, presents the aspect of organic soil fertility management and its potential in increasing the productivity and resilience of African smallholder farmers by increasing soil health. The idea of feeding the soil to feed the crop is highlighted as being critical in abating the challenges caused by soil degradation and climate change. The chapter indicates that technologies like mixed cropping, crop rotations, using improved organic matter sources like biochar, residue retention and minimum tillage are principal drivers in increasing the productivity among the smallholder farmers. The aspects where more research is still required to enhance the adoption of these technologies are also highlighted.

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6.1 Introduction

In Southern Africa, most smallholder or subsistence farmers are typically located in regions with poor soil quality, mainly sandy soils due to colonization-driven resettlements (Baudron et al. 2012). The historic settlement plan has seen the majority of the smallholder farmers experiencing low crop productivity when compared to the commercial farmers who were settled in areas characterized by rich clayey soils with high productivity potential. Furthermore, during the 1960s, several Green Revolution technologies which include the heavy use of inorganic industrial fertilizers, pesticides, monoculture, and intensive soil tillage were introduced in most of the southern African countries. These technologies were more sustainable for commercial farmers, who could afford to purchase these expensive resources, rather than the resource-poor communal farmers, though it enabled the world to feed its growing population. Since the 1970s most of the smallholder subsistence farmers were almost compulsorily required to adopt the improved Green Revolution technologies, which saw them shift from their mainly traditional mixed and ecological farming practices. As most of these farmers had already been resettled in areas with poor quality soils, activities like constant soil disturbance through tillage and use of industrial fertilizers, increased soil degradation among these farmers. The soil degradation has been mainly exacerbated by the loss of soil organic matter in the smallholder farmer's soils, as the new technologies favoured feeding the crop directly with nutrients whilst ignoring to feed the soil (Mupambwa et al. 2020). The degradation of the communal farmers' soils now coupled with climate change effects such as increased occurrence of drought, flooding and excessively high temperatures has further increased the stresses of crop production for these farmers, thus resulting in the continued decrease of mostly cereal yields.

Of late, there has been a push on research among smallholder Southern African farmers on the various technologies that focus on ecological farming techniques with technologies such as conservation agriculture having been promoted widely (Nciizah et al. 2021). The growing realization that for crop productivity to increase among the smallholder farmers, there is a need to focus on feeding the soil in as much as it is critical to feed the crop. This idea of considering the soil as a resource has now seen organic agriculture being promoted more aggressively in twenty-first century agriculture. The concept of organic agriculture was pioneered by Rudolf Steiner in the early twentieth century and was a direct response to the industrialization of soil fertility management (Rahmann et al. 2017). However, the uptake of this concept has been very slow until recently when the benefits of feeding the soil, through technologies that promote the accumulation of soil organic matter. This chapter, therefore, presents information on the importance of organic agriculture with a *feed the soil to feed the crop* approach, and how it can be critical in increasing the productivity of smallholder resource-poor farmers, whilst enhancing their food security and resilience to climate change, with special reference to farming in the southern Africa region.

6.2 Characteristics of Soils Among Smallholder Farmers in Africa

One characteristic of smallholder farmers in sub-Saharan African (SSA) is the location of their farms on highly degraded, marginal lands, which are shallow with low water holding capacity (AGRA 2014; von Loeper et al. 2016). Most of the soils have low soil organic matter (SOM) content and are inherently infertile due to deficiency in key nutrients such as nitrogen, sulphur, phosphorous and carbon (Tully et al. 2015). Soil organic matter serves as a binding agent between primary soil particles, which decreases clay wetting and the consequent soil aggregate breakdown (Blanco-Canqui and Lal 2004). Consequently, soils with low SOM are weakly structured due to poor aggregation, high bulk density and have poor water retention. The poor structural stability predisposes the soils to degradation particularly soil erosion, which is the most severe form of soil degradation in SSA (Few Resources 2021). For instance, SSA loses approximately 50 tons of topsoil per hectare annually (FAO 2008), which in turn causes significant losses of soil nutrients and huge production losses for smallholder farmers since most farmers cannot afford to buy sufficient fertilizers.

Another key characteristic of smallholder farms is their location on predominantly sandy soils, which are fundamentally poorly aggregated, and have low fertility status and water holding capacity. Sandy soils have lower SOM than clay-dominated soils due to lower surface area than clayey soils (Zinn 2005). Specific surface area, which determines the binding strength between soil particles and SOM, increases with a decrease in particle size. Consequently, clay soils have higher SOM content and stability due to the formation of organo-mineral complexes between clay and organic particles with strong bonds, which resist disruption by external forces such as rainfall (Blanco-Canqui and Lal 2004). For this reason, sandy soil requires higher external inputs to increase productivity. This however comes at a cost to smallholder farmers who in most cases do not have the financial means to acquire adequate inorganic fertilizers or to adopt new knowledge-intensive practices.

In addition to soil texture, soil mineralogy also governs the concentration of SOM in soils. Soil mineralogy is a determinant of the capacity of soil minerals to adsorb and protect soil organic carbon (Zinn 2005). It has been consistently shown that the presence of soil minerals such as smectite in the clay fraction, which has a high specific surface area, increases soil's capacity to adsorb and protect SOM. Consequently, such soils are more stable with good water infiltration, and soil fertility due to improved microbial activity and nutrient cycling. However, most smallholder farmers are located on soils dominated by quartz, mica and kaolinite in the clay fraction (Mandiringana et al. 2005; Nciizah and Wakindiki 2012). A study by Mandiringana et al. (2005) showed that most soils in smallholder farms in the Eastern Cape province, South Africa, were dominated by low activity clay minerals such as kaolinite and weathering-resistant minerals such as quartz. These two minerals result in poor soil chemical and physical process, which explains the high instability, crusting and soil erosion in most smallholder farms in the Eastern Cape Province (Nciizah and Wakindiki 2016). Similarly, Manyevere et al. (2015) reported high soil crusting in some resettlement schemes in Zimbabwe due to the poor soil structure of the soils. It is therefore prudent that smallholder farmers adopt sustainable farming practices that improve SOM content, improve soil structure and reduce the raindrop impact.

6.3 Indigenous Farming Technologies Being Promoted by Smallholder Farmers

The indigenous farming technologies involve the unique, culturally acceptable and existing systems of crop and animal production, which have been developed and adopted in a particular region (Sharma et al. 2020). These systems have been passed from generation to generation in African farming systems, with very limited documentation to build this body of knowledge though. As highlighted by Sharma et al. (2020), these indigenous technologies are endangered due to a lack of archiving of this knowledge as well as due to changes in cultural values. Some of these techniques which are currently being practised by smallholder farmers in southern Africa are highlighted below.

6.3.1 Mixed Crop-Animal Farming

In most African countries, animals are regarded as a source of reserve wealth, similar to a banking system, such that the more animals one has, the higher their rank within the community. Since animals play a critical role in the livelihoods of these farmers, under these systems, biomass from the crops is often seen as animal feed rather than feed for the soil. In most of these systems, the dominant enterprise is crop production which is then linked to animal production. With maize (*Zea mays*), sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*) being among the most grown cereal crops, animals like cattle (*Bos tauras*), goats (*Capra aegagrus hircus*) and sheep (*Ovis aries*) are usually made to feed on the stover generated after harvesting. Unlike commercial farmers who can use the entire plant biomass to make animal feed even before harvest, communal farmers rarely harvest the biomass from these cereal crops as feed exclusively for animals.

With these domestic animals having significant monetary value, most animals are kept in a confined area especially at night to protect them from predators and even theft. Due to this popular arrangement, these confinement areas called kraals become sources of animal manure, which is often collected and applied to crop fields as a source of nutrients. Furthermore, as the animals feed on the stover from the different crops, they often leave the highly lignified and dry stems, which farmers then collect into piles and burn before the rains. The burning of the stalks that would take ages to decompose creates nutrient-rich ashes that also act as a nutrient amendment for soils. Though these mixed crop-animal farming techniques have been practised over centuries, there has been very little whole system quantification of the changes in soil properties, crop and animal productivity, with most of this knowledge being anecdotal.

6.3.2 Intercropping or Companion Cropping

This practice is very popular among subsistence farmers and this involves the growing of two or more crops in the same space and within the same cropping cycle. These are crops that usually do not compete with each other for space, light, nutrients and water, but also do not always complement each other like in crop rotations. Typical of most traditional farming systems which are diverse, intercropping systems tend to cushion subsistence farmers from crop failures especially in this changing environment as the different planted crops usually have varying adaptabilities (Singh and Singh 2017). Within the African context, intercropping is at times practised between a cereal crop and another crop that can be harvested as a vegetable or eaten as a field snack.

In most intercrops, the main crop is usually planted first to allow for all the labour and resources to be dedicated to the success of the primary crop. The companion crop is then usually planted later after the successful establishment of the main crop and usually has a smaller growing period, a system also called relay intercropping Various intercropping systems involve the following; maize-pumpkin; maize—beans; maize—sweet sorghum; maize/pearl millet—cowpeas; with an in-depth discussion on intercropping being provided by Maitra et al. (2021). Within southern Africa, traditional intercropping systems have been one of the main reasons for the lack of adoption of newer technologies that use powered tools and pesticides for mainly weed control, during the production cycle. This has however resulted in high labour requirements for these farmers, which can directly influence per capita output.

6.3.3 Traditional Organic Composting

Composting is a process that dates back centuries ago and is based on the basic principle that every living organism (organic) once dead will decompose into its various constituent molecules. Crops grown for food and all other plants are not able to absorb organic nutrients and thus these organic nutrients require undergoing a process of decomposition so that the organic nutrients can be converted into inorganic nutrients before plants can absorb them (Mupambwa et al. 2020). This is unlike animals that can absorb organic nutrients like proteins, carbohydrates, vitamins, among others, without the need for decomposition.

Interestingly, though these chemical processes are hardly understood by the smallholder farmers, composting has been a practice for the purpose of generating organic fertilizers that were applied periodically to crop fields. Various materials are widely used as compost sources or for composting and these mainly include animal manures (cow, goat, chicken and sheep) and dead plant biomass (stover, leaves, grass). However, though these materials have been widely used by smallholder farmers as nutrient sources, there is very little in the literature that indicates the deliberate application of the science of composting by these farmers. Critical information such as the C/N ratio; level of potentially toxic heavy metals, nutrient levels; and application rate have barely been considered by the smallholder farmers; and these also make soil-plant application levels very complicated to recommend (Raimi et al. 2017). On the contrary, though traditional compost has been used as nutrient sources by most subsistence farmers, there is an increasing concern about its potential to release greenhouse gasses into the atmosphere (Raimi et al. 2017).

6.3.4 Legume-Based Crop Rotations

Crop rotations involve the sequential growing of different plant species on the same piece of land, usually with mutual benefits on nutrition or pest control. This cropping technology dates back to centuries ago and has also been widely researched in modern agriculture (Singh and Singh 2017). Crop rotations are different from intercropping in that the crops under crop rotation are not planted in the same field at the same time but different crop species are alternated in the same piece of land, whilst intercropping involves having the different crop species on the same piece of land at the same time. Generally, in Africa, the mean effect of cultivating maize after a legume due to enhanced N nutrition and soil organic matter increase was estimated to be around 500 kg of increased maize grain yield compared to maize monocrop (Vanlauwe et al. 2019). Among the southern African smallholder farmers, most of the crop rotations have involved the cycle of planting a cereal and legume crop mainly due to the ability of legume to fix atmospheric nitrogen into the soil. Important to note is that most smallholder farmers in Africa prioritise the cultivation of grain legumes such as soya beans (*Glycine max*), cowpeas (*Vigna unguiculata*), groundnuts (*Arachis hypogaea*), bambara nuts (*Vigna subterranean*), common bean (*Phaseolus vulgaris*), among others, as these provide nutritional benefits and can also be sold (Vanlauwe et al. 2019). So important is the issue of nitrogen-fixing in crop rotations that a project titled *N2Africa—putting nitrogen fixation to work for smallholder farmers in Africa* was initiated in 2009 (Vanlauwe et al. 2019).

Though crop rotations have been practised by smallholder farmers, the practice has not been judiciously followed as indicated by the small areas in sub-Saharan Africa that are committed to legumes. This has been attributed to the fact that if these grain legumes are being cultivated for home consumption, not much of a large area is required to satisfy family food requirement, with a family of seven requiring only about 58m^2 to meet its annual requirements (Vanlauwe et al. 2019). Apart from the small areas being dedicated to these beneficial legume crops, the other major limitation on the traditional practice of using legumes in crop rotations has been the belief that these legume crops do not require any fertilizer application. However, supplementing legumes with fertilizers has been shown to double yields and increase the plant growth and the crop's ability to fix nitrogen (Chianu et al. 2011). Furthermore, the issue of using *Rhizobium* inoculants has rarely been explored by smallholder farmers in most southern African countries except in countries like Zimbabwe. It is also important to note that most smallholder farmers have crop yield as their ultimate target and the unseen benefits to the soils are rarely considered with crop rotations.

6.3.5 Agroforestry

This is a system where selected beneficial trees are grown in combination or in sequence with food crops and at times with livestock. Though this system has been existing for centuries mainly in the tropics, agroforestry saw its aggressive promotion and research for smallholder farmers in the 1970s which also saw the establishment of the International Center for Research in Agroforestry (ICRAF) (Mercer and Pattanayak 2003). However, unlike the research thrust of agroforestry that was being promoted by ICRAF in southern Africa, the traditional agroforestry systems involve a system where various indigenous multi-purpose trees are left by farmers to grow in a dispersed and irregular pattern on croplands (Amare et al. 2019). Improved and mainly nitrogen-fixing tree species were introduced by ICRAF to the same farmers from 1987 and the trees were grown either in intercrops or separately (Kwesiga et al. 2003). The main drive was to increase the soil quality of the smallholder farmers' fields by growing trees either in situ or on other parts of the farm and transfer biomass from these trees to the cropped land (Kwesiga et al. 2003). Furthermore, unlike the traditional non-cropped fallow system, beneficial, soil nutrient improving trees were also introduced to complement the fallow system.

Various leguminous trees and shrubs have been promoted or evaluated by ICRAF for potential use as nitrogen fixers, fodder source, soil organic matter source and even firewood by smallholder farmers and include *Sesbania sesban*; *Tephrosia* *vogelii*; *Gliricidia sepium; Cajanaus cajan* and *Leucaena leucocephala; Faidherbia albida; Leucaena pallida; Acacia angustissima* (Katanga et al. 2007; Kwesiga et al. 2003). In various studies, Akinnifesi et al. (2010) reported that maize yields increased by up to 350%; 583% and 233% under gliricidia; sesbania and tephrosia, respectively. However, these yield benefits were not immediate and this has been one of the many challenges to the adoption of improved agroforestry systems among the smallholder farmers. The system of agroforestry presents a potential climate adaptation, mitigation and resilience option for smallholder farmers, and there is a need to stress the benefits to soil quality as opposed to yield alone for these farmers.

6.4 Organic Agriculture: The Principles

The idea of organic agriculture is widely believed to have been pioneered by Rudolf Steiner (1861–1925) through a series of lectures that gave birth to the movement of biodynamic agriculture (Rahmann et al. 2017). Rudolf Steiner ran this first course on organic agriculture in 1924 to a group of farmers in the Polish village of Koberwitz now known as Kobierzyce (Paull and Hennig 2011). According to literature, Rudolf Steiner's lectures were in partial response to the growing chemicalization of agriculture which was being principally driven by the industrialization of the Haber-Bosch process developed by Fritz Haber and Carl Bosch in 1909, allowing for the production of nitrogen fertilizer (Paull and Hennig 2011). Generally, the system of organic agriculture which arose at the beginning of the twentieth century has gone through three stages outlined by Rahmann et al. (2017) as organic 1.0; organic 2.0 and organic 3.0. According to Rahmann et al. (2017) organic 1.0 is that period led by organic pioneers who developed the vision of organic agriculture (OA); organic 2.0 described a recent period that saw the growth and marketing of OA, founding or organic research institutes culminating the formation of the International Federation of Organic Agriculture Movements; whilst organic 3.0 addresses the future challenges and aims at pushing for OA at a global scale.

The FAO/WHO (1999) Codex Alimentarius Commission has by far given the most accepted definition of organic agriculture, describing it as *a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, agronomic, biological, and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system*. Due to the environmental challenges associated with modern agricultural practices, the period between 1980 and 1990 saw a great revival in organic agriculture (Kirchmann et al. 2008). In simpler terms, organic refers to anything derived from living matter and in crop-based agriculture, the term 'organic agriculture' loosely refers to a farming system where plant nutrition is provided for by decomposing materials of usually animal or plant origins such as manure and leaf

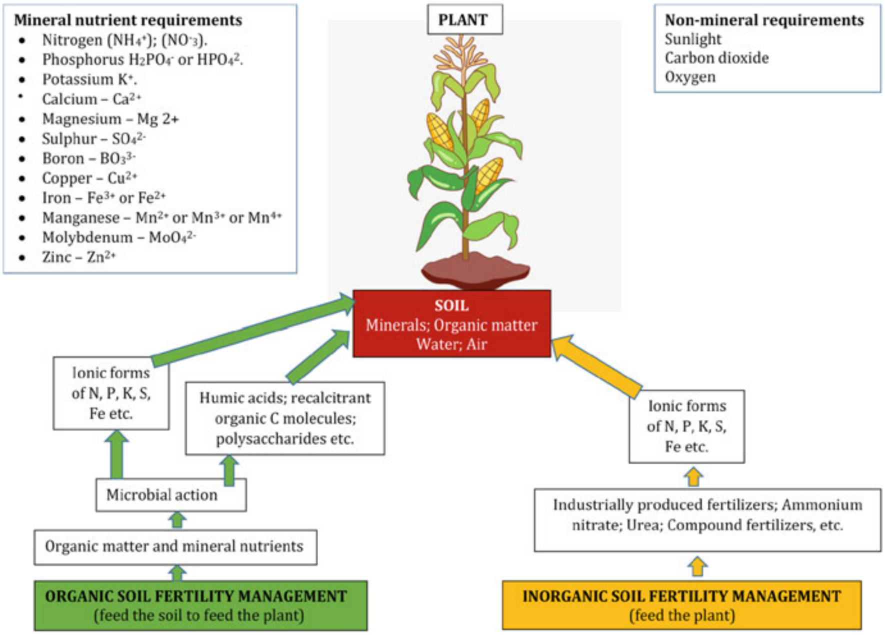

Fig. 6.1 A schematic representation of how organic and inorganic soil fertility management operates in providing nutrition to the crop and soil. (Source of maize plant image: https://pngtree.com/freepng/crop-corn-beautiful-corn-green-leaves-red-soil_3874083.html accessed 14 May 2021)

litter. In chemical terms, the final nutrients delivered to the plant from an organic soil fertility management system and that from the inorganic (industrial fertilizer) system are the same, as plants cannot absorb complex molecules like carbohydrates, but absorb mostly simple molecules in their ionic form as indicated in Fig. 6.1. The important concept of organic agriculture is that it recognizes the value of soil as a living ecosystem that requires to be fed in order for it to maintain its health and productivity. It is however important to indicate that organic soil fertility management also without external inputs from synthetic fertilizers is less likely to be productive enough to generate yields that can sustain the ever-growing world population. The guiding thread in organic agriculture is always to focus on feeding the soil so that the soil can then feed the crop.

6.5 Climate Smart Soil Fertility and Quality Systems with a Thrust Toward Organic Agriculture

In the twentieth century, various technologies have been promoted as improved technologies that smallholder farmers in southern Africa can adopt as a means of improving soil health and feeding the soil. Furthermore, these technologies have also been driven by the realization that agriculture is not only affected by climate change but also contributes to climate change as the soil is a huge storage component of the global carbon cycle. Over millions of years, the soil has been a sink for most of the plant biomass fixed carbon. Soil disturbance due to agricultural activities has exposed this stored carbon which is released back into the atmosphere. Therefore, the conversion of natural forest areas into agricultural land has greatly affected the carbon balance within the planet. The main cropping systems that present great potential in soil fertility management for smallholder farmers whilst creating a climate-smart management option are discussed below.

6.5.1 Conservation Agriculture

Conservation agriculture (CA) is widely promoted in Africa to arrest the high rates of soil degradation and the decline in productivity. It is regarded as a sustainable climate-smart agronomic practice (Nciizah et al. 2021) based on the following three principles (FAO 2014):

1. Reduction in tillage: The objective is to achieve zero tillage, but the system may involve controlled tillage seeding systems that normally do not disturb more than 20–25% of the soil surface.
2. Retention of adequate levels of crop residues and soil surface cover: The objective is the retention of sufficient residue on the soil to protect the soil from water and wind erosion; to reduce water run-off and evaporation; to improve water productivity and to enhance soil physical, chemical and biological properties associated with long-term sustainable productivity. The amount of residues necessary to achieve these ends will vary depending on the biophysical conditions and cropping system.
3. Use of crop rotations: The objective is to employ diversified crop rotations to help moderate/mitigate possible weed, disease and pest problems; to utilise the beneficial effects of some crops on soil conditions and the productivity of subsequent crops and to provide farmers with economically viable cropping options that minimize risk.

Increased soil organic matter deposition and preservation are central to CA's success (Nyambo et al. 2020a). Soil organic matter plays a vital role in crop production by controlling soil fertility and below ground system stability (Lal 2004; Debska et al. 2020). Each of the three CA principles plays a crucial role in ensuring the increase and maintenance of soil organic matter (SOM), a significant factor in soil quality (Delgado et al. 2011). The Zero/no-tillage is a fundamental CA component, which usually involves eliminating soil tillage and inversion. Zero tillage/no-tillage systems can potentially enhance crop and soil productivity in the face of climate change. Soil tilling changes the physical state of the soil (e.g., stability, penetration resistance, bulk density, moisture, aeration and porosity) and exposes crop residues to microbial decomposition and mineralization (Nyambo et al.

2020b). The resultant SOM decomposition results in greenhouse gas emission (GHG), in particular carbon dioxide (CO_2) (Lal 2010; Nyambo et al. 2020c). According to Carter (1992), no-tillage results in higher moisture levels, higher soil stability and lower soil temperatures compared to soil tilling. Furthermore, tillage can potentially influence the quality and quantity of organic matter inputs to soils through altering crop growth and the consequent biomass allocation.

Mulching is another essential component of CA whose relevance and importance in sustainable agriculture in the African smallholder context is slowly gaining recognition in Africa. Crop residues retained in the field after harvesting create mulch, which softens the impact of raindrops, holds water increasing infiltration rates and is a vital SOM source. In some situations, residue retention can cause nitrogen immobilization and waterlogging (during periods of heavy rain), which negatively affects crop performance. Additionally, residue retention has been reported to harbour pest and disease, which can be a problem for the follow-on crop (Nyambo et al. 2020a).

Crop rotation is also a crucial component in agricultural systems as it intensifies crop production and ensures the maintenance of permanent organic cover (FAO 2008). The introduction of cover crops into maize systems would be a counterbalance to the fact that smallholder farmers in Africa do not practice full crop rotations. In most African farming systems, cover crops have been seen to improve soil fertility and crop yields in subsequent seasons (Table 6.1). An integrated systems approach, on incorporating crop rotations and other agronomic practices, is believed to attain optimum crop yields.

Various research has been carried out on the effects of CA on soil quality, crop productivity and climate change mitigation (Table 6.1). Reports show that the responses vary with conditions involved (climate, soil, management, cropping system, age of experiment). The varying results make it difficult to generalize or relate them to all areas under smallholder farming systems (Corbeels et al. 2006). In cases where results are positive, its applicability to smallholder farmers is still questionable because the adoption statistics do not reflect it (Gowing and Palmer 2008). Therefore, an understanding of the principles and related practices that contribute to the desired effects on crop productivity is needed.

Conservation agriculture has been promoted as a package that encompasses all the three key principles of minimal soil disturbance, crop rotation and crop residue soil cover (Muzangwa et al. 2017); but its practice on many smallholder farms shows that many farmers will undergo intermediary CA steps before full adoption (Nyambo et al. 2020c). In the first step farmers usually adopt no-till only, then after some time adopt either crop rotation or residue management before taking up all three CA principles. In the process to full CA adoption, though research has been done, it is not conclusive what changes occur in the short term with regard to soil physico-chemical properties and yield. Smallholder farmers practice mixed farming of crops and livestock and this poses challenges in the promotion of CA because of the competing use of residues. However, land preparation practices adopted by many farmers show that some residues remain in the crop field after the livestock has finished grazing (Muzangwa et al. 2017). Farmers burn residues or bury them by

Table 6.1 CA effects on soil quality, crop productivity and climate change as influenced by experiment age, climate and soil type

Objective and experimental treatments	Experiment age (years)	Soil and climate	Soil changes	Reference
To investigate CA as a sustainable alternative for conventional maize production practices	17	Semi-arid environment, clay soil type	CA increased total C content by 17.1 mg ha^{-1} relative to CT	Dendooven et al. (2012)
To understand the trends of soil quality improvement in maize-based cropping systems in the first 5 years considered as a medium-term period	5	Semi-arid climate; soils were ferruginous latosols soils	CA significantly increased soil organic matter from the fourth year. Soil aggregates of >2 mm and earthworm activity also increased under CA after 5 years	Ligowe et al. (2017)
To study the effect of CA practices on selected soil properties and nutrient availability and nutrient (N and K) savings after 4 years of cereal-based cropping systems in western IGP of India	4	Semi-arid and subtropical; haplic Solonetz (siltic) soil	Bulk density was reduced in a partial CA-based rice-wheat-mung bean system relative to full CA. CA-based rice-wheat-mung bean and CA-based maize-wheat-mung bean systems increased penetration resistance, SOC, available and infiltration rates compared to conventional rice-wheat cropping system	Jat et al. (2018)
Evaluated the impact of conventional practices and CA on SOC and phosphorus.	8	2 sites Buffelsvlei (arid climate and sandyloam soils). Zeekoegat (warm temperate and clay soils)	SOC was high under reduced tillage than CT in clay soil but not in the sandy loam	Swanepoel et al. (2018)
To assess the effect of different tillage, crop establishment and residue management options on system productivity, economics and soil properties of an irrigated RMS under the climatic conditions of north-West India	5	Sandy loam, average annual rainfall is 831 mm	Water-stable aggregates, bulk density, penetrometer resistance and infiltration rate were higher under CA relative to CT	

ploughing when they prepare the land for planting though the amount of residues that remain is not known. However, the concept of conservation tillage promoted in Zimbabwe in an earlier study by Oldrieve (1993) recommended leaving 30% of the residues in the field and this has found favour with some smallholder farmers. This practice was adopted by Kwazulu Natal (KZN)—no-till club farmers who also extended it to small farmers in the surrounding areas. While working with smallholder farmers, Smith et al. (2007) acknowledged positive results of sustainable approaches, involving CA, to crop production. Whilst practising CA has been observed to benefit soil and crop output, the results are not applicable in all environments and farmer situations. There is a need to tailor agronomic practices according to geographic area, environment, resource availability and the type of farming system.

6.5.2 *Biochar in Organic Farming*

Biochar has attracted interest amongst researchers as a technology for sequestering carbon, mitigating GHG and improving the soil quality, thus reducing the problems and effects of climate change (Lehmann and Joseph 2009). The UK Biochar Research Centre (2011) defines biochar as a 'carbon-rich solid product of the thermal stabilisation of organic matter, which is safe and potentially beneficial when stored in soil'. Biochar production is similar to that of charcoal production, with the difference being that biochar is charcoal produced specifically for soil or agronomic use. The production of biochar is done through a process called pyrolysis, which involves heating the biomass in the absence of oxygen; thus, no combustion takes place. Scientific evidence on the benefits of biochar dates back to the 1850s with documented research being available from 1915 where biochar was recommended in various horticultural activities (Lehmann and Joseph 2009). The recent interest in biochar has already been alluded to, firstly, the observation that biochar-like materials were responsible for the high SOC and enhance fertility in Amazonian dark earth soils known as *terra preta de indio*. Secondly, the recent research observations that biochar is more stable than other organic amendments in soil and that it is very effective in retaining plant nutrients relative to traditional organic amendments like composts (Lehmann and Joseph 2009).

Under resource-poor farming systems, the pyrolysis process can be done using a cheap and simple drum retort as indicated in Fig. 6.2. The feedstock holder under Fig. 6.2 is a smaller 25 L container sealed with a lid to limit the amount of oxygen entering and this is burnt inside a 200 L oil drum retort at a temperature of up to 500 °C (Nyambo et al. 2018). The choice of biomass used depends on many factors, mainly the availability of materials and cost of acquiring and transporting the materials (Gwenzi et al. 2015). Feedstock material gives biochar its specific characteristics such as chemical composition, and its physical and chemical stabilisation mechanisms in soils that determine its effects on soil functions (Nyambo et al. 2018).

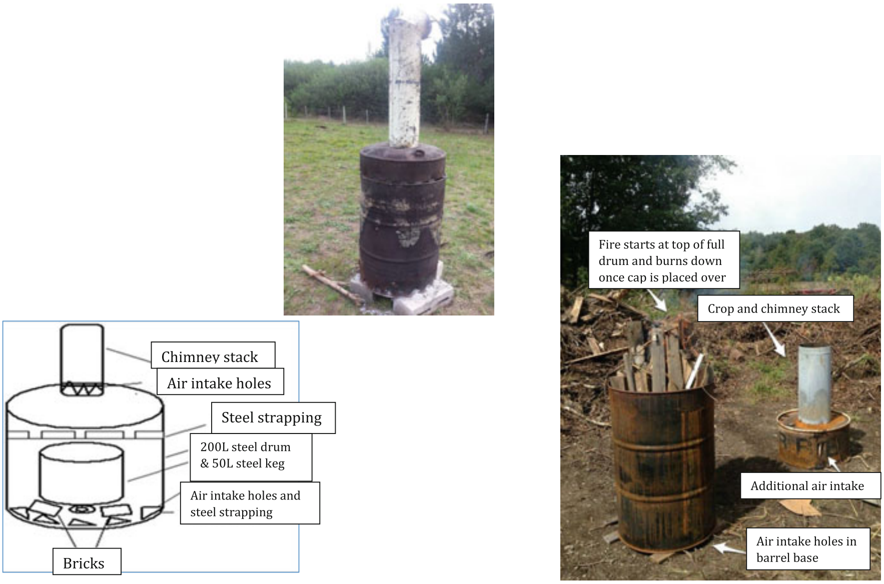

Fig. 6.2 Simplified representation of biochar producing set-up recommended for smallholder farmers. (Source of images: Shareef and Zhao (2017); https://www.appropedia.org/Simple_Biochar_Kilns (accessed 17 May 2021))

Nonetheless, any organic waste material from household waste, leaves and other biomass from agroforestry, crop biomass residues and animal waste can be used.

Biochar composition can vary depending on the source of biomass used and the temperature at which the thermal decomposition occurred. Biochar produced from non-woody feedstocks, i.e., manures and plant residues in general, is richer in nutrient content and has higher pH values and less stable C than biochar produced from lingo-cellulosic feed stocks such as wood (Dahlawi et al. 2018). Amending soils with stable forms of biochar increase the size of C pools and long-term C sequestration (Lehmann et al. 2006). Chan et al. (2008) showed that using poultry litter biochar produced at 450 and 550 °C can significantly increase organic C in an Alfisol soil. Darby et al. (2016), however, reported that biochar produced at low temperatures is easily mineralized by microbes and can result in degradation of the organic fractions. There have been reports that the C content of biochar varies from <1% to >80%, subject to the feedstock and the pyrolysis conditions. Because of this, biochar not only increases SOC but can also provide a unique opportunity to improve physicochemical properties and protect soils from erosion using locally available materials (IBI 2017). Besides being the source of nutrients, biochar can improve the capacity of a soil to retain nutrients and subsequently plant uptake (Cheng et al. 2018).

Though there is evidence of the positive effects of biochar, its uptake and use by smallholder farmers in Africa is very low. One of the main reasons is the lack of knowledge about the technology. The feasibility of biochar use by smallscale farmers depends on the availability of feedstock material and production equipment, economic possibilities and potential to improve soil and crop. Its use can potentially benefit the smallholder farmers who practise low input agriculture. Besides being used as a soil amendment, biochar can be used as a source of much-needed energy for cooking and heating, hence improving smallholder farmers' livelihoods (Gwenzi et al. 2015).

6.5.3 Ecological Agriculture

The concept of ecological agriculture was proposed by Kiley-Worthington (1981) and defines a cropping system that aims to integrate natural ecosystems, which would have been disturbed deliberately to produce food and fodder, into a more resilient agro-ecosystem without causing many changes to the original environment (Nciizah et al. 2021). Having proposed the concept, Kiley-Worthington (1981) described ecological agriculture as *the establishment and maintenance of an ecologically self-sustaining low input, economically viable, small farming system managed to maximize production without causing large or long-term changes to the environment or being ethically or aesthetically unacceptable.* Several authors have also proposed new terms which all still speak to the same concept of using an ecological approach to agriculture and these include agro-ecology; sustainable agriculture; sustainable intensification, climate-smart agriculture, to mention a few. The management framework of the concept of ecological agriculture is indicated in Fig. 6.3 and this makes it clear that several other cropping systems can be incorporated into ecological agriculture.

As highlighted earlier, most of the smallholder farmers in southern Africa are located in lands characterized with poor quality soils and these lands are highly susceptible to degradation under minimum soil disturbance. The concept of ecological agriculture, therefore, has great potential in creating a smart agriculture tool for resource-poor smallholder farmers. The practices include the use of improved quality manures like vermicomposts; using improved varieties of crops; using synthetic fertilizers to complement organic fertilizers; employing smart-weed and pest controls; all with the objective of getting the best out of the farmer's field with limited environmental damage.

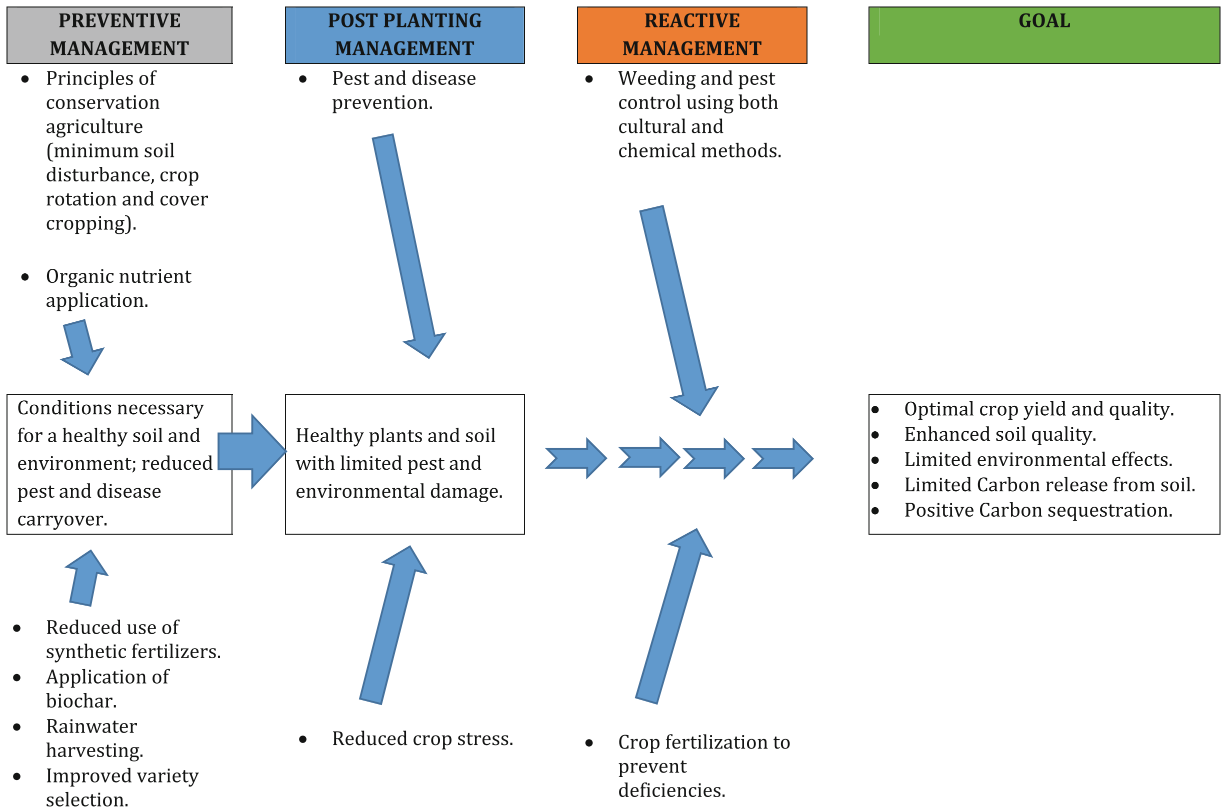

Fig. 6.3 Schematic representation of the ecological agriculture management framework as adopted from Magdoff (2007)

6.5.4 Mixed or Companion Cropping and Crop Rotation Benefits

In most African societies, crop production by smallholder farmers has been linked to various cultural beliefs and traditions. These traditions have a great influence on which crop is grown in an area and even on what technologies are used to produce these food crops. This has also seen most of the smallholder farmers holding on to their traditional methods or crop production such as mixed crop farming versus mono-cropping; use of animal power versus mechanical power; use of the hand hoe for weed control versus herbicides, to mention but a few of these practices. Mixed or intercropping in the smallholder farming system has mainly been a system where a cereal grain crop is usually planted with another secondary crop which can either provide some other fruits, grain or leaves for another harvest. The cropping systems have not been informed by scientific knowledge but rather by indigenous knowledge; therefore, benefits from the companion crops or mixed system are less pronounced.

Research has now moved in to cover this gap of scientific evidence and various systems that can benefit smallholder farmers have been developed. The benefits of the various intercropping systems on soil health and crop productivity are highlighted in Table 6.2. This summary indicates that legumes provide a definite benefit to farmers as they can fix atmospheric nitrogen which subsequently increased the yield of the next cereal crop. However, though research shows these benefits, most smallholder farmers rarely accrue these benefits as the area under legumes is always not proportional to that under cereals.

6.6 Conclusions

Most smallholder farmers in southern Africa are located in areas characterized by poor-quality soils which are prone to degradation. However, as agricultural technology changed, most of these farmers have not benefited from most technologies, and have rather realised a decline in yields under the changing climate. It is imperative to understand that to increase the resilience of the degraded smallholder farmer soils, their agricultural systems should drive towards feeding the soil to feed the crop. Unfortunately, the Green Revolution technologies that recommend technologies like mono-cropping, soil tilling and supplying soil nutrition using synthetic industrial inorganic fertilizers will only make these farmers more vulnerable to soil degradation and climate change. Technologies that involve the aspects of conservation agriculture, use of biochar and inter or mixed cropping are more likely to result in positive benefits in terms of soil nutrition and crop productivity, for smallholder farmers. However, research has indicated that most farmers rarely practise organic farming techniques like full crop rotations as cereal crop requirements always outweigh those for legumes. Socio-economic studies also need to be undertaken to

Table 6.2 Summary of research done on the effects of various intercropping or crop rotation systems on soil quality and crop productivity

Cropping system	Experimental design	Duration (years)	Agronomic impact
Common bean and soya bean with inoculation, rotated with maize combined with P fertilizer and manure application (Rurangwa et al. 2018)	Established in farmers' fields in 3 agro-ecological zones with rainfall ranging from 800 mm to 1400 mm. The trial had a factorial design with 3 factors, i.e. 1. without or with inoculation with *Rhizobium tropici* for common bean and *Bradyrhizobium japonicum* for soybean 2. manure at three rates: 0, 5 and 10 t ha^{-1} 3. P fertilizer at two rates: 0 and 30 kg P ha^{-1} added as triple super phosphate Next to each treatment block, a plot sown with maize served as a reference crop to assess biological nitrogen fixation (BNF).	2	Grain yields varied from 1.0 t ha^{-1} to 1.7 t ha^{-1} in unamended control plots to 4.8 t ha^{-1} for common bean and 3.8 t ha^{-1} for soya bean in inoculated plots with both P and manure addition Furthermore, the crop yield responses were dependent greatly on the rainfall pattern Maize yields greatly increased up to 6.5 t ha^{-1} in plots with manure application and common bean inoculation and P fertilized and 0.8 t ha^{-1} in the control Similarly, maize yield increased from 1.9 t ha^{-1} (control) to 5.3 t ha^{-1} in soya bean grown under similar conditions Common bean fixed up to 198 kg N_2 ha^{-1} whilst soya bean fixed up to 186 kg N_2 ha^{-1} under inoculation, P and manure application
Maize was intercropped with cowpea, soybean and groundnut in a fertile and poorly fertile fields (Kermah et al. 2018)	The treatments consisted of cowpea—*Vigna unguiculata*; soybean—*Glycine max* and groundnut—*Arachis hypogaea* intercropped with maize (*Zea mays*) or grown as sole crops In the intercrop treatments, maize and legumes were grown within the same row at varying spacing depending on the legume crop The rainfall was 598 mm at site 1 and 532 mm site 2 and all experiments were established in Plinthosols	1 year	Legume crops yielded more under sole crops and fertile soils. Intercropping significantly reduced the yield of all 3 legumes and maize Similarly, the sole crops across the sites fixed more nitrogen compared to the intercrops The nitrogen that was fixed was larger in fertile fields (16–145 kg N ha^{-1}) than in poorly fertile fields (15–123 kg N ha^{-1}) due to greater shoot dry matter

(continued)

Table 6.2 (continued)

Cropping system	Experimental design	Duration (years)	Agronomic impact
	Two field types representing fertile and poorly fertile soil conditions were selected at each site		
A review of 44 research items comparing continuous cereal performance with that of a grain legume-cereal rotation (Franke et al. 2018)	Review of literature	n/a	Maize showed stronger yield responses after a legume than millet and sorghum All grain legume types significantly improved Cereal yields, with stronger residual effects observed after soybean and groundnut than after cowpea Grain legumes are unlikely to have a major influence on the availability of nutrients other than N and P, or on soil pH Evidence of impacts of grain legumes on weeds is limited to *Striga* spp. An amount of N_2 fixed (kg N ha^{-1}): Cowpea (4–201); Groundnut (10–124); soya bean (3–302); common bean (1–31). The variation is due to fertility, soil condition, rainfall, location etc.
Maize–pigeon pea intercropping system (Rusinamhodzi et al. 2012)	A split-plot design in which the main plot factors was (a) an additive design of within-row intercropping in which legume was intercropped with alternating hills of maize within the same row; maize plant population was the same as sole crop maize, and (b) a substitutive design with distinct alternating rows of maize and legume Split plot factor treatments were: (a) no	3 years	Intercrops were relatively more productive than the corresponding sole crops The average maize yield penalty for intercropping maize and pigeon pea in the within-row was small (8%) compared with 50% in the distinct-row design Intercropping maize and cowpea in within-row led to maize yield loss of only 6%, whereas distinct-row intercropping reduced maize yield by 25%

(continued)

Table 6.2 (continued)

Cropping system	Experimental design	Duration (years)	Agronomic impact
	fertilizer, (b) 20 kg P ha^{-1}, (c) 20 kg P ha^{-1} + 30 kg N ha^{-1}, and (d) 20 kg P ha^{-1} + 60 kg N ha^{-1}		In the third season, maize in rotation with pigeon pea and without N fertilizer application yielded 5.6 t ha^{-1}, eight times more than continuous maize which was severely infested by striga (*Striga asiatica*) and yielded only 0.7 t ha^{-1} Maize–legume intercropping is a feasible entry point to ecological intensification
Intercropped maize (*Zea mays*) with grain legumes, cowpea and pigeon pea (*Cajanus cajan*), as well as maize rotated with cowpea (*Vigna unguiculata*) and sunnhemp (*Crotalaria ochroleuca*) was studied (Thierfelder et al. 2012)	Conservation agriculture and conventional agriculture systems with various intercrops at 2 different sites Maize, cowpea, soya bean, velvet beans, pigeon pea and sunnhemp were planted to achieve various cropping systems	7–8 years	The comparative productivity analysis between continuous maize, maize intercropped with cowpea or pigeon pea and maize in rotation with cowpea or sunnhemp showed marked benefits of rotation, especially in conservation agriculture systems The on-station and on-farm results show an increase of up to 331% in water infiltration, a 31% greater soil carbon in the top 60 cm than on adjacent conventionally ploughed fields However, not much was mentioned on the potential benefits in terms of soil nutrition based on the intercropping systems

understand the driving force behind the lack of technology adoption among smallholder farmers, which greatly increases their cost and time of production. Overly, technologies that enhance the adoption of organic soil fertility management present a positive future for our smallholder farmers in southern Africa.

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Chapter 7
Precision Agriculture Under Arid Environments: Prospects for African Smallholder Farmers

H. A. Mupambwa, A. D. Nciizah, E. Dube, and M. Fanadzo

Abstract Precision farming is usually associated with high-tech equipment, requiring huge capital and infrastructure investments. In developed countries, precision farming has been linked to high-end computer technologies and remote data collection. In smallholder farming systems where such technologies do not exist, the discussion of precision agriculture has been limited. Our chapter presents precision farming in smallholder farming systems as an ideal approach for helping farmers to manage spatio-temporal crop and soil variability in order to increase site-specific productivity and sustainability. We present options that are critical in driving precision farming within the smallholder resource poor farming, context focusing on soil fertility management, water saving technologies, genetically modified crops, herbicides and hand-held fuel powered equipment. There is a need to demystify precision farming among African farmers and promote new knowledge sharing on the benefits of site-specific management options in increasing productivity and resilience under a changing climate. African governments will also need to expedite the changes in policies on genetically modified organisms, based on current research data, whilst also supporting farmers where technology requires capital and infrastructure investments.

Keywords Genetically modified crops · Hydroponics · Controlled environment · Herbicides · Parasitic weeds · Hand weeding · Soil fertility management

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7.1 Introduction

Agriculture throughout the world is faced with the dilemma of feeding an increasing population, and this calls for intensive production systems such as massive tillage, clearing of permanent forests, excessive use of industrially manufactured nutrients and use of chemicals in controlling pests. Though intensive farming systems have managed to increase land productivity in the nineteenth century, agriculture in the twenty-first century is now faced with a new challenge of climate change and soil resource degradation. Interestingly, technologies that increased land productivity in the previous century are now contributing to global change in the carbon cycle, which is making agriculture a contributor, yet also a victim of climate change. Climate change has become a major challenge to agriculture, and the world may soon not be able to produce enough food in the future due to a changing climate.

Climate change–related problems are already affecting the resource poor farmers in Africa and Asia. In Africa, smallholder farmers contribute up to 70% to the food basket, which means a decrease in these farmers' productivity will translate into food insecurity. Smallholder farms in southern Africa are mainly located on marginal lands where soils are poor in quality. With climate change resulting in increased frequency and intensity of droughts, flooding, higher temperatures, increased pest and disease incidences; the smallholder farmers will need to adopt new technologies. Subsistence farmers in southern Africa are sometimes located in semi-arid environments, where water limits productivity. Therefore, the adoption of precision farming can be critical in increasing the resilience and adaptation of the smallholder farmers in a sustainable way. Precision farming is being promoted in developed countries for mostly commercial farmers. However, research in Africa has been aimed at adjusting these technologies to be adoptable by local resource poor farmers. This chapter therefore presents information on precision farming technologies available for smallholder farmers with the intention of driving technology adoption, which is critical in securing household food security.

7.2 The Arid Environments of Africa and Agriculture

Africa is one of the driest continents of the world with 45% of its landmass falling under dry lands. Furthermore, 38% of this land is occupied by hyper-arid or desert land. About 50% of the African population lives in the arid, semi-arid, dry sub-humid and hyper-arid areas (Kigomo 2003). Africa which is dominated by the Sahara Desert in the north and the Namib and Kalahari Deserts in the south, contains a preponderance of hyper-arid and arid lands, which are mostly unsuitable for agricultural activities. The regional statistics of aridity zones for Africa are shown in Table 7.1.

With climate change, it is expected that heat waves will last longer, resulting in more persistent hot days approaching the year 2100 (Niang et al. 2014). The

Table 7.1 Percentage of area per aridity zone by sub-region for Africa

Sub-region	Hyper-arid	Arid	Semi-arid	Dry sub-humid
Northern Africa (%)	81	11	7	0
Western Africa (%)	33	20	18	7
Central Africa (%)	0	0	2	4
Eastern Africa (%)	14	27	28	12
Southern Africa (%)	2	13	42	15
Africa Total (%)	27	16	21	8

Source: Corbett (1996), UNDP/UNSO (1997)

warming trend experienced toward the end of the twentieth century is expected to continue into the future. For example, for the period 2071–2100 relative to 1971–2000, temperature increases of 4–6 °C are likely to occur in the African subtropics under low mitigation futures (Pereira 2017). These increases are projected to be associated with drastic increases in the frequency of extreme temperature events such as very hot days (>35 °C), heat waves, and high fire-danger days (Engelbrecht et al. 2015). Although rainfall projections for Africa are less certain than the corresponding temperatures, it is generally believed that the continent is becoming drier. Apart from changes in total or mean summer rainfall, certain intra-seasonal characteristics of seasonal rainfall such as onset, duration, dry spell frequencies, and rainfall intensity as well as delay of rainfall onset have changed (Niang et al. 2014). An increasing frequency of dry spells is accompanied by an increasing trend in daily rainfall intensity, which has implications for run-off characteristics (New et al. 2006). Over southern Africa, there is a greater likelihood of heat waves associated with reduced rainfall conditions. With the current trends, Africa is at a high risk of severe droughts and dry spells.

Much of African agriculture's vulnerability to climate change lies in the fact that agricultural systems remain largely rain-fed. It is estimated that about 95% of all cropping systems in Africa are rain-fed (McKinsey Global Institute 2020), and in the sub-Saharan regions, the figure is estimated to be 98% (FAO 2002). Climate change will impact temperature and rainfall, which are the most important variables for crop growth. This is expected to adversely affect yields of most crops. It is expected that the mean annual temperature across Africa will increase by more than 2 °C before the end of this century (Niang et al. 2014). In addition, changing rainfall patterns are a cause for concern. High temperatures and changes in rainfall patterns are likely to reduce cereal crop productivity across sub-Saharan Africa. A 2% decrease is expected for sorghum and a 35% decrease is expected for wheat (Nelson et al. 2009). Maize-based systems are particularly vulnerable to climate change, with yield losses predicted to be in excess of 30% (Schlenker & Lobell 2010). Under climate change, pressures from animal pests, weeds, and diseases are also expected to increase, with resultant detrimental effects on crops.

7.3 Climate Change in Agriculture Under Dryland Environments

Climate change has emerged as the foremost challenge curtailing agricultural production for African smallholder farmers. This has led to countless national and international organisations pushing several initiatives aimed at cushioning these farmers. The smallholder farmers are the most affected group of farmers due to their weak ability to adapt to changes in climate. The most anticipated changes are those of rainfall and temperature with wet areas likely to get wetter whilst dry areas will become drier (IPCC 2007). Consequently, smallholder farmers, whose farms are predominantly located in the drylands, which includes arid (with low rainfall between 200 and 500 mm/year) and semi-arid areas (500–1000 mm rainfall/year), will bear the brunt of climate change due to increased frequency of drought and water scarcity in these already water stressed environments (UNCCD 2009). Drylands include all regions (dry, dry-sub-humid, semi-arid and arid, exclusive of hyper-arid areas) in which the production of crops is limited by water (UNCCD 2009). These areas will experience frequent droughts, which will shorten the length of the crop growing season and will expose critical crop phenological stages to extreme weather events resulting in poor crop yields (El-Beltagy and Madkour 2012; AGRA 2014).

Unless farmers adopt new initiatives and technologies, climate change will certainly worsen the current challenges and further curtail the attainment of the Sustainable Development Goals (SDGs). Other challenges faced by dryland smallholder farmers in Africa include but are not limited to unsustainable farming practices, which cause land degradation, poor irrigation methods, lack of technical and financial support inequality, etc. In the worst-case scenario, climate change will render rain-fed agriculture unsustainable and therefore restrict the potential of smallholder farmers to meet their food requirements (Mupangwa et al. 2008).

7.4 Older Adopted Technologies in Farming

As food production shifted from the nomadic system to permanent settlement, smallholder farmers in Africa started using various technologies that are based on indigenous knowledge and other imported green revolution–based technologies. The major technology adopted was the use of industrially processed fertilizers to provide nutrients for crops. This saw a huge increase in crop yields of most farmers, though making production costs expensive, with some farmers being unable to afford the costs. With the introduction of synthetic fertilizers, smallholder farmers began applying fertilizer as close to the crop roots as possible to improve the fertilizer use efficiency. However, most of the farmers continue to use blanket application rates that are not informed by soil analyses. Though fertilizer application resulted in yield increase among smallholder farmers, the continuous use of the inorganic fertilizers also resulted soil degradation as organic matter was no longer applied to the soils when inorganic fertilizers were used.

Apart from inorganic fertilizers, the adoption of improved hybrid crop varieties caused the crops to yield more. The hybrid varieties have mainly been exploited in cross-pollinating grain crops like maize where yields increased from as low as 1 tonne per hectare to above 10 tonnes per hectare. Moreover, hybrid varieties were bred for specific areas which allowed farmers in different areas to have varieties that were almost tailor-made for their environmental conditions. However, similar to the synthetic fertilizers, the hybrid seeds came with a cost to resource poor subsistence farmers, who had a poor understanding of the hybrid seed technology. Such farmers preferred to retain seed from the hybrid crops as a cost-cutting measure, and this resulted in reduced crop yields due to a reduction in hybrid vigour over generations. Recently, open pollinated varieties are being promoted to allow for the harvesting of seed from the parent crops with limited reduction in vigour and productivity across harvests.

Conventional farming systems tend to favour weeds, and these have become a major challenge for smallholder farmers. As a smart solution to the traditional hand-hoe technique of managing the weeds, there has been an introduction of herbicides that selectively kill targeted plant species. Herbicides have been effective in the control of certain weed species in the commercial farmer sector, with very limited success among the smallholder farmers. This is due to the lack of proper extension services to promote this technology, coupled with the mixed cropping systems of legumes and cereals used by most smallholder farmers, which prevented the effective use of herbicides.

7.5 Precision Agriculture in African Agriculture

The idea of precision agriculture, also known as precision farming, is rarely discussed amongst resource poor smallholder farmers. It is associated or linked with high-end technology which most smallholder farmers would likely view as alien. In developed countries, advanced information systems that rely on sensors, data loggers while collecting data from satellites or drones are used in precision farming (Aune et al. 2017). However, such systems are quite expensive in developing countries where even the infrastructure is limited. Hence precision agriculture in developing countries should involve less remote data collection and less use of high-tech ICT equipment. For smallholder farmers, precision agriculture can be defined as a holistic approach that helps farmers to manage the spatio-temporal crop and soil variability within the field in order to increase site-specific productivity and sustainability and increase profits (Alemaw and Agegnehu 2019).

Precision agriculture in developing African countries allows for the timely farming operations (planting, weeding and harvesting); the use of precise amounts of fertilizers and irrigation water as well as using correct crop types and varieties specific to each site (Aune et al. 2017). Therefore, the precision farming system

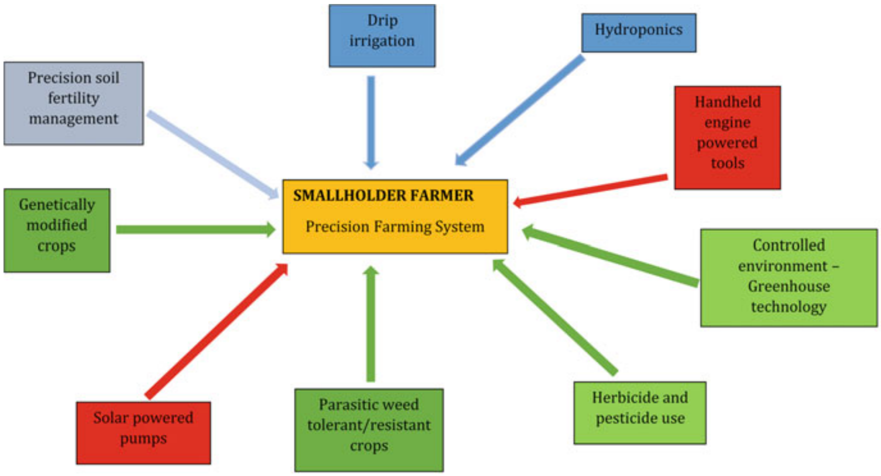

Fig. 7.1 A schematic representation of some aspects of crop farming that can be applicable to precision farming under smallholder farming systems in southern Africa

basically increases the chances of farmers making correct decisions during their production cycle. Under the traditional farming systems, smallholder farmers use blanket recommendations, for example, in fertilizer and seeding rates, with the aim of increasing productivity but with limited site-specific crop management (Alemaw and Agegnehu 2019). Precision agriculture is thus an important aspect of "sustainable intensification" which focuses on producing more food intensively with a limited environmental footprint (Aune et al. 2017). Due to site-specific management, precision agriculture is also considered as a climate smart agriculture practice as it results in increased productivity with limited greenhouse gas emissions (Aune et al. 2017). Of the various precision agriculture systems, those that have great potential for adoption by resource poor African farmers are indicated in Fig. 7.1.

7.6 Current Precision Farming Technologies Adoptable by Smallholder Farmers

7.6.1 Soil Fertility Management

With the shift from nomadic way of cultivating crops, where farmers would look for virgin land to plant crops with no fertilizer inputs, intensive tillage systems have resulted in high nutrient mining in most cropped lands. This mining resulted in the depletion of the nutrient levels in soils which translated into reduced crop yields and therefore led to the drive towards the introduction of industrial fertilizers. Inorganic fertilizers now constitute the major cost of production for resource poor smallholder farmers. As a way of assisting farmers, most governments in southern Africa came up with blanket recommendations for fertilizer application rates, which are still being used to date by extension officers. However, as indicated earlier, precision agriculture seeks to promote site-specific recommendations, and this applies to fertilizer recommendations as well.

On smallholder African farmlands, soil spatial heterogeneity is inherent, and this is due to the interactions between geological diversity; land use and management over time (Tittonell et al. 2015). The smallholder farmer's lands can be divided into various unique and similar zones which should be managed differently based on their characteristics (Ahmad and Dar 2020). The main elements that are deficient in most soils are nitrogen, phosphorus and potassium, and these need to be applied in higher quantities relative to other micro-nutrients, for enhanced crop yields, especially for cereal grain crops. Important to also note is the level of soil organic matter, pH and electrical conductivity on smallholder farms, which are all critical in improving soil fertility and health. However, most smallholder farmers rarely analyse the chemical fertility of their soils. This is a critical step in effecting the site-specific soil fertility management system under these farming conditions as it allows the farmer to determine the amounts of fertilizer required to bring their soils in each zone, back to high productivity for different crops. The variation in nutrient levels within the same farming unit has been core to the development of the variable rate technology that aims at applying inputs such as fertilizers, manure and seeding rate based on the individual requirements of the soils and crops (Ahmad and Dar 2020). The variable rate technology can be based on data collected physically through mapping or remotely using sensors, and for smallholder farmers, the use of physical mapping is recommended as it is less costly and complicated.

Another aspect important to also consider under smallholder farming systems is the use of staggered fertilizer applications during the cropping cycle. As indicated earlier, most farmers simply use blanket nutrient requirements, and this is applied as a once-off application. However, as most of the soils under the smallholder farming setup are poor in water and nutrient retention capacity, once off applications result in extreme loses through leaching and runoff. As a way to guard against this, it is therefore advised to apply precise amounts of nutrients which the crop is able to absorb through split applications, thus increasing the fertilizer use efficiency in relation to productivity at the farm. The various factors and linkages in informing the implementation of a precision-driven soil fertility management system for smallholder farmers are shown in Fig. 7.2.

7.6.2 Hydroponics

In southern Africa, most smallholder farms are located in arid to semi-arid regions where fresh water is a major limitation to productivity. This water challenge is further exacerbated by climate change, which has increased the intensity of droughts in these regions. As most of the smallholder farmers in Africa rely on rain-fed agriculture, inadequate rainfall translates into poor crop productivity, and reduced

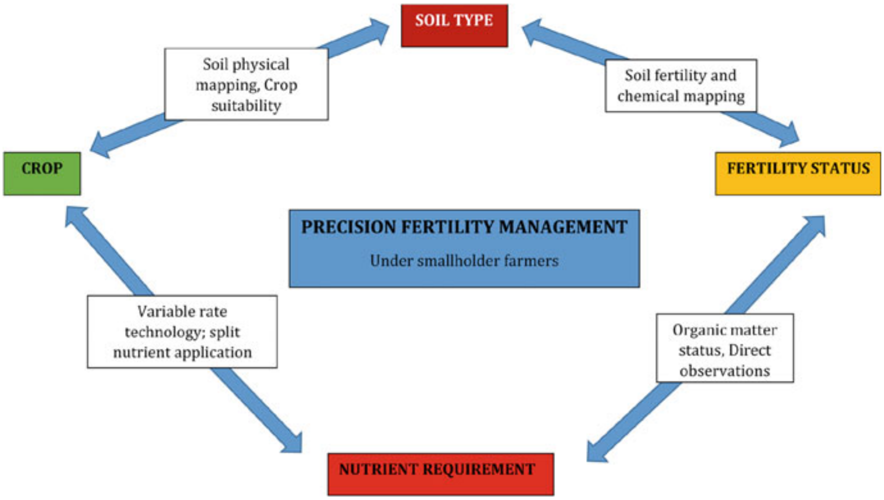

Fig. 7.2 A diagram showing the various factors to consider when implementing precision soil fertility management for smallholder farmers in southern Africa

food security. As part of precision farming, there is a need for the adoption of water saving methods of crop production, and hydroponics and drip irrigation are quite plausible for smallholder farmer adoption. The technology of hydroponics involves the growing of plants in the absence of soil, which ensures that most of the water applied contributes directly to crop growth, with very limited losses due to infiltration and evaporation. However, it is important to note that not all crops can be grown easily using the hydroponic technology, and this system has been reserved mainly for vegetable crop production with very little research having been done on grain crops. Interestingly, in a study Miller et al. (1989) observed that maize grown in a hydroponic system yielded much more compared to that planted in the soil. However, it is important to note that, though hydroponics can be used to produce cereal crops, the areas required to attain yields that can sustain smallholder farming household's annual food requirements, will require huge capital investments if hydroponics are to be used.

The technology of hydroponics, which is a precision farming technology, can be effectively used to produce horticultural crops among smallholder farmers. Crops like tomatoes, spinach, onions, peppers, cucumbers among others can be grown using various hydroponic systems, with yields that are quite high compared to soil planted crops. In some smallholder farming systems, farmers produce horticultural crops for household consumption and for income generation. Most of these farmers use non-water saving techniques like buckets, flood irrigation and overhead irrigation, which wastes water and nutrients. Of the various hydroponic technologies which include drip; deep water culture; ebb and flow (flood and drain system); nutrient film technique and aeroponics hydroponics systems; the drip system and the deep water culture system have potential for adoption by smallholder farmers. The deep water culture system has been shown to be effective in producing leafy vegetables, whilst the drip system using artificial planting media like coco-peat can be used for fruity vegetables like tomatoes and peppers. Most smallholder farmers rarely consider hydroponics as it is also linked to high-tech systems which require thorough understanding, though this technology is very simple to adopt. What is important to note is that for hydroponics, an inorganic water-soluble fertilizer source is often used, and this is often expensive for resource poor farmers. Research on the development of organic nutrient sources in the form of vermicompost leachate is currently underway at the University of Namibia, with the aim of producing a cheap source of nutrients that can be acceptable to smallholder farmers for vegetable production (Mupambwa et al. 2020).

7.6.3 Controlled Environment

As indicated in the previous section, smallholder farmers in southern Africa also produce horticultural crops for household food security and for generating income. Horticultural crops, unlike cereal grain crops, are more sensitive to changes in the environment which limits their productivity during dry or cold periods of the year. Controlling the above-ground environment in which the crop grows under is a very critical precision farming technique that can be used to reduce water uptake by plants, reduce pest and disease incidences and also increase the accumulation of heat units for low-temperature-sensitive crops. However, most smallholder farmers have a notion of the controlled environment agriculture as high-tech systems that require huge capital investments, though the low-cost systems are available and are preferred for smallholder farmers, whilst allowing the control of the most important biotic factors (Nordey et al. 2017). The low-cost controlled environment systems use simple covers on the soil or over the crops to reduce water, gas, heat and pest transfers between the crops and the outside environment (Nordey et al. 2017). Depending on the environment, the material used to control the environment is usually translucent plastic (to increase temperature) or shade netting (to reduce temperature) as illustrated in Fig. 7.3. Unlike the high-tech systems that make use of galvanised steel, the structure of a smallholder farmer can be constructed using ordinary wooden poles for the frame, with the use of UV protected plastic or shade netting. Having the ability to control the environment coupled with hydroponics technology presents great potential for smallholder farmers to increase their productivity and profits in horticulture, thus improving their livelihoods.

7.6.4 Genetically Modified Crops

In most countries in the SADC region, genetically modified crops are prohibited as these countries have taken a precautionary approach towards regulating this

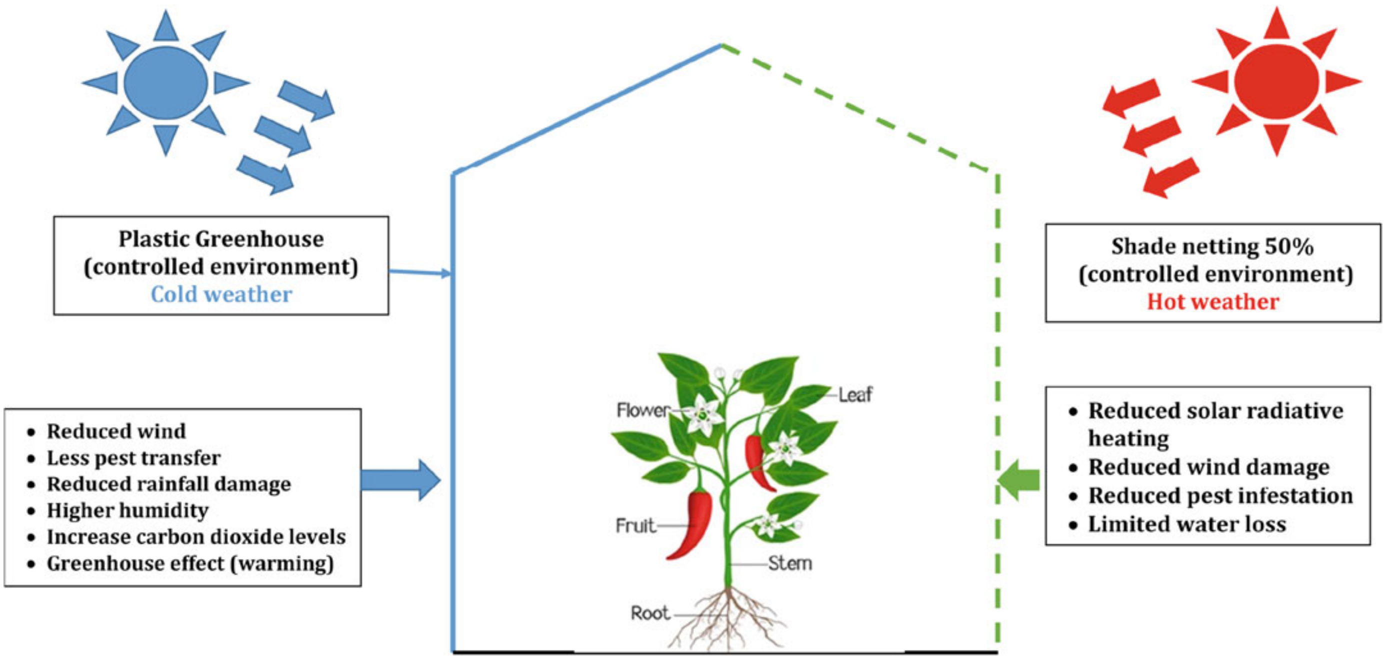

Fig. 7.3 An illustration of the potential benefits of the controlled environment on the farmer under both cold and hot environments. Plant image source: https://www.shutterstock.com/image-vector/illustration-showing-parts-plant-red-pepper-1018043545 accessed 01 June 2021

biotechnology (Muzhinji and Ntuli 2020). This approach has seen limited growth of genetically modified cropping systems in southern Africa due to fear of the unknown effects of these crops on the environment, genetic biodiversity and human health. In the entire southern African region, only South Africa and Eswatini have allowed the commercial growth of genetically modified maize, cotton, soya bean, among other crops (Muzhinji and Ntuli 2020). Interestingly, most of the cultivated crops available to all farmers these days are modified genetically through the use of conventional breeding methods, though these are not labelled as genetically modified organisms (GMO). In most terms, genetically modified crops are those that have had their genetic make-up artificially and precisely modified using laboratory-based methods employing genetic engineering to give the plant characteristics that does not naturally possess (Muzhinji and Ntuli 2020). The United Nations' Food and Agriculture Organization recognizes the improvement of crop genetics through innovative technologies such as genetic engineering and conventional breeding as critical in achieving sustainable increase in food productivity and ultimately food security.

Smallholder farmers in southern Africa are affected by several biotic and abiotic stress that include droughts, weeds, pests and diseases, which further increases their vulnerability to food insecurity. Yield losses due to these stresses have been reported to be up to 100% especially from the pests and diseases among smallholder farmers, which therefore presents a great challenge in attaining the sustainable development goals (SDGs) of zero hunger by 2030. However, genetically modified crops present an opportunity to introduce foreign genetic material into the crop's genetic make-up which can create instant benefits like pest, disease and herbicide resistance. Using genetically modified cotton, studies done in Argentina, China, India, Mexico and South Africa reported that insecticide use was reduced by up to 75% whilst yield was increased by up to 35% when compared to conventionally bred cotton (Qaim and Matuschke 2005). With weeds constituting the greatest labour requirement and production constraint for smallholder farmers, the wide adoption of genetically modified maize that is resistant to the non-selective systemic herbicide glyphosate could make a significant impact. Apart from pest and disease resistance, another important aspect of genetically modified crops is that of biofortified grain crops that are modified for enhance nutritional composition (Qaim 2009).

Though the production of GM crops in southern Africa remains controversial with very limited acceptance at national level, it is imperative to indicate that these GM crops present an important precision farming technique that can contribute to the attainment of the zero hunger SDG. As indicated by Qaim (2009), these GM crops have been shown to produce large aggregated welfare gains and these are more pronounced among the farmers from developing countries. Furthermore, the GM crops have been reported to reduce the environmental impact of agricultural activities linked to the use of chemical pesticides, which create huge health benefits through bio-fortification. As concluded by Muzhinji and Ntuli (2020), *Failure to adopt GM technology based on socio-economic issues or the precautionary principle is not hurting the scientist, the politician nor the policy maker but the poor peasant farmer, who expend a lot of energy toiling in infertile and unproductive land in anticipation of a bumper harvest each year. It therefore seems tragic to disregard* *a tool that has already been developed while the poor and the vulnerable communities suffer and depend on donor aid for survival.* It is important for the African governments to reengage the researchers to expedite the development of a GMO policy and allow the smallholder farmers to benefit from increased productivity attached to the use of GMO.

7.6.5 Herbicide Use

The use of herbicides in most smallholder farmers is also regarded as a new technology requiring sophisticated equipment that is mainly applicable to commercial farmers. This is further compounded by the high toxicity of some of these herbicides to humans and other animals if not carefully used, coupled with the misinformation that herbicides also kill the soil. For example, developing countries use only 25% of the global world pesticides though they experience 99% of the deaths linked to the improper use of these pesticides. However, with weed management being a critical element capable of reducing farmers' productivity by 55–90% (maize), 50% (common bean), 40–80% (sorghum), 40–60% (cowpea), 80% (groundnut) and 80% (cotton), the use of herbicides presents a precision farming technique that not only increases productivity but also reduces the drudgery of farming associated with weed control among smallholder farmers. Weeds compete with farmers' crops for space, sunlight and nutrients and cost time and money for the farmer to control manually. According to Gianessi (2009), smallholder farmers require 378 h per ha (groundnuts), 276 h per ha (maize) and 150 h per ha (sorghum), to undertake complete hand weeding, a task mainly done by women and children in southern Africa.

Herbicides that are applied post emergence of the crop have been effectively used to control some weeds that are propagated vegetatively such as couch grass (*Cynodon dactylon*), wandering jew (*Commelina benghalensis*), purslane (*Portulaca oleracea*), to mention a few, which are very difficult to control using hand hoes. Furthermore, pre-crop and weed emergence herbicides have also been shown to be effective against those weeds that produce huge quantities of seeds, making post-weed germination control difficult. Another group of weeds that have been effectively managed through herbicide use are the parasitic weeds that form parasitic interactions with the roots of the crop. The most yield-reducing parasitic weeds include *Striga asiatica* in maize and sorghum, whilst for cowpeas and groundnuts, there is *Alectra vogelii*. Parasitic weeds are unlike other weeds in that they require a host plant, which is usually the crop planted, to trigger germination, and usually remain attached to the host plant roots underground for most of the season, only to emerge during crop maturation, to produce seeds. The parasitic weeds produce huge quantities of seeds, with a *Striga asiatica* plant having been reported to produce up to 500,000 seeds (Mangosho and Mupambwa 2013). These parasitic weeds have been reported to cause yield losses of 50–100% if not controlled in crops like maize, sorghum.

With this information about the various weeds that present a challenge to improved productivity to most smallholder farmers in Africa, there is a need for proper extension of knowledge on the benefits of herbicides. Though herbicides present a precision farming technique for most resource poor farmers, its widespread adoption should be accompanied by proper education as herbicides are dangerous both to the user and to the crop, if incorrectly used. With most smallholder farmers practicing mixed crop farming systems, it is also imperative that the specificity of the various herbicides to certain crops be fully understood by these farmers before use.

7.6.6 Handheld Engine Powered Farming Tools

Draught power has been the main source of power for most smallholder farmers which mainly involves the use of donkeys, cows and horses for power at the farm. Though the use of animals at the farm is almost inseparable from any smallholder farmer in southern Africa, this technology has had its limitation in the new age. The changing climate, diseases, reduced grazing land due to population growth are now reducing the animal stocking of most smallholder farmers. Furthermore, though animals are effective in carrying out field operations, they tend to be slow and require more than one person to operate most times. The use of animal power has thus been associated with a similar drudgery as that of weeding at the farm. However, in the twenty-first century, new technologies are now emerging that are powered by fossil fuels and electricity, which can be used to drive most of the farm implements. These machines present a new precision farming opportunity that can be easily be taken up by most smallholder farmers, with a small capital investment. Of most importance are the powered rotary tillers, ploughs and planters, which can be operated by even younger persons at the farm. This technology will require support and buy-in at the government level as it requires some capital investment. The handheld fuel-powered machines are much cheaper than tractors and their heavy implements, and its possible for a farmer to sell a few livestock to fund the purchase of such equipment like handheld fuel-powered ploughs. However, there is definitely a need for government assistance in the form of subsidies to reduce the prices of this equipment, which are now mass manufactured in countries like China.

7.7 Conclusion

Most of southern African countries are located in semi-arid to arid regions, which greatly limits the water availability for crop production. Furthermore, smallholder farms, which are the food producers of most of these countries, are located in areas characterized by poor quality soils, which limit productivity in the face of climate change. Our chapter presents the option of precision agriculture from a smallholder farmer perspective. Though most precision farming techniques in developed countries are now powered by computer technologies, in the African context, precision agriculture focuses more on improved production systems that are holistic and site specific, sustainable and increase profits. In this chapter, technologies that focus on improving the crop productivity both in the soil and above soil whilst reducing competition have been presented. It is clear that smallholder farmers will need to adopt precision farming techniques to increase their productivity under a changing climate or these farmers will become food insecure. There is a need for demystifying some of the technologies presented here so that smallholder farmers feel comfortable to adopt some of these. Proper extension and knowledge sharing with the farmers is critical in driving the site-specific management farming systems. Overly, there is a need for government support on the adoption of other capital intensive technologies as well as development of new policy informed by research data, for the use of genetically modified crops in southern Africa.

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Chapter 8
Challenges and Opportunities for Soil Fertility and Food Security Improvement in Smallholder Maize-Tobacco Production Systems: A Case Study from Svosve Area, Mashonaland East, Zimbabwe

Nothando Dunjana, Rebecca Zengeni, Pardon Muchaonyerwa, Menas Wuta, and Ernest Dube

Abstract Balanced food and cash crop production is important to meet the food and income needs, and livelihoods of smallholder farmers in Africa. Smallholder maize-tobacco systems have the potential to cushion farmers from food and nutrition insecurity and livelihood uncertainty. This chapter seeks to outline some socio-economic and biophysical challenges within maize-tobacco smallholder systems, as well as highlight some promising prospects that can be promoted or further investigated in order to enhance food security and livelihoods. The challenges include shortage of labour, poor soil fertility, and increased risk of soil disturbance, while the availability of additional organic material that can be used in integrated soil fertility management practices, with associated improvement to soil properties such as pH and maize yields, represent some of the opportunities. Further, tobacco production generates direct on-farm income, which could cushion the farmers from poor yields of maize and price shocks. Therefore, food-cash crop systems present a viable alternative to the mainly subsistence based maize systems with the potential to sustain the food security, income and livelihood needs of smallholder farmers.

Keywords Cash crop · Food security · Household income · Smallholder farms · Soil management

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8.1 Introduction

Sixty-three percent of sub-Saharan Africa's (SSA) population is found in the rural areas, positioning SSA second among regions with the highest number of rural inhabitants, after South Asia (The World Bank 2010). Rainfed smallholder agricultural production is the main livelihood source for many people residing in the rural areas. In Southern Africa, maize is grown to meet households' food requirements as well as income generation. As such, most households' food security and livelihoods are dependent on maize. Notwithstanding, maize yield in SSA, estimated at 1.8 t ha^{-1}, is significantly lower than global average of 4.9 t ha^{-1} (Smale et al. 2011; Berge et al. 2019) and thus fails to sustain the populace's food and livelihood needs, with the situation likely to be worsened by the growing population (Hall et al. 2017). Although several efforts have been channelled towards alleviating hunger in Africa, food insecurity is widespread and represents an urgent global challenge (Sasson 2012). Crop diversification is largely accepted as a strategy to increase farm productivity, income and food variety while reducing the severity of food insecurity among rural folk (Mango et al. 2018).

Secondary crops in smallholder systems commonly include groundnuts, sugar beans, and cowpeas, as well as cash crops such as cotton and tobacco. However, with maize production being dominant, the contribution of secondary crops to food security is limited. Balanced production of food and cash crops presents an opportunity to improve farmers' livelihoods and harness their food security. For instance, tobacco has been on the increase across smallholder farming systems in developing countries as it is considered a viable enterprise with the potential to improve farmers' incomes. This, however, is despite the global health concerns, as most developing countries prioritise economic benefits (Hu and Lee 2015). Tobacco is grown in at least 21 countries in Africa with the leading producers being Malawi, Tanzania and Zimbabwe (CTCA 2014). While many secondary crops are grown in generally smaller plots compared to maize, tobacco is usually cultivated in equally large plots as maize or sometimes bigger (Masvongo et al. 2013; Dunjana et al. 2018), resulting in smallholder farms displaying considerable commercial orientation (Dunjana et al. 2018). Although maize availability is the main factor assessed when considering food security in Southern Africa (Mango et al. 2018), significant cultivation of a cash crop, which generates immediate farm income, is also of importance with regard to household food security and livelihood.

Consequently, in the context of fostering sustainable soil fertility management and food security in African smallholder systems, this chapter explores some of the socio-economic and biophysical challenges and opportunities arising within smallholder maize-tobacco systems, as observed in the Svosve farming area in Mashonaland East, Zimbabwe (Fig. 8.1), which is a typical maize-tobacco farming area. Household surveys, focus group discussions and on-farm trials carried over 2 years were used as the primary sources of information in our study.

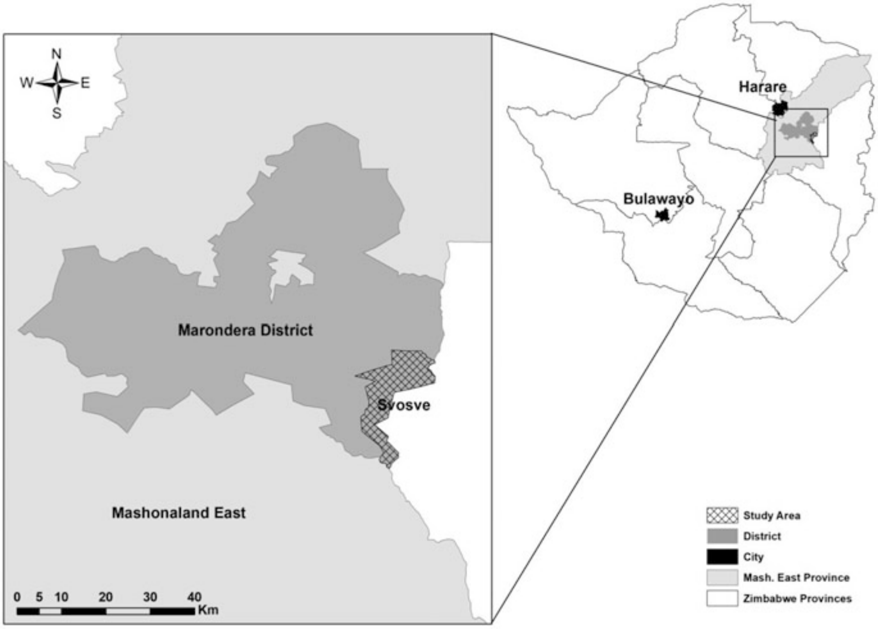

Fig. 8.1 Map showing the Svosve farming area, Mashonaland East province, Zimbabwe

8.2 Description of a Maize-Tobacco Farming System in Zimbabwe

Tobacco production on smallholder farms is not new. However, limitations such as small land holdings, limited access to inputs and lack of institutional support previously limited smallholder tobacco production in communal areas (Shumba and Whingwiri 2006). Progressively, various government initiatives, regulations and policy changes have alleviated some of the barriers and resulted in increased participation of smallholder farmers in commercial production, such as tobacco. For example, in Zimbabwe, the surge in smallholder tobacco farming has mainly been attributed to increased access to land due to the government's fast track land redistribution programme (FTLRP) of the 2000s (Shumba and Whingwiri 2006), while in Malawi, the liberalisation of the tobacco sector in the 1990s resulted in massive entry of smallholders into the sector (Jaffee 2003). Consequently, the combination of food and cash crop production culminates in unique farm dynamics, as it has a bearing on farm decision-making, resource allocation, farm operations and socio-economic implications.

Smallholder tobacco farming systems in Zimbabwe occur in three forms, differing according to the settlement type, i.e. communal, old resettlement and newly resettled or FTLRP farms (Rubhara 2017). *While maize production dominates the communal and old resettlement farms (Moyo 2006; Mutami 2015), tobacco* *production is considerable on FTLRP farms.* For example, Dunjana et al. (2018) reported equal allocation of land for maize and tobacco production in medium-resourced farms in the Svosve area, while tobacco was grown on double the land planted to maize in resource endowed farms, *possibly owing to the higher economic returns from tobacco.* Thus, maize-tobacco farms consist of both maize and tobacco as the priority crops within the crop mix.

The heterogeneity of smallholder farms, which is a widely acknowledged phenomenon, has also been observed in maize-tobacco farms. Farm heterogeneity is a result of the interaction of various biophysical (climate, soil fertility, slope, etc.) and socio-economic (preferences, prices, production objectives, etc.) factors (Tittonell et al. 2010; Kuivanen et al. 2016). Such variability has implications on the ability of the farms to cope and withstand environmental and economic shocks. Dunjana et al. (2018) *identified three farm typologies in Svosve, a typical maize-tobacco farming area, namely (1) resource-endowed, commercial-oriented farms, (2) medium-resourced and (3) resource-constrained farms practising subsistence and income-oriented production, leading to variable capacity and strategies by the households to sustain their food security needs.*

8.3 Challenges of Maize-Tobacco Systems

8.3.1 Shortage of Labour

Shortage of labour is a common limiting factor hindering the productivity of agriculture. Under smallholder systems, household labour is the main source of labour, especially in medium-resourced and resource-constrained households (Mugwe et al. 2009). This was especially amplified in the Svosve area, as maize and tobacco are grown simultaneously and cultivated areas are also large. Further, tobacco's labour requirements are high due to numerous operations undergone during its production cycle. These include seedbed and land preparation, transplanting, fertiliser application, weeding, spraying for pest and disease control, topping, harvesting, curing as well grading and packaging. This was echoed across different socio-economic groups as it constrained both maize and tobacco production and impacted food security and livelihood sustainability (Dunjana et al. 2018).

8.3.2 Infertile Soils

Fifty-five percent of land in Africa consists of land that is unsuitable for cultivated agriculture (Bationo et al. 2006), yet significant smallholder crop production occurs on such soils. Such is the case in the Svosve communal area, as most of the farms are located on granite-derived sandy soils (Chimhowu and Woodhouse 2010). Sandy soils are characterised by numerous limitations ranging from a high degree of weathering, low nutrient contents, susceptibility to leaching and acidity, low soil organic carbon and poor water holding capacity (Soropa et al. 2018). The poor soil quality makes it a big challenge to meet the nutrient requirement of crops, moreso, as most of the smallholder farmers are resource constrained. Thus, if food security is to be achieved, suitable soil management practices should be adopted to alleviate some of the inherent and human induced soil constraints.

8.3.3 Soil Disturbance and Its Effects on Soil Quality

Proper agronomic practices require that tobacco should be grown in rotation with other crops. Examples include tobacco-maize, tobacco-groundnut, tobacco finger millet or tobacco-wheat in 1- or 2-year cycles. Alternatively, Katambora Rhodes grass (*Chloris gayana)* may be incorporated in the rotation (TRB 2011). The rotations seek to lower nematode levels and maintain soil structure, which is imperative to maintain soil productivity as tobacco poses the most damage to the soil in any rotation, according to the Tobacco Research Board (TRB 2011). Land preparation for tobacco involves deep ploughing up to 25 cm with an ox-drawn plough and up to 40–45 cm with a tractor-drawn plough. Thereafter, ridging is done as tobacco requires good drainage, while transplanting seedlings requires opening of planting stations using hand hoes. Weeding is also performed using hand hoes although herbicides have been found to be useful and can be used to provide a weed-free environment, which is critical for tobacco (TRB 2011). As such, the amount of soil disturbance where tobacco is cultivated tends to be significant. Excessive soil disturbance reduces soil productivity through its negative effects including loss of soil organic matter, reduced aggregate stability, increased susceptibility to erosion and nutrient leaching (Liu et al. 2021). Results from tobacco monocropping research at Kutsaga Research Station have shown gradual tobacco yield reduction after 3 successive seasons related to reduction in soil organic matter, disintegration of soil structure and increased disease problems (TRB 2011).

8.4 Opportunities in Maize-Tobacco Systems

8.4.1 Generation of High Nutrient Value Organic Wastes

The recovery and reuse of organic materials on-farm is one of the strategies through which nutrient mining from soils can be reduced (Cofie et al. 2016). Like maize, tobacco is also grown as a main crop, in areas where land holding is not limiting. For example, tobacco is reported to be grown on 1.3 ha plots on average in resettlement areas (Masvongo et al. 2013), which generates significant quantities of on-farm organic waste (Magama et al. 2015). Two main forms of waste are generated on-farm from tobacco, namely tobacco leaf scrap or fines generated during

Table 8.1 Average chemical composition of tobacco leaf scrap, stalk and cattle manure in the Svosve area

	TSC	TSK	CM
pH (H_2O)	5.91	6.6	6.8
Total N (g kg^{-1})	20.1	15.7	8.3
Total P (g kg^{-1})	4.6	5.0	2.5
Total K (g kg^{-1})	20.5	14.7	12.8
Total Ca (g kg^{-1})	14.7	11.1	5.9
Total Mg (g kg^{-1})	4.1	3.6	2.9
Total C (%)	45.4	47.3	33.7
C/N	22.6	30.1	40.1
Nicotine (mg kg^{-1})	19,500	6920	–

TSC tobacco leaf scrap, *TSK* tobacco stalk, *CM* cattle manure
Source: Dunjana (2020)

harvesting, curing, grading and packaging of tobacco for sale and tobacco stalks, which remain after leaves have been harvested. Unlike maize residues, which are commonly fed to livestock and cattle manure, which is frequently of low nutrient value and limited quantities (Rufino et al. 2011), tobacco waste generally, is of high nutrient value (Gülser and Candemir 2012). Nutrient composition of tobacco wastes obtained in our study in Svosve had higher total N, P, bases and carbon with lower C/N ratio than cattle manure as shown in Table 8.1, pointing to its potential usefulness in soil management on-farm. Tobacco waste uses can include direct application as mulch or incorporation. While direct application of tobacco wastes is beneficial, the high nicotine content may affect the quality of the produce, and prior processing such as biochar production or composting could be essential. *The positive effects of tobacco waste derived biochar on the remediation of heavy metal contaminated soils with concomitant increases in soil pH, organic matter and available phosphorus has been elucidated (Zhang et al. 2019).*

8.4.2 Composting Opportunities with Tobacco Waste

The CGIAR's Resource Reuse and Recovery (RRR) program established composting as an integral component for value addition to waste organic materials serving to both mitigate environmental pollution and return nutrients to soil (Cofie et al. 2016). Although compost quality varies as a function of a number of factors such as feedstock quality, composting methods and conditions, the composts are more valuable than the feedstocks. Composts produced from tobacco waste and cattle manure in our study conducted in the Svosve farming area had consistently better quality than cattle manure (Table 8.2). Consequently, the improved quality of tobacco-based composts provides an opportunity to supply more nutrients and augment the low organic resource quantities in low input systems. The use of these composts has a huge potential to improve nutrient supply and water holding capacity of the sandy soils in these systems.

Table 8.2 Chemical composition of tobacco waste and cattle manure composts in the Svosve area

	pH (H_2O)	Total N	Total P	Total K	Total Ca	Total Mg	Total C	C/N	Nicotine
		g kg^{-1}					%		mg kg^{-1}
TSC-CM	8.70^{a}	23.3^{a}	3.52^{a}	21.9^{a}	20.5^{ab}	5.35^{b}	30.5^{a}	13.1^{a}	<100
TSC-TSK	9.10^{a}	26.9^{a}	3.55^{a}	21.3^{a}	27.4^{b}	8.41^{c}	35.6^{a}	13.2^{a}	<100
TSK-CM	8.40^{a}	15.1^{b}	2.75^{a}	13.9^{b}	16.2^{a}	3.79^{a}	41.9^{b}	27.7^{b}	<100

TSC-CM stands for tobacco leaf scrap + cattle manure compost; *TSC-TSK* tobacco leaf scrap + stalk compost, *TSK-CM* tobacco stalk + cattle manure compost. Values in the same column followed by different lowercase alphabet letters are significantly different at $p < 0.05$
Source: Dunjana (2020)

8.4.3 Improvement of Soil Properties and Maize Yields with Tobacco Waste Composts

The combined application of organic and inorganic amendments to soil is at the core of integrated soil fertility management (ISFM), which has been promoted as a practical strategy towards sustainable intensification and a critical step to climate smart agriculture (Roobroeck et al. 2015). While farmers do not afford to apply the recommended rates of chemical fertilisers, a combined application of organic and inorganic fertilisers improves nutrient use efficiency of the applied nutrients (Vanlauwe et al. 2011). When tobacco and cattle manure composts were used as basal fertiliser with inorganic fertilisers as top dressing, soil pH and maize yields were improved (Fig. 8.2), thus highlighting their potential in sustainable soil management and yield improvement, which assures food security. Although the results of the 2016–2017 season were higher than 2017–2018 season, the trend of the treatments was consistent. Additionally, though the effects were comparable with cattle manure, when applied at the same rate, it is essential to note that the quantity of compost from tobacco waste and cattle manure mixture is significantly higher than the available manure and that the tobacco waste would otherwise have been burnt, with negative environmental effects.

8.4.4 Income Generation

The profitability of a cropping enterprise on a farm is important as it influences several aspects such as access to inputs, food and livelihoods sustenance. Masvongo et al. (2013) showed that tobacco is highly viable; generating a mean gross margin of US $2352 per hectare, with a margin of safety of 50% when breakeven analysis was conducted. Dunjana et al. (2018) reported an accumulation of capital assets from tobacco sales, namely, buying of farming equipment such as tractors and ploughs,

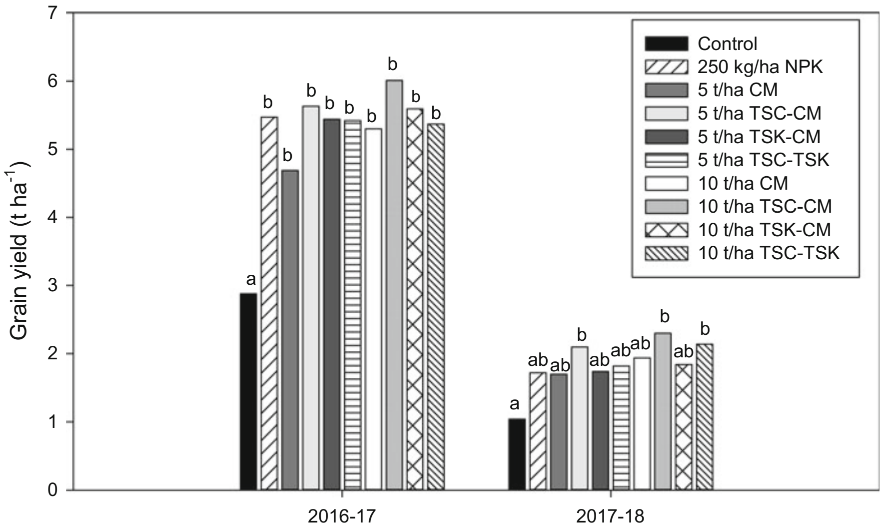

Fig. 8.2 Maize grain yield from an on-farm trial during the 2016–2017 and 2017–2018 seasons. All treatments received 100 kg N ha^{-1} as a top dressing fertiliser, except control. TSC-CM stands for tobacco leaf scrap-cattle manure compost, *TSK-CM* tobacco stalk-cattle manure compost, *TSC-TSK* tobacco leaf scrap-stalk compost, *CM* cattle manure. Means followed by a different lowercase alphabetic letter are significantly different at $p < 0.05$ according to Tukey's HSD. Source: Dunjana (2020)

which improve the productive capacity of the farms and funding of other non-farm investments. Clearly, income generated from tobacco was linked to improved livelihoods, which can cushion farmers against food insecurity due to low yields or price shocks. A study by Rubhara et al. (2020) confirmed that cash crop production increased food security of smallholder farmers by 62%. In our study, there existed a group of farms that sometimes would opt not to grow maize during some seasons, as they could rely on the income generated from tobacco to buy maize (Dunjana et al. 2018). Thus in the wake of climate change, rainfall uncertainty and variability and tobacco's relatively lower requirement for water, maize-tobacco systems offer a pathway to alleviate food insecurity, although the extent to which it does will need to be quantified.

8.5 Conclusion

Food security issues on the smallholder farms are complex and multifaceted as smallholder farms and farming systems are heterogeneous. Endemic food insecurity in principally maize-based smallholder farming systems points to the inadequacy of the system to sustain the food needs and livelihoods of the households. *On the other hand, although the integration of cash crops, such as tobacco, may bring about* *some challenges, more importantly, numerous opportunities that can enhance smallholders' food security and livelihoods can be realised*. This chapter highlighted some challenges and opportunities observed in a maize-tobacco system. The opportunities include generation of income from the cash crop in addition to the food crop, production and use of higher quantities of nutrient rich composts from the tobacco waste and cattle manure, that improves soil properties and maize yields through integrated soil fertility management practices, enhancing food security and income generation. Although cultivation on infertile soils, with increased disruption, could result in potential decline in soil quality, the composts could ameliorate the soils, leaving increased labour burden as the main challenge. Consequently, to improve food security in African smallholder farms, there is merit in exploring and optimising maize-tobacco smallholder systems.

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Chapter 9
On-Farm Research Challenges for Agronomic Field Trials in Smallholder Systems: A Practical Experience from Zanyokwe Irrigation Scheme, South Africa

Morris Fanadzo, Ernest Dube, and Nothando Dunjana

Abstract On-farm field trials are important for validating agronomic interventions aimed at improving crop yields on smallholder farms. However, on-farm field trials on African smallholder farms potentially bring about new, peculiar challenges that are sometimes not well documented by researchers. This chapter is a chronicle of researcher experiences through practical research on a smallholder irrigation scheme in rural South Africa, including the lessons learnt. Improvements in agronomic practices such as weed control, cultivar choice, soil tillage and irrigation water management had a significant positive effect on yields and farmer profits. However, several challenges also emerged, and these include accessing the trial sites, language barriers, pest problems, labour shortages, theft of produce and negative attitudes of the farmers towards research trials. It was concluded that these challenges could be overcome through an interdisciplinary approach to the agronomy field trials research. In this case, a holistic research design for the on-farm trials, which addresses both agronomic and socioeconomic challenges of the farmers simultaneously, is proposed.

Keywords On-farm research · Interdisciplinary research · Practical challenges · Resource poor farmers · Pest problems · Farmer cooperation

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9.1 Introduction

The need to create employment and reduce poverty, particularly among rural black people in South Africa, is a topical issue on many platforms. Over the years, many smallholder irrigation schemes (SIS) have been established in South Africa in order to gain accessibility to productive land and increase production in the different regions of the country. In the Eastern Cape Province, six SIS, with a total area of 2447 hectares, were developed in the former homeland of Ciskei (Van Averbeke et al. 1998). The irrigation schemes were planned and established following a centralised estate design whereby control over farming activities and decision making was strictly enforced by central management with little or no input from farmers. This created a high level of dependency among farmers in the schemes and poor performance when farmers were left to manage the schemes on their own. Intended beneficiaries of most of these schemes initially worked as wage labourers of the core scheme, which was then handed over to them to manage without adequate preparation in its operation and maintenance.

It is believed that an increase in the number of SIS and the revitalisation of existing schemes can result in an increase in food output, reduction in the unemployment rate and poverty alleviation within the rural communities of South Africa (Van Averbeke et al. 2011). However, SIS in South Africa have consistently performed poorly and failed to achieve the development objectives of sustaining rural livelihoods, partly due to low and unsustainable crop yields. Improvement of crop yield can significantly contribute to reduction in poverty, as well as economic sustainability of smallholder irrigation. A good understanding of dynamics involved in smallholder crop production is critical for the development of appropriate interventions or strategies aimed at improving crop yields. At the field level, yield obtained in a given area is a function of management, biological and environmental factors. The biological factors mainly relate to plant pests, whereas environmental factors relate to climate and soils. Agronomic strategies can be refined in order to overcome environmental and biological challenges. Irrigation water mismanagement, pests and poor soil fertility are among the major challenges reported to be causes of poor yields on smallholder irrigation farms in South Africa.

On-farm field trials are important to evaluate improved agronomic practices under more representative and realistic farmer growing conditions. It is nearly impossible to simulate the exact circumstances as found on a typical smallholder farm through field trials that are carried out on-station. Hence, it is routine practice for agronomists to carry out technology demonstration or evaluation trials on farmers' fields. On-farm trials serve to validate agronomic interventions within the targeted end-users' environment, but can also provide an understanding of farmer willingness to adopt proposed practices. Whilst substantial scientific evidence was gathered through on-farm trials at Zanyokwe Irrigation Scheme in South Africa to demonstrate that high levels of productivity could be realized through improving agronomic management of crops, a number of unanticipated challenges in implementing research in the SIS were also noted. If not addressed, these could potentially derail efforts to conduct research towards improved productivity of these schemes, and elsewhere in smallholder farmer systems of Africa. In this chapter, a detailed account of these challenges and possible ways to address them is provided in order to guide future research efforts, based on experiences from Zanyokwe Irrigation Scheme located in the Eastern Cape Province of South Africa.

9.2 On-Farm Field Trial Challenges

The challenges experienced in Zanyokwe Irrigation Scheme are summarised via a flow diagram as presented in Fig. 9.1. These challenges are not unique to this irrigation scheme, but much similar to those generally experienced elsewhere in Africa, wherever on-farm trials are carried out on resource-poor smallholder farmlands.

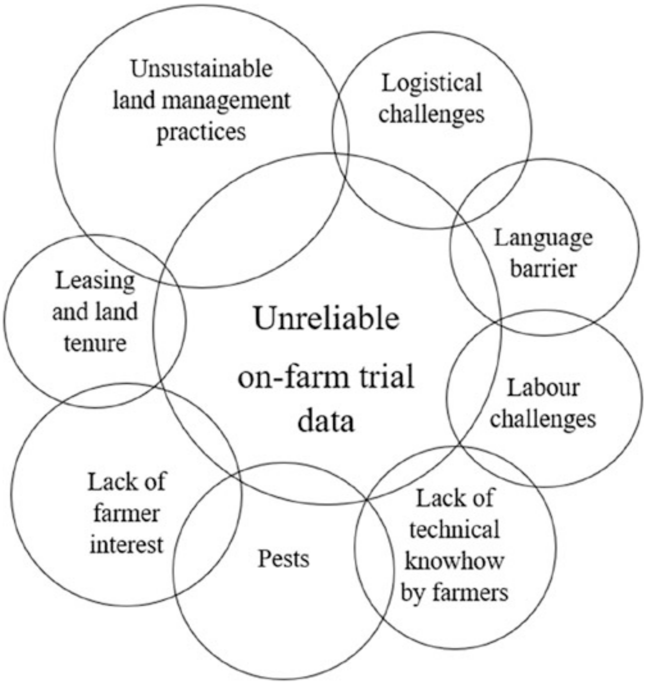

Fig. 9.1 Summary of inter-related challenges experienced through on-farm trials at Zanyokwe Irrigation Scheme in South Africa

9.2.1 Logistical Challenges

Smallholder farmers in the Eastern Cape Province of South Africa are in remote areas that are underdeveloped in terms of road networks. It was exceedingly difficult to access on-farm trial sites, especially during the rainy seasons of the Eastern Cape because of slippery and muddy roads. On rainy days, fields were mostly inaccessible by vehicle. This had a significant effect on timeous execution of tasks, data collection and monitoring exercises. Research trials in such areas would require proper all-terrain vehicles for ease of patrolling, yet this would have been too expensive for the project and had not been budgeted for.

9.2.2 Language Barrier Challenges

South Africa has many native languages, as much as 11. In the Eastern Cape Province, the native language is called *isiXhosa*. Literacy rates are low in South Africa (Posel 2011), and a majority of people in rural areas do not use the English language. In carrying out on-farm trials on SIS in the Eastern Cape, researchers encountered first-hand, the challenge of a language barrier. This was because the researchers were not native to the region, but from other places that did not use the *isiXhosa* language. Therefore, nearly all meetings between the researchers and farmers were ineffective, and sometimes chaotic. The inability to clearly communicate with the farmers may be one of the reasons for lack of farmer interest in embracing the new technologies. The project had not budgeted for an interpreter; hence it was not possible to recruit one.

9.2.3 Labour Challenges

The availability of labour at the household level for managing the trials was a major challenge. In the Eastern Cape households, the male is head of household and responsible for most farm activities, contrary to observations in other smallholder farming systems of Africa where women shoulder most of the work in the fields. Hence, the researchers observed that there was little participation of women in farming activities. Though most households relied on hiring, labour was not always available in the numbers, skills and work output required. Labour was not available on the days when farmers were engaged in traditional ceremonies, contributing to delays in planting and weeding, especially during the November/December period. Labour for weeding was so difficult to source from villages that surrounded the farming community, and weeds forced the researchers to write off some of the on-farm trials.

Labour shortage did not only affect weeding operations, but also planting operations as researchers relied on hired casual labour from the farming community. This meant that planning was very difficult and in many cases the researchers had to spend many days planting the trials by themselves simply because there was no labour available from the farming community. Except for trials where herbicides could be used for weed control as part of the experiment, there was a challenge where trials tested the effect of spatial arrangement of plants and weeding regime on weed dynamics and maize yield. Bearing in mind that on-farm trials are normally planted on bigger plots with more replications compared to on-station research, this meant that it was difficult to manage weeding in the trials as anticipated.

9.2.4 Leasing and Land Tenure-Related Challenges

The uncertainty of tenure in land issues has always been a hindrance to the advancement and progression of farming-based enterprises. Not only is this a problem for the farming individuals, but it is far reaching, as research efforts are also impacted by the uncertainty. Such was the case in Zanyokwe Irrigation Scheme. In our study, getting land to establish on-farm trials was a huge challenge. This was mainly because most of the farmers were not direct land owners, but leaseholders. At the same time, some landowners were fearful of losing their land through leasing it. They viewed land within the irrigation scheme as a highly prized asset and needed to hold on to it. This became a huge challenge when the researchers were identifying farmers who could host farmer-managed trials. Ideally, the researchers would have wanted to select farmers based on the ability to meet cost of land preparation, fertiliser, labour and evidence of record-keeping. However, most of the farmers who were capable and willing to host the trials did not own land.

9.2.5 Pest Problems

Pest problems experienced on-farm can be so severe to the point that trials can be totally destroyed, rendering the experimental data unreliable. This was nearly the case for on-farm trials on irrigation schemes in the Eastern Cape. Right at the onset of the trials at planting, birds, particularly crows (*Corvus corax*) fed on emerging seedlings, resulting in significant reduction in maize crop stands. This necessitated replanting in some cases, because the plant stand had been reduced so significantly that gap filling would not help. Replanting meant that timely planting was not possible, inputs such as fertilisers and seed were wasted and more labour was needed. This particularly affected planting date trials where timing is critical. These birds are endangered in South Africa, and so could not be poisoned. Scarecrows did not help much and the researchers resorted to hiring casual labourers to guard the fields for a period of about a week during the crop emergence period. In addition to birds, monkeys became a pest problem at harvest time. The major problem was that the monkeys tended to invade the fields during the night to feed on the nearly ripe ears (cobs) of maize. Researchers came to the point where they had no idea how to deal with this problem, especially given that the law forbids trapping or killing monkeys as is the case with the endangered crows.

9.2.6 Lack of Technical Knowhow

Lack of practical knowledge of irrigation water management among farmers and extension officers came up as an issue of major concern. During the course of the season, farmers did not practice purposive irrigation scheduling, resulting in a constant amount of water being applied throughout the growth cycle of the crops. This led to over-irrigation in early crop stages and under-irrigation in advanced crop stages. Farmers expressed the ignorance of the importance of irrigation scheduling, and it also appeared that the extension officers who assisted farmers (in the absence of researchers) did not have the required expertise in irrigation water management either. Indeed, experience by the researchers showed that in many cases, the farmers were better knowledgeable than the extension officers. In some cases, farmers irrigated overnight, resulting in flooding, waterlogging and an unnecessary wastage of water. The reason for irresponsible water management could be the fact that the farmers did not pay for the water. In addition, farmers used different nozzle types and sizes, and risers of different lengths in one lateral. Moreover, since the research was participatory adaptive, the researchers did not have much control on the amount of water applied because they could not be in the scheme every day of the week. These challenges meant that it was impossible to measure the amount of water applied to the crops for the entire period of their growth duration, as part of the data collection requirements for irrigation trials.

9.2.7 Unsustainable Land Management Practices

A common practice observed throughout the monitoring period was the burning of fields as part of land preparation for the subsequent summer season. This practice was mainly used as a weed control strategy, particularly in fields that would have been left fallow for some time. This practice resulted in the burning of plastic water hydrants in the field, leading to unavailability of water infield. Burning of fields results in the deterioration of organisms that are key to the ecological balance and functioning of the environment as well as destruction of their natural habitat. In addition to the deterioration of faunal and microbial organisms, burning results in top soil loss and erosion during periods of heavy rainfall (Gafur 2001).

9.2.8 Tillage-Related Crop Loss

When tillage is not done properly, crop and soil loss can be major problems. In Zanyokwe Irrigation Scheme, post-emergence weed control in maize was sometimes done using inter-row cultivation using a tractor-drawn cultivator. This unfortunately resulted in major crop losses, as some crops were uprooted by the cultivator due to poor timing of cultivation and planting rows which were not straight. Excessive tillage under irrigation can result in soil compaction, leading to salinity problems. In addition to accelerating the process of soil salinization and alkalization, irrigation water salinity also affects the available soil nitrogen, enzymes, microorganisms, nitrification and denitrification, all of which can affect soil N_2O emission (Tam 1998; Irshad et al. 2005).

9.2.9 Limited Understanding of On-Farm Trials by Farmers

Field monitoring and data collection is critical to measure the success or failure of an experiment or intervention. Because on-farm trials are carried out at sites that are far from where the researchers dwell, it is difficult if not impossible to monitor the trials as would be the case with on-station trials. Researchers rely on the good will and cooperation of the farmers hosting the trials as well as the surrounding community. Unfortunately, in our case, unregulated harvesting of green maize (also commonly known as table maize, green mealies, maize on the cob or garden maize), by hawkers, whose aim was to select the best cobs, resulted in difficulties in the documentation of yield, as this was done in the presence of the farmers only, without the researchers. Often, control plots, which were not meant for harvesting, also fell prey to uncontrolled harvesting due to chaotic picking by hawkers aided by little understanding of the importance of controls and sometimes greed by the farmers. As such, yield data was often missing or incomplete in some trials, thus rendering the data unsuitable for scientific exploration. Additionally, persistent theft of the produce forced the researchers to harvest some of the on-farm trials prematurely, and this obviously affected the accuracy of results. Therefore, this proved to be a cause for concern on on-farm trials which negatively affected collection, documentation and analysis of observations.

9.2.10 Negative Farmer Attitudes Towards Research Trials

Farmers' understanding of the need and possible benefits that a project may bring often shapes their attitudes towards a project. Participatory approaches of research methods have been shown to be effective as they not only increase accessibility by farmers to externally developed technology as well as enhancing local capacity to address problems and devise solutions, but also result in the joint development of relevant and appropriate technology by farmers and scientists (Chanie 2015). On the other hand, lack of feedback, which is usually the case when data has been collected, creates farmer apathy. This observation was apparent at Zanyokwe Irrigation Scheme as farmers often expressed what appeared to be a negative attitude towards the researchers. It emerged that the farmers' negative attitude was due to their previous experiences with student researchers who did their research in the same irrigation scheme. The scheme was over-researched, mainly by students doing social science and business-related studies such as those doing Agricultural Economics and Agricultural Extension at the local University. Because these students mostly rely on interviews to collect data, they would at times ask questions which would raise the expectations of the farmers, yet would not give anything to the farmers. The farmers also did not receive any feedback from previous survey studies and overtime, did not see the benefit of investing their time in answering survey questions. The farmers felt that these researchers just wanted to come and get what they wanted without offering any help or solutions to their problems.

9.3 Increase in Productivity Based on Scientific Advice at Zanyokwe Irrigation Scheme

Maize is the most important summer grain crop in terms of both the cultivated area and the number of growers in most SIS in South Africa. The predominant cropping patterns are a monoculture of maize, or maize in rotation with either cabbage or butternut (Fanadzo et al. 2010). Yields obtained in SIS have generally been observed to be below optimum due to an interaction of factors (Crosby et al. 2000; Van Averbeke et al. 1998; Fanadzo 2010). Monitoring of 20 farmers over a 3-year period at Zanyokwe Irrigation Scheme showed that cropping intensity averaged only 48% (potential is 200%) and that the yields of the two main summer crops, grain maize (2.4 t/ha) and butternut (6 t/ha), were only 20–30%, and 20–24% of the potential for the two crops, respectively (Fanadzo et al. 2010). Subsequently, on-farm field trials were carried out to demonstrate the importance of agronomic management practices in improving the yield of various field crops over an extended period. Table 9.1 summarises main findings with respect to the effect of best management practices on crop yield at Zanyokwe Irrigation Scheme.

Table 9.1 The effect of best management practices on yield through on-farm trials at Zanyokwe Irrigation Scheme in South Africa

Production challenge	Best management practice	Summary of results
Low profitability of maize crops	Shifting from grain to green maize cultivars	Farmers sold green maize at an average price of R2.00 per cob, with a gross income of R80 000.00/ha at a time when they could make only R2 500/ha from a tonne of grain. Green maize also had a shorter production cycle, leaving enough time to prepare for winter planting. With green maize, there was no need to invest in labour for harvesting, processing and packaging as customers purchased the green cobs directly from the field
Bird damage and high seedling mortality of maize	Transplanting maize rather than direct seeding	Transplanting resulted in a significantly higher crop stand of 96% compared to direct seeding, which achieved 48%. Transplanted maize had shortened growth duration in the field, reaching flowering stage 11–15 days earlier than direct seeded maize. The net benefits were R15 005/ha for transplanted maize and R6 232/ha for direct seeded maize. All farmers were in favour of transplanting, citing bigger cobs, early maturity and the absence of bird damage
Weed challenges in butternut production	Pre-plant weed control with herbicides and increasing planting density from 10,000 plants/ha to 30,000 plants/ha	There was significant reduction in weed pressure. This resulted in the increase of yield to 26.7 t/ha. Previously, no marketable butternuts could be obtained under heavy weed pressure
Irrigation water management challenges	Using the wetting front detectors	The wetting front detector was an effective tool for helping farmers to visualise how well their last irrigation filled the profile. This helped to make irrigation management tangible and realistic for the farmers
Poor choice of planting dates and cultivars for cabbages	Early summer planting and appropriate cultivar choice	When farmers started to produce the crop in summer on the advice of the project team, they realised higher income as each cabbage head could be sold at an average R4.00, whereas in winter, the maximum that can be charged per head was R2.50 at the time

(continued)

Table 9.1 (continued)

Production challenge	Best management practice	Summary of results
Poor cultivar choice	Adoption of higher yielding maize hybrid cultivars as opposed to open pollinated varieties	The new hybrids such as SC701 could yield as high as 5 t/ha more grain yield as compared to the open pollinated varieties, which had a yield of 3.5 t/ha
Low plant population density	Increasing planting density	Increasing planting density above farmers' practice of 40,000 plants/ha to 60,000 plants/ha resulted in more marketable green cobs and up to 30% higher grain yields

Source: Fanadzo and Dube (2019)

9.4 Lessons Learnt

9.4.1 Importance of Appropriate Research Approaches

As already shown, participatory approaches in the design and implementation of on-farm trials are key in addressing the complex issues in on-farm research. The time spent conducting the study, which was 5 years, allowed for the development of trust between the researchers and the farmers, such that the farmers started to open up and confessed that they sometimes lied to the social science researchers or gave them the answers that they thought were expected because they felt that this was a waste of time. The farmers expressed that they need to feel that they are partners who can contribute something worthwhile, as indeed they do.

9.4.2 The Importance of Understanding Farmer Attitudes and Perceptions

On-farm trials are mainly conducted to come up with best management practices for the farmers and by the farmers. However, it is important to acknowledge that not all people residing in farming communities are indeed interested in farming. Failure to acknowledge the diversity of the smallholder agricultural sector may be a serious barrier to implementation of appropriate solutions. There is an assumption that all people residing in African farming communities such as irrigation schemes are indeed interested in pursuing farming as a business or a major source of livelihood. This proved to be simply not the case in SIS of the Eastern Cape. An observation was that there were indeed "farmers" who were not interested in farming, but needed benefits from the researchers, such as input handouts and financial benefits from the sale of produce from the trials after data collection. For instance, some farmers sold the fertiliser bags handed out to them by the researchers, or bags of fertilisers were seen dumped and wasted in the scheme. It was indeed a tall task to ask the farmers to help the researchers to monitor and manage the trials as part of the participatory adaptive research methodology used. It is probable that previous government farmer support programs where everything was done for the farmers and all the farmers did was to provide the land, had created a dependency syndrome among the farmers. When the researchers arrived, the farmers were looking for more financial benefits in terms of what they would get out of the partnership.

9.4.3 Issues Arising

The original assumption by the researchers were that farmers were not aware of the benefits of the improved agronomic practices such as use of herbicides, improved and appropriate cultivars and proper fertiliser management in their crop production; hence, they were obtaining poor yields. It can be stated that the various non-experimental challenges observed by the researchers mirrored, in most cases, the same challenges which the smallholder farmers faced when attempting to produce crops on the irrigation scheme. For instance, all farmers (about 80 in total) in the entire irrigation scheme (about 473 hectares irrigated area) relied on hiring one of two tractors operating in the scheme. Several new questions therefore arise. Could the pest problems with crows and monkeys be a major reason for farmer disinterest in crop production on the scheme? Or perhaps the rampant theft of produce? Would farmers still be interested to invest in inputs such as fertilisers and labour for weeding and irrigation on the crops, when they know very well that the produce would be stolen? The reasoning here was that the farmers may have been aware that they may not be able to harvest anything from their fields because of theft and pests; hence, they were reluctant to invest in crop management efforts that would increase crop yields. Would the results have been better if there was better communication (in terms of language) between the farmers and researchers? Could the research have been more successful if there was an involvement of female members of the households? Could the combination of all these challenges be the reason for farmers' lack of interest in agronomic management of the crops?

9.4.4 Interdisciplinary Approach to On-Farm Research

It is proposed that an approach that addresses all the possible farmer challenges simultaneously would be the ideal strategy for farmer engagement in scenarios such as these. Interdisciplinary research can be defined as "a mode of research by teams or individuals that integrates two or more disciplines or bodies of specialized knowledge to solve problems whose solutions are beyond the scope of a single discipline or area of research practice" (Aboelela et al. 2007). Instead of working independently, agronomists should work collaboratively with other socioeconomic researchers for dealing with various socioeconomic challenges of a typical farmer. The disciplines that should be involved could include sociologists (farmer engagement and gender roles), agricultural engineers (transport and logistics) and ecologists (theft by monkeys). Another lesson is that on-farm trials in smallholder farmer systems should be well-funded and budgeted for. Additional budget items could include all-terrain vehicles, services of an interpreter (who understands agriculture), fencing of fields against theft and guarding services. Additionally, efforts must be made to empower farmers so that they become independent entrepreneurs who do not rely on outsiders to run their farming business.

9.5 Conclusion

On-farm agronomic trials yield several benefits and are the most practical way for farmers to learn how practices, products and equipment will work in cropping systems under their circumstances. They are important for validating agronomic interventions aimed at improving yield on smallholder farms. However, the benefits can only be realised when the trials are managed tactfully, and farmers consider themselves as major stakeholders and when major obstacles are addressed. Our 5-year practical experience showed that the major challenges relate to logistics, data collection and the attitude of farmers towards the research. We concluded that these challenges could be overcome through an interdisciplinary approach to the agronomy field trials research. In this case, a holistic research design for the on-farm trials, which addresses both agronomic and socioeconomic challenges of the farmers simultaneously, is proposed.

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Part II
Water Resources in Agriculture and Fisheries

Chapter 10
Agricultural Water Resource Governance for Sustainable Food Production: Lessons from Developing Economies

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Abstract Agricultural water governance systems are critical in shaping the long-term sustainability of the Food-Energy-Water (FEW) nexus. The agricultural sector in most developing countries is characterised by poor collective management of water resources, collapse of infrastructure and low returns. The Institutional Analysis and Development (IAD) framework and Ostrom's eight institutional design principles have been reviewed to establish their relevance in enhancing the performance and effectiveness of institutions governing agricultural water resources. The water and agricultural sectors in Africa are dominated by informal water governance systems. As such, user participation in collective management of water is mainly driven by informal arrangements ahead of formal policies. The involvement of water-user associations as formal water-governing institutions and their linkages to the local irrigation committees and agricultural production cooperatives is weak due to lack of clarity among farmers on how the water associations operate. Weak regulatory instruments, characterised by poor rule enforcement mechanisms, lack of property rights and lack of water security, negatively impact irrigation water management among smallholder farmers. Farmer training and capacity building processes are required to enhance coherent institutional linkages at the local level. While technical interventions like provision of lockable water supply infrastructure ensure easy control of unsanctioned withdrawal of water, upgrading of supply

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capacity and water measurement devices can be pursued at the scheme level. Furthermore, the focus on improving the institutional arrangements, management capacity and the governance systems can achieve better water allocation and enhance sustainable food production.

Keywords Water governance · Institutional arrangements · Water management · South Africa

10.1 Background

Smallholder irrigation in South Africa is governed by both formal and informal institutional arrangements. Ostrom (2007) defined irrigation institutional arrangements as the set of rules for supplying and using irrigation water in a particular area. These can be measured by the capacity of water institutions to protect water resources, enforce exclusivity and accountability, and ensure compliance with water use regulations (Hassan 2011). On the other hand, inefficient institutions are characterised by weak enforcement mechanisms, unequal distribution of resources, lack of accountability, wide-spread free-riding (Wilson et al. 2013) and a tendency to discourage user participation and investment in the management of common pool resources (Kirsten et al. 2009; Sharaunga and Mudhara 2018). The paradigm shift from the centralised and state-driven natural resource management regimes to community-based management regimes in developing countries (Dorward and Omamo 2009) is articulated in the theories of collective action and common property resource management (CPRM) (Ostrom 1991; Perret 2002). The shift is also influenced by the adoption of Irrigation Management Transfer (IMT) and Participatory Irrigation Management (PIM) approaches within the water sector worldwide (Perret and Geyser 2007; Gomo et al. 2014; Dirwai et al. 2018).

In South Africa (SA), the water sector is regulated through the National Water Act (NWA) of 1998, which prescribes the need for the establishment of appropriate water management institutions to ensure smooth management of water resources. The most common formal avenues to implement the NWA include the Catchment Management Agencies (CMAs), Water User Associations (WUAs) and the Water Tribunal (WT) (DWAF 2004). Furthermore, the informal institutions such as local irrigation committees and individual involvement in water management form an integral part of the institutional arrangements governing irrigation water in South Africa (Gillitt et al. 2005; Dlangalala and Mudhara 2020).

Institutional arrangements governing the use of community irrigation water and its access to members differ depending on the type and water source (Saleth and Dinar 2004; Backeberg 2005). However, according to Gakpo et al. (2001), the decision support and management tools for the proper functioning of the formal institutions including CMAs and WUAs in South Africa may be inadequate. The need for capacity building and education to enable the water management institutions to function effectively has been identified (Backeberg 2005; DWAF 2006;

Chipfupa and Wale 2018). This is in response to a gap in water management at the local level.

Drawing from several cases that attempted to contextualise the challenges of smallholder farmers, there is consensus that most smallholder irrigation schemes (SIS) in South Africa and other developing countries perform poorly and face collapse (Perret 2002; Denison and Manona 2007; Fanadzo et al. 2010). The problem of under-performance of schemes emanates from infrastructure deficiencies due to inappropriate planning and design (Dirwai et al. 2018), poor operational and management structures, lack of technical know-how among irrigators, weak participation of irrigators in water management (Sharaunga and Mudhara 2018), inadequate institutional structures and inappropriate land tenure arrangements (Perret 2002). Furthermore, the scheme revitalisation and rehabilitation programme that aims to upgrade the technical, managerial and institutional arrangements of the schemes to enhance resource utilisation and water delivery is yielding minimal benefits (Perret 2002; Gomo et al. 2014). Scheme revitalisation and rehabilitation in South Africa tend to be biased towards irrigation infrastructure and technology improvement through scheme rehabilitation and less focus is given to addressing human capacity and institutional development at local level (Denison and Manona 2007; Maepa et al. 2014). The approach fails to address institutional challenges at scheme level and contributes to repeated failure of state-funded interventions due to perverse behaviour by water users (van Averbeke et al. 2011).

The chapter analyses how various governance and institutional arrangements in managing agricultural water at smallholder level can enhance food production as well as food security, drawing lessons from case studies in developing countries. The characteristics and performance of governance systems, resource systems, resource users and the resource unit have been evaluated to identify the required institutional innovations in the context of smallholder irrigation management. Alternative governance mechanisms and the policy implications are also presented.

10.2 Unpacking the Food-Energy-Water Nexus

According to Hoff (2011), the Food-Energy-Water nexus (FEW) embraces the natural resources and their systems, the associated physical infrastructure, the institutions, and socio-economic systems that develop, use, guide, benefit from, and impact conditions in the WEF. It is important to note that understanding the linkages within the dynamic, nested, hierarchical and evolving systems that comprise the FEW nexus and considering them in decision-making and appropriate policy could increase the efficient use of scarce resources (Wang et al. 2015). This has a potential to improve the quality and security of food, energy and water supplies, as well as provide opportunities to grow economies and provide support for livelihoods (Wang et al. 2015). The Water-Energy-Food (WEF) nexus is a framework that captures the inter-relations, synergies and trade-offs between the demand on water, energy and food, in the context of the emerging constraints of sustainable development in particular regions or systems (Scott 2015). However, the nexus approach is based on a systems thinking and often uses the socio-ecological system as a primary point of reference. Although the WEF nexus is argued to be valuable for understanding complex systems, and for decision making to achieve improved livelihoods and wellbeing of households and sustainable development, it relies more on a sound application of the socio-ecological system approach. When one looks at the governance of water sector, one framework that was formalized in the early 1990s was Integrated Water Resources Management (IWRM), which is still battling to solve the challenges in the sector, hence the need to continuously explore other frameworks to unpack the global challenge affecting water and the food security of countries.

10.2.1 Conceptual and Analytical Framework

To enhance the understanding of the institutional arrangements (IA) and governance systems in water management, the Institutional Analysis and Development (IAD) framework was central to the analysis. The IAD framework, developed by Ostrom (1990), has been widely applied, for example, by Kirsten et al. (2009) and Sserunkuuma et al. (2009) to analyse the management of Common Pool Resources (CPRs). The IAD framework presented in Fig. 10.1 enables the organisation and analysis of variables that affect patterns of interactions and outcomes observed at project or programme level.

Ostrom (1990) argued that the environment, which includes the governance system, resource system, resource unit and the resource users, can only have positive impact if sufficient conditions exist in the management of CPRs (Fig. 10.1). As such, Ostrom (1990) developed eight design principles sufficient for effective management of CPRs: (1) the existence of clearly defined boundaries, (2) clarity on proportional sharing of costs and benefits, (3) mechanisms facilitating collective-choice autonomy to serve as necessary conditions to deal with appropriation and provision problems, (4) congruence between resource appropriation and provision rules, (5) graduated sanctions, (6) the establishment of dispute-resolution mechanisms, (7) the recognition of user rights to self-organize and (8) the need for appropriate coordination among relevant groups. The core design principles have a wider range of application and are relevant when people must cooperate to achieve shared goals (Wilson et al. 2013). In the case of irrigation water irrigation management, absence of principles 1, 2 and 3 leads to the collapse of CPRs due to poor maintenance, while lack of sanctions and monitoring mechanisms may lead to free riding and unfair distribution of canal irrigation water. The ultimate consequences are negative and are characterised by low agricultural output, poor household food security, low income flows and subsequent collapse of the infrastructure.

However, possible limitations of both the IAD framework and the Ostrom's design principles should be noted. For instance, Wilson et al. (2013) highlighted the weak emphasis on social variables and its failure to incorporate the impact of

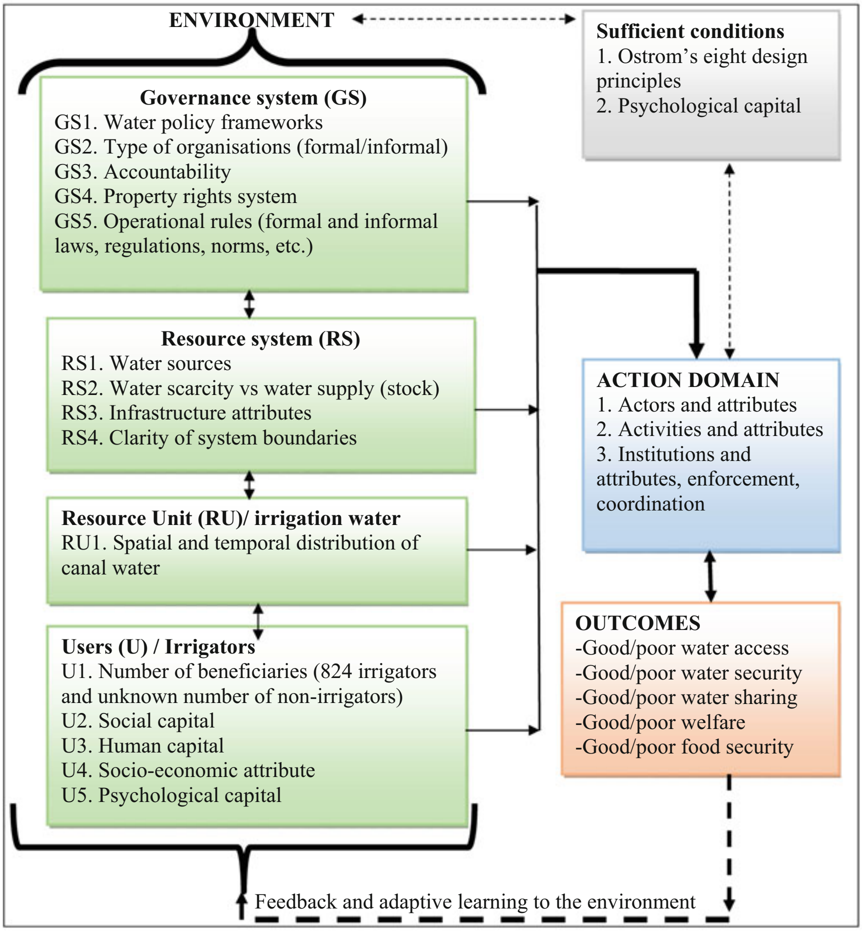

Fig. 10.1 IAD framework showing institutional linkages in canal water management. Source: Adapted from Ostrom (1990), Dorward and Omamo (2009) and Sarker (2013), Muchara (2014)

global problems, such as climate change, water scarcity and food insecurity. Furthermore, the eight design principles are criticised for not accounting for other conditions and constraints, like market integration, globalisation and rapid economic development (Wilson et al. 2013). Furthermore, both the IAD and the eight design principles do not recognise the importance of psychological capital, which was defined broadly by Luthans et al. (2007) as the motivation of individuals through self-efficacy, optimism, hope and resilience. Psychological capital is considered critical in influencing the outcomes of CPR management, including the utilisation of irrigation water (Phakathi and Wale 2018). Rather than focusing on any one individual fact in particular, it is expected that the combined motivational effects are broader and more impactful than any one of the constructs individually. It can, therefore, be argued that positive psychological capital greatly influences human behaviour of each user and their interactions in the management of CPRs, hence its inclusion as the ninth sufficient condition in the framework.

10.2.2 Agricultural Water Access and Management System in Developing Economies

Smallholder farmers in southern Africa face challenges of water shortage emanating from low rainfall and seasonal fluctuations of water levels in the rivers, especially the low levels experienced during the winter and dry seasons. Where dams exist in the upper sections of the rivers, this necessitates the opening of feeder dams located at these upper part of the rivers to boost water supply to downstream users. On the other hand, commercial farmers equally face similar challenges. However, due to their resource endowments, they often have means to access other water sources like ground water to supplement river water. Furthermore, access to agricultural water supply by the smallholder and commercial farmers varies partly because of the way the two groups are organised. Smallholder farmers often operate as individuals or cooperatives. The major bottleneck is that this group of farmers is usually not registered as formal entities, and there may not be legally recognised as formal water users. This is slightly different from commercial farmers who operate privately but are well organised into water user associations and irrigation committees to manage their common pool water resources. In the case of South Africa, this group of commercial agricultural water users makes official requests for the opening and closing of the feeder dams, which may not be possible with smallholder farmers. Although smallholder farmers also benefit from the same water by virtue of sharing the same river with commercial farmers, challenges of enforcing exclusivity rights against non-registered water users complicates the approximation of quantity demanded. There have been disputes between commercial farmers and smallholder farmers, with the former being accused by the latter of having an unfair advantage over the water resource (Muchara et al. 2015). This is worsened by the fact that some commercial farmers pump water directly from the main canal and river, upstream from the diversion points. As such, smallholder farmers complain that commercial farmers pump too much water from the source and little water is left to flow into the common pool infrastructures like rivers and canals. This shows that institutional arrangements and governance systems differ to the extent in which they address water use efficiency and equity objectives (Shah 2005). The need for communities to organise water provision, i.e. involvement in the design, construction and maintenance of infrastructure, is crucial that positively contributes towards irrigation water management. The characterisation of the IAs influencing water management within the agricultural sector was done using the IAD framework (Fig. 10.1). Essentially, clearly specified water-use entitlements and infrastructure to deliver water at negligible economic, social and ecological externalities are critical for effective irrigation water management at a local level. The following sections, therefore, scrutinise the institutional arrangements by focusing on the influence of governance systems, resource systems, resource units and resource users on the water management outcomes (water access, food security, increased output etc.).

10.2.2.1 Irrigation Organisations and Water Governance Systems (GS)

An important issue is how the water legislative policy in South Africa and other developing countries is linked to the current governance systems in irrigation schemes and how the whole system impacts the provision of water to smallholder irrigation farmers. Shah (2005) defined various government agencies, international agencies, government's water policy and water-related laws that directly or indirectly deal with water as the institutional environment (IE). The IE, closely linked to IAs, is defined by Shah (2005) as humanly devised rules that govern the behaviour of water-users. Understanding the linkages between water policies and users is critical because lack of user cooperation, especially due to a knowledge gap about statutory instruments between users and regulatory bodies, can hamper the public allocation of resources.

In the case of South Afirca, 23 years after the adoption of the National Water Act (NWA) of 1998, not all water management structures are in place. This agrees with Backeberg (2005) who noted in his theoretical analysis of the South African NWA of 1998 that the reform process may take 10–20 years for the design of appropriate institutions and implementation of the policy. Due to non-compliance of most smallholder irrigation schemes with the legal requirement to be registered as water using entities with the Department of Water Affairs (DWA), the Minister of Water Affairs in South Africa, through the NWA of 1998, has the power to reallocate all or portion of the water in rivers and weirs to other registered users, without consultation with the unregistered farmers (DWAF 2004), consequently exerting pressure on production activities in schemes. For instance, starting 2012, water from the Mooi River weir in KwaZulu-Natal Province of South Africa was made available to supply domestic water to Gudwini community, which was about 30 km from the scheme (Muchara et al. 2015). Although domestic allocation takes precedence over all other water uses, recognition of the scheme as a water user could have influenced the quantity of water to be reallocated or even the point of abstraction could have been constructed after the weir to avoid interference with water supply for irrigation purposes. Legal recognition of the irrigation schemes is, therefore, critical to improve agricultural water security and access at local levels.

Most irrigation schemes are governed by both formal and informal management systems, which are embedded within each other. However, the problems associated with irrigation water access in most government-funded schemes in Southern Africa arise from poor management of infrastructure, inadequate enforcement of regulations and subsidised prices. These challenges result in poor irrigation performance (Perret and Geyser 2007). Furthermore, lack of proper business plans as per legislative requirements during formation of Water User Associations (WUA), poorly articulated transfer of ownership and poor capacity building for collective management of the schemes can all be attributed to the low success rates.

Drawing on examples from South Africa's KwaZulu-Natal Province, although informal arrangements that include the traditional norms and values, belief systems and kinship are important, they are not directly involved in securing water rights by the irrigators (Muchara et al. 2015), especially where government agencies (Catchment Management Agencies (CMA), Water User Associations (WUAs), etc.) and water policies are involved (Muchara et al. 2015; Sinyolo and Mudhara 2018). This is critical for smallholders, where farmers misunderstand the RSA water policy and perceive formation of formal structures like WUAs as a way by the government to introduce water levies on smallholder farmers, despite the anticipated benefits of securing water rights for the users. Change of mind-set and building on positive psychological capital through capacity building is therefore important among smallholder irrigation water users.

Most countries in Southern Africa (South Africa, Zimbabwe, Zambia, Mozambique, Malawi, etc.) are enforcing formal structures that include formation and operationalisation of Catchment Management Agencies (CMAs) and Water User Associations (WUAs). These formal institutions come with their own institutional and management challenges (Gadzikwa 2008). Firstly, there are individual farmers of the schemes who may not be prepared to be part of the associations but still expected to have access to the same amount of irrigation water as the members. In the case of Mooi River Irrigation Scheme and Tugela Ferry Irrigation Schemes in South Africa, some farmers located at the upper section of the canal/scheme, who were perceived to be accessing more water than their downstream counterparts, were less willing to be part of the WUA and were interested in preserving the *status quo* while the tail-end farmers, who were facing more water supply challenges, were willing to take part in the change process. This is in line with Diaz and Rojas (2006) and Madani and Dinar (2013) who concluded that head and tail-end farmers have opposing motivations when it comes to cooperating with regulatory authorities. As long as water is available in the common pool canal or river that supplies a group of farmers, anyone can access the resource; hence, the members of the WUA do not receive any additional benefits over non-members. Secondly, in countries where smallholder farmers do not pay for irrigation water usage, their inclusion as the members of the WUA means they have equal access rights with commercial farmers in the area, who pay for irrigation water. Thirdly, the nature of irrigation infrastructure used by smallholder farmers makes it difficult to measure actual volumes of water used by individual farmers unlike the sprinkler systems used by most commercial farmers. Whilst furrow irrigation is cheaper to maintain and much easier to operate (Crosby et al. 2000), water budgeting and equitable allocation remains a challenge due to lack of measuring devices (flow meters) and uncoordinated cropping patterns among smallholder farmers in the scheme. This is worsened by non-adherence to water sharing rules or scheme irrigation rosters and the widespread unsanctioned diversions of water from the common pool canals/rivers, which negatively affect the consistency of supply and consequently crop production.

Furthermore, the main concept underlying IMT through formation of WUAs includes high pay-offs if successful (Shah 2005). Success is measured in terms of revenue collection, cost recovery mechanisms, equity and improved coordination of water users, which were not being met due to a number of factors including non-cooperation among users and resource constraints. For instance, Shah (2005) noted that IMT tended to be smooth and relatively effortless where the irrigation system is high-performing and average farm size is large enough for command area farmers to operate as agri-businesses. The smallholder irrigations schemes in Southern Africa resemble a complex system, where farmers in the command area have small land holdings with less output, making it a challenge to bring them together to negotiate. Although smallholder farmers qualify to access government financial assistance, the long-term sustainability of the WUAs might need to be considered, given the scepticism of smallholder farmers over the ability of the WUA, as a potential state organ, to collect irrigation maintenance fees and water levies from farmers.

Accountability System (GS.2) and Operational Rules (GS.4) with the Agricultural Water Sector

Accountability systems (GS.2) are critical for effective collective management of irrigation schemes. The inclusion and subsequent participation of resource users in the monitoring and enforcement of operational rules through rotational management can be adopted as a possible strategy to improve scheme management. Through rotational management, irrigators can be subdivided into smaller groups to monitor the behaviour of other users from a given canal section and reporting opportunistic user behaviour to the local irrigation management committee for sanctioning. By so doing, every member becomes accountable and irrigation water management might improve.

The informal governance procedures are guided by rules that are often not written and enforcement is weak (Gadzikwa 2008); hence, some members served on the committees for more than 10 years without being re-elected. The challenge of informal governance arrangements are that there are often no incentives to join the committees (Van Der Zaag and Rap 2012); hence, some potential committee members were not willing to take up responsibilities and therefore bad governance persists in some irrigation schemes.

The clarity of operational rules (GS.4) determines the success or failure of CPR management where large numbers of beneficiaries are involved (Agrawal 2001). Although irrigation committees serve as recognised and accepted institutions to address the problems of provision and sharing of irrigation water, a number of players are involved in the formulation and enforcement of water use rules. Some agencies operating within or around farming communities like irrigation committees, traditional leadership, canal attendants and ordinary members follow unwritten rules defined by the community together with irrigation water users. Therefore, the enforcement of the rules and the effectiveness of the agencies in managing local water-use are compromised.

Property Rights System (GS.3) in Agricultural Water Sector

Clearly defined property rights (GS.3) of water and land can improve ownership and accountability (GS.2) among users (Ostrom 1990). A number of case studies (Muchara 2014; Fanadzo 2012; Sinyolo and Mudhara 2018) revealed that no entity has a complete bundle of rights over all or some of the components of the resource system (RS) and units (U). Smallholder irrigators in South Africa, Zimbabwe and Zambia have rights to use land and water, but the access is not privately secured; hence, land can be reallocated to other users by traditional authorities if it is deemed to be underutilised. Furthermore, water-use security is not guaranteed, and the "use it or lose it" principle applies to all common pool water users. Lack of clarity of the water access rights system (GS.3) negatively impacts water management due to unreliability of supply and lack of commitment by some users to invest in CPR infrastructure maintenance. Farmers are hesitant to commit financial resources to upgrade their water infrastructure due to non-exclusivity of the costs and benefits, with a potential impact of lowering resource productivity. This is consistent with Perret and Geyser (2007), who noted that smallholders in South Africa view irrigation schemes as government property, and as such maintenance and upgrading of the canal is assumed to be government's responsibility. This shows that positive psychological capital among irrigators is weak and its enhancement through capacity building workshops and training can improve farmers' attitude towards collective infrastructure maintenance.

10.2.2.2 Resource System and Irrigation Management in Smallholder Irrigation Schemes

A resource system represents a stock of water and irrigable land that is available for everybody in the community (Sarker 2013). Considering the case of canal water in some irrigation schemes in South Africa, users find it nearly impossible to exclude individuals from the resource system (Muchara et al. 2015). This was mainly due to weak institutional by-laws regulating water access for non-participating members. The existing scenario was such that appropriators took advantage of any improvements on the system, even without making the required contributions. Furthermore, there is a strong linkage between land access and access to canal water in most irrigation scheme.

Access to irrigation water is partly influenced by owning an irrigable piece of land within the canal's command area. However, there is often no proper accountability and record keeping systems to account water usage; hence the technical complexity of defining, with precision, the quantity of water available and demanded for crop production compromises output by farmers. This limited capacity of local communities and canal water users to manage water efficiently affects production and ultimately food security (Muchara et al. 2014). Although the traditional authorities had the power to reallocate idle irrigation land within the scheme to the landless community members, cases of reallocation are rare in rural communities due to close ties of families (kinship) and inheritance issues surrounding land ownership in Southern Africa. Conflicting objectives of land access and utilisation *vis-a-vis* inheritance issues at a household level to guarantee access to land by family members in the future and immediate productivity concerns are a challenge impeding the productivity potential of smallholder schemes in Southern Africa.

10.2.2.3 Resource Unit in Irrigation Water Management Systems

The study considers irrigation water as the resource unit that requires community or user management. The challenge of managing irrigation water stems from its attributes, which include high mobility, highly subtractable and having an economic value born from the cost of infrastructure maintenance (Sarker 2013). Most schemes draw water from rivers, and it is diverted into fields by pumps or gravity-fed canals that supply the fields. Where water enters the common pool canals, it changes from a public good to a common pool resource (CPR). Such cases demand high management and monitoring mechanisms. Due to high subtractability, when water is available in the canal, the motivation for users is to abstract it. Furthermore, water savings made by an individual and “left” (stored) in the storage reservoir or canal may at a later stage, be used by another operator deemed to have a higher priority of use at that time (Safarzynska 2018). Lecler (2004) referred to this outcome as the “use it or lose it” mind-set. This phenomenon is inherent in the common property resource (CPR) and consequently diminishes the farmers’ incentive to save water. Apart from the potential for recurrent conflicts, the major problem affecting effective water conservation and demand management strategies on canal water is lack of rule enforcement and compliance among water users. This might be because individual users have very limited or no control over water abstraction by other beneficiaries.

10.2.2.4 Resource Users and the Decision-Making Process in Irrigation Water Management

The effectiveness of water governance structures can be assessed on how diversity of interests is considered during the decision-making process. In this context, Wilson et al. (2013) emphasize two elements in the process of balancing interests: getting everybody truly represented in the decision-making process and facilitating the negotiation process by the timely distribution of credible, easy-to-access and understandable information, and by ensuring that all stakeholders’ problems and interests are catered for. It is important to note that user-based allocation of water is undertaken through collective management of water sources. However, low level of cooperation among scheme members hampers infrastructure maintenance, resulting in poor allocation of the scarce water resource among users (Gomo et al. 2013). Failure to identify and develop positive psychological capital among farmers was one of the factors leading to poor cooperation among farmers. The transaction cost of managing a large group size is the other institutional factor negatively affecting participation in collective activities. Moreover, lack of clearly defined water distribution rules and mechanisms and non-compliance to appropriation rules by irrigators was resulting in water allocation inefficiency and poor performance of irrigation schemes.

10.2.2.5 Importance of Positive Psychological Capital in CPR Management

According to Luthans et al. (2007), the major components of psychological capital allow resource users to have confidence (self-efficacy), make positive contributions (optimism), persevere toward goals (hope) and build a sustaining effort, allowing them to bounce back to attaining success when faced with obstacles and adversity (resilience). The notion that smallholders in most communally managed schemes that were/are still being funded by the government regard the infrastructure as belonging to government (Perret 2002) can be changed through a mind-set shift, defined in the context of psychological capital (Chipfupa and Wale 2018; Phakathi and Wale 2018). Self-efficacy, hope and resilience are currently missing among farmers in MRIS, and this is evident as farmers quit farming and infrastructure deteriorates as farmers fail to participate in collective activities like irrigation maintenance.

Other indicators of low positive psychological capital among farmers include: the slow pace at which irrigators were willing to join and participate in the local WUA for the fear of being charged water fees, poor chances of farmers volunteering to serve as committee members leading to the prolonged stay of existing members, prevalence of free-riding and rule violation at the expense of other irrigators, and the prevalence of fallow plots across the scheme. Abandonment of plots by farmers citing water distribution challenges was viewed as a lack of resilience and hope (Chipfupa and Wale 2020). Farmers might tap into positive psychological capital to address water challenges instead of quitting or underutilising land. As such, the positive thinking processes brought along with psychological capital ensure effectiveness and success in the collective management of CPRs. A broader focus and adoption of strategies to enhance psychological capital among irrigators might improve irrigation performance (Cele and Wale 2018). It can be argued that technical skills training and the redesigning of irrigation policies without supporting the psychological component might yield minimum results in the long run.

10.3 Alternative Agricultural Water Governance Mechanisms for Increased Production

There are polycentric water governance systems of irrigation water in most schemes in South Africa, made up of local irrigation committees, traditional leaders, officials from the Department of Agriculture, Forestry, and Fisheries (DAFF), CMA, WUA and crop production cooperatives. The multiple organisations present a complex set of both formal and informal governance structures. However, clarity of organisational roles and relevance in water management was critical. Although focus could have been put on the improvement of operational rules, these may fail to yield positive results if the enforcement agencies are weak and not supported by the users. Furthermore, this has to be complemented by effective irrigation committees that can enforce operational rules for the benefit of the entire scheme. The effectiveness of irrigation committees can improve if the majority of users have the know-how of the best practices in irrigation management, which can be acquired through training. A combination of irrigator training and effective irrigation committees can ensure effective cooperation in water management and collective action activities, as stipulated in Ostrom's third institutional design principle. The study, however, found that irrigators were willing to improve irrigation management rather than having government authorities involved in the crafting and enforcement of local water management rules. Similarly, irrigators have shown their dissatisfaction with the involvement of political leadership in the management of irrigation water.

10.4 Conclusion and Recommendation

The chapter sought to understand the governance and institutional arrangements around smallholder water management by applying the IAD framework and diagnosing the prevailing institutional arrangements at against Ostrom's institutional design principles. Given the research design that focused on qualitative review of the institutional linkages, there was no test to identify which arrangement was superior to achieve good irrigation management. Some of the main findings include:

1. Rule-violations are common, yet sanctioning is rare among smallholder irrigators. The review, therefore, asserts that CPR users could tap into the deep-rooted social capital of kinship, trust and positive psychological capital to monitor each other's actions, providing little room for rule violation.
2. It is important to note that irrigators often had internal mechanisms to resolve the problems associated with the appropriation and provision of water to avert the tragedy of the commons. The state did not deal with various internal problems around water sharing, sharing of benefits and costs as well as compliance with operational rules, which were resolved by informal institutions. However, institutional mechanisms to ensure that additional benefits accrue to those who cooperate and comply with membership rules of user associations were missing and need to be developed.
3. Traditional leadership was found to have strong linkages with the socio-cultural aspects of rural irrigators. Therefore, there was a need to capitalise on the respect afforded to traditional leaders at a local level and integrate them into the formal water management structures. The anticipated benefits of such an action include

enhancing community participation in collective activities and possibly improving revenue collection mechanisms, which form the basis for the cost recovery objectives of the IMT and PIM.

4. Institutional by-laws clarifying ownership, access rights and specific incentives for water users need to be strengthened. To ensure equity in water allocation and effective behaviour monitoring, rotational management of canal water by all irrigators might have to be explored to ensure accountability.

While technical interventions like provision of lockable water supply infrastructure to ensure easy control of unsanctioned withdrawal of water is critical, upgrading of supply capacity and water measurement devices can be pursued at a scheme level, the focus on improving the institutional arrangements, management capacity and the governance systems can achieve better water allocation and minimize supply uncertainties. Without investing in building effective local institutions, promoting user cooperation and building positive psychological capital among users, engineering interventions for CPR management are often subject to vandalism and infrastructure decay. However, further research should focus on case-specific quantitative analysis to ascertain which among the water governance factors are statistically significant. The impact of psychological capital in the management of previously government-funded smallholder schemes is also recommended for further research.

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Chapter 11
Aquaculture and Fisheries Production in Africa: Highlighting Potentials and Benefits for Food Security

Yemi Akegbejo-Samsons

Abstract Fish is a staple food for Africans. Fish farming is one of the fastest growing food production sectors in the world. Despite significant natural resources and a high demand for fishery products, fish production in Africa is yet to meet up with this global trend. It is not an overstatement to say that Africa needs fish and fishery products. Fish is a source of animal protein as well as fatty acids and micronutrients for African peoples. The per capita fish consumption has declined over the past decade in Africa as populations grow and fewer aquatic products reach markets. This decline in fish supply has noticeable negative nutritional effects and alarming food insecurity. In Africa, because of poor materials and meagre production inputs, the optimal use of the resources has been impaired. Several enabling factors are required for expanding the potentials of aquaculture in Africa. These, among others, include (a) positive perception of aquaculture, (b) sound policies at the national level, (c) strong public institutions, (d) availability of nutrient inputs, (e) conducive investment policies to attract increased private-sector participation, and (f) access to credit for commercial-scale enterprises.

In this chapter efforts have been made to present the potentials and benefits of aquaculture and fisheries as cultured and captured food products that can be harnessed for human consumption and sustainable livelihoods in Africa. While aquaculture is an integrated production system which can be tested by laboratory scientific research, fisheries is more or less controlled by and from multi-faced dimensions. Based on the four dimensions of food security, viz. (1) food availability, (2) access to food, (3) utilization and (4) stability, aquaculture and fisheries could be a major contributor in enhancing and improving food security in Africa. Majorly, secured access to fish can produce positive impact, improved utilization and stability through improved technology adoption will also enhance and ensure national and rural food security in Africa.

Keywords Aquaculture · Africa · Fisheries · Food security

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11.1 Introduction

One challenge the world is facing is food security, though it seems as if the African continent suffers the most based on weak infrastructures for food production. There is poverty across the geographical clime which is evident in hunger and malnutrition of the African populace. It is not a new observation or belief that Africa is endowed with favourable climates and fertile soils, what remains is for the African leaders to direct and channel all the available resources (human and material) towards averting food shortage. Food production, especially African agriculture, is at crossroads. Production from both terrestrial and aquatic environments needs both continental and country attention if the African population is to survive in the current rampaging of climate change and corona-virus pandemic. Food security in Africa has always been poor and it may sadly continue to be of grave concern to Africa, Africans and the international communities.

This chapter examines and highlights the potentials and benefits of the aquaculture sector of the aquatic environments of Africa in the fight against the looming famine and food shortage in the continent. When considered from the four dimensions of food security, aquaculture and fisheries could be a major contributor in improving food security in Africa.

Majorly, secured access to fish can produce positive impact, improved utilization and stability through improved technology adoption will also enhance and ensure national and rural food security in Africa.

11.1.1 What Is Aquaculture and Fisheries?

Probably one of the most detailed definitions ever given to aquaculture is by the Japanese Resource Council, Science and Technology Agency. It states, "Aquaculture is an industrial process of raising aquatic organisms up to final commercial production within properly partitioned aquatic areas, controlling the environmental factors and administering the life history of the organism positively and it has to be considered as an independent industry from the fisheries hitherto" (Jhingran 1987). Technically, the terms "fishery" and "fisheries" only refer to the production of wild fish, while "aquaculture" applies to farmed or cultured fish. Both fisheries and aquaculture are included within the agriculture sector (USAID 2016).

However, from my own personal point of view, the simplest grassroot definition is that aquaculture is the farming or raising of fish, crustaceans, mollusks, aquatic plants, algae and other organisms under controlled conditions.

Aquaculture is inherently a resource-efficient means of cultivating food. This is possible in freshwater, brackish water and the marine. Aquaculture in the marine environments requires no land, and minimal fresh water. Fish are grown in the water; hence the effects of gravity are lessened and subsequently devote more energy towards growth and need less food per unit of production than animals on land.

Farming in the ocean gives us more advantages as it allows much more animal protein to be produced in the same area.

Oceans generally are not subject to the same extent of governance as land; however, many countries/governments undertake robust marine spatial planning, through which they can have better planning of aquaculture growth (WEF 2018).

Where and when critical habitats like mangroves, corals, seagrasses, etc., are zoned, aquaculture can be practiced in areas that have the right bio-economic conditions for growing seafood, reducing many of aquaculture's negative impacts in the process.

Aquaculture can even be integrated with other emerging ocean uses like offshore sustainable energy production, including wind turbines (WEF 2018).

Capture fisheries produce more than 90 million metric tonnes of fish per year, providing the world's growing population with a crucial source of food (Bennett et al. 2018). Due to the particular nutritional characteristics of fish, fisheries represent far more than a source of protein. They provide essential micronutrients—vitamins and minerals—and omega-3 fatty acids, which are necessary to end malnutrition and reduce the burden of communicable and noncommunicable diseases around the world. Yet the contributions of fisheries may be undermined by threats such as overfishing, climate change, pollution, and competing uses for freshwater (Bennett et al. 2018).

It is very obvious that both capture fisheries and aquaculture are important food production systems that can make enormous contributions to food availability and nutrition security.

It is very interesting to recall three of the six major observations of the USAID (2016) report on the need for integrated policies and planning as far as aquaculture and fisheries are concerned and their effects on food security.

The report (USAID 2016) inter alia stated thus: (a) Many national food security plans do not include wild foods such as fish. (b) Over $50 billion is lost each year from the marine fishing sector due to poor governance and lack of secure tenure and (c) About 20–30% of wild fish caught are used as fishmeal, primarily exported for aquaculture; these small fish are important for food security and livelihoods for coastal communities and for healthy ecosystems. It is very clear that these statements have serious implications for food security especially in Africa.

11.1.2 What Is Food Security?

In the language of the *United Nations' Committee on World Food Security,* food security is defined as "the means that all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their food preferences and dietary needs for an active and healthy life." According to *Wikipedia,* food security "is a measure of the availability of food and individuals' ability to access it." However, the term "food security" is defined by different organisations in different ways. FAO defines food security as "a condition when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (World Food Summit 1996).

Food security can be achieved in two dimensions: (a) making food directly available to those in need and (b) providing employment opportunities to people so that they can have income and use it to buy food of their choice.

The four pillars of food security as stipulated by FAO are: food availability, access to food, utilization, and stability. High population growth associated with increasing pressure on natural resources is asserted as a major factor for food insecurity in the sub-Saharan region. Various experts on the study of food security point out that feeding a growing global population put pressure on natural resources.

It is very obvious that food security is very important and is required so that citizens of each country can have unhindered access to both safe and healthy food all the year round, whether it is during summer or winter in the cold regions or during rainy or dry season as it happens in tropical nations. In addition, food security guarantees that even during disaster or bad climate, at least citizens are able to feed properly.

11.1.3 State of the Aquatic Environments in Africa

There are different aquatic environments in Africa. They include freshwater (lakes, ponds, rivers, and streams), freshwater/brackish water (estuaries and wetlands), and marine (inter-tidal regions, coral reefs, oceanic pelagic zones, and abyssal zones) (El-Shabrawy and Al-Ghanim 2010).

There is no way that the issue of the importance and potentials of fish will be discussed in Africa without mentioning the terrestrial and aquatic environments of Africa. Globally, terrestrial and aquatic environments have been treated as a common commodity for the use of man.

The commons are the cultural and natural resources accessible to all members of a society such as water, air, and other resources. The traditional examples of the commons include forests, fisheries, or groundwater resources.

Africa is blessed with both terrestrial and aquatic habitats (especially lakes) with abundant resources (Table 11.1). Africa, and especially east African nations, has many lakes that support very important fisheries. These lakes among other uses serve as a means of livelihood to millions of people, thus contributing significantly to the food supply.

However, these environments and the natural resources face a lot of serious threats, which are often caused by human activities. The numerous activities that include pollution, sedimentation, deforestation, landscape changes and disruption account for the diminishing production of fish and fish resources in Africa. Most of these activities have triggered climate change that has affected total production of fish for our daily diet. The terrestrial environments which include the humid freshwater ecosystems, brackish and adjacent wetlands are all very suitable for

Table 11.1 Principal lakes in Africa

Country	No of lakes	Percentage
Uganda	69	10.0
Kenya	64	9.5
Cameroon	59	8.7
Tanzania	49	7.2
Ethiopia	46	6.8
South Africa	37	5.5
Rwanda	29	4.3
Ghana	29	4.3
Morocco	26	3.8
Madagascar	25	3.7
Egypt	16	2.4
Nigeria	16	2.4
Mali	15	2.2
Tunisia	15	2.2
Zaire	15	2.2
Malawi	13	1.9
Botswana	12	1.8
Gabon	8	1.2
Others	134	20.0
Total	677	100

Source: World Lakes Network (2004)

aquaculture in Africa. The oceans with some measure of technology are also very conducive for fisheries and aquaculture.

The African continent is blessed with numerous water bodies and resources in lakes, rivers and floodplains and oceans (e.g. Indian and Atlantic). Fisheries are some of the major resources in these water bodies. Therefore, fishery is a key subsector to Africa's agricultural productivity. This includes both capture fisheries and aquaculture (Emmanuel Kaunda and Sloans Chimatiro 2015).

However, Emmanuel Kaunda and Sloans Chimatiro (2015) observed that vast land and suitable water environment are unexploited for fish production in many African countries.

They include brackish waters, coastal areas and land where cages, ponds and other culture systems which can be conveniently practiced.

For instance, there are extensive coastal areas in west Africa that are suitable for shrimp farming yet they remain unexploited. In addition, much of the South African coastal area is also good for seaweed culture, shrimp and other aquatic products (Emmanuel Kaunda and Sloans Chimatiro 2015).

11.1.4 Aquatic Components and Food Security in Africa

Fish can be found naturally, especially where there are aquatic resources. Tropical lakes, rivers, ponds, open sea and coastal waters harbour fish and other edible aquatic organisms and plants.

Fish as one of the aquatic components is the most nutritious traded food commodities globally and it is a very important staple food in many countries. The Food and Agriculture Organization of the United Nations (FAO) policies highlight the importance of both cultivated and wild fish to food security. In addition to other highlights, aquaculture and fisheries are of critical importance for the food, nutrition and employment of millions of people across the globe, many of whom struggle to maintain reasonable livelihoods. There are culturable fish species that can easily be farmed in the different climatic zones of Africa. In Nigeria, for example, fish species such as Carp, Tilapia, *Heterobranchus* and *Clarias* sp. are most commonly found. There are conventional and unconventional culturable species such as *Labeo coubie*, *Parchnna obscura*, *Bagrus sp*, *Heterotis niloticus*, *Lates niloticus*, *Gymnarchus niloticus*, and *Citharinus citharus*. In addition, most of the various types of marine fish (*Agnatha, Chondrichthyes, Osteichthyes*) are food fish (FAO 2000).

In the sub-Saharan countries of Africa, fish can be easily raised using different aquatic environments. Investment (time and money) in fish production will guarantee reasonable financial returns if and well planned. Increased fish food production and reduction of hunger can be ensured by investment in aquaculture in sub-Saharan Africa.

Many underprivileged poor people in many parts of Africa and Asia that depend on a combination of fishing and farming to feed their families can be empowered by their governments. According to the FAO (2020), fish are the most widely traded foods in the world, with about 50% coming from developing countries. This FAO report estimates that the net value of fish exports from developing countries in 2011 was over $20 billion –greater than the net exports of rice, coffee, tea, tobacco, and meat combined.

Global fish production is estimated to have reached about 179 million tonnes in 2018, with a total first sale value estimated at USD 401 billion. Out of the above, 82 million tonnes, valued at USD 250 billion, came from aquaculture production. Aquaculture accounted for 46% of the total production and 52% of fish for human consumption. China has over the years remained a major fish producer, with about 35% of global fish production in 2018 (FAO 2020). The other significant share of production in the same year was from Asia (34%), the Americas (14%), Europe (10%), Africa (7%) and Oceania (1%) in a descending order. From this report it is shown that Africa produced only 7% (FAO 2020).

11.2 Aquaculture and Fisheries in Africa

According to Hecht et al. (2006), aquaculture was first introduced to many countries in Africa at the turn of the twentieth century mainly to satisfy colonial recreational fishing needs.

Table 11.2 shows the different phases and periods and the various adjoining activities that accompanied the process. The colonial administrators between 1940 and 1950 introduced aquaculture as a means of sustainable food production (Brummett et al. 2008). The sole aim was to improve the nutritional levels in rural areas, supplementing their income generation capacity, among other objectives.

Aquaculture and fisheries are of critical importance for the food, nutrition and employment of millions of people, many of whom struggle to maintain reasonable livelihoods.

FAO (2018a) revealed that 99% of fish produced from the African continent are from the inland freshwater systems. Tilapia and the African catfish dominate the cultured species while mariculture contributes a meagre 1% to the total production quantity. The top aquaculture producers in Africa are Egypt, Nigeria, Uganda, Ghana, Tunisia, Kenya, Zambia, Madagascar, Malawi, and South Africa. In Africa, Egypt, Nigeria, and Uganda account for about 90% of total aquaculture production from the region (Satia 2011, 2017). Based on the work of the Consultative Group on International Agricultural Research (CGIAR), Figures 11.1 and 11.2 shows the Global and Africa share of fish production, 1950–2015, and the Africa fish production sector by sector, 2000–2015, respectively. It is observed that both Africa (Aquaculture) and Africa (Capture) need improvement and a continental attention.

Generally, it is observed that demand for fish has been increasing rapidly. This is driven chiefly by population and income growth, but has also been spurred on by an increasing appreciation for the health benefits of fish consumption as well as changes in lifestyles and preferences associated with rapid urbanization and globalization (Thurstan and Roberts 2014). In this regard, Africa is not an exception.

Table 11.2 Evolution of aquaculture in Africa

Phase	Period	Description of activities
I	1950–1970	– Introduction of aquaculture – Limited knowledge and understanding of aquaculture – Fish farms were built by governments
II	1970–1995	– Expansion of aquaculture – Significant donor support – Active R&D – Government involvement in seed supply and extension services – Commercialization of aquaculture in some countries such as Nigeria, Madagascar, C^ote d'Ivoire, Zambia, and South Africa
III	1995 till today	– Reduced donor support – Emergence of commercial aquaculture – Re-orientation of public support toward facilitation

Adapted from Hecht et al. (2006)

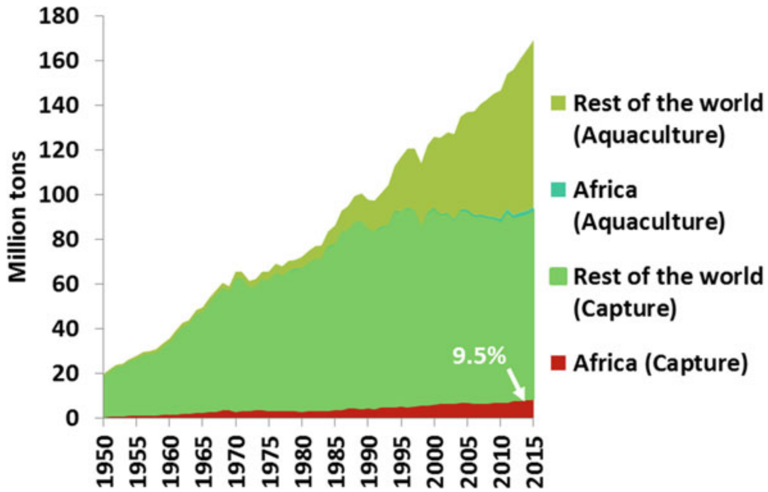
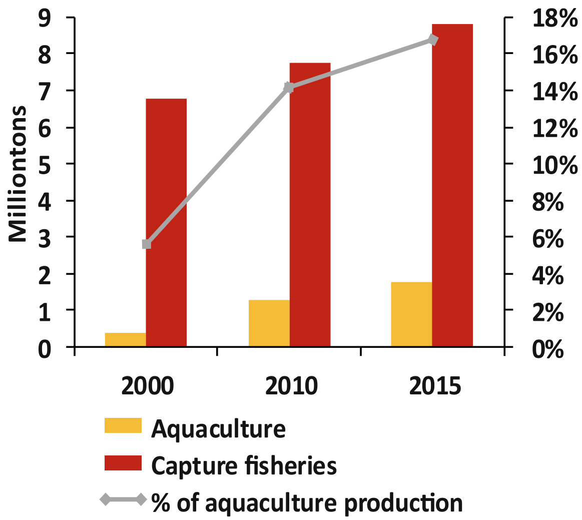


Fig. 11.1 Global and Africa share of fish production, 1950–2015

Fig. 11.2 Africa fish production sector by sector, 2000–2015



Africans are gradually sliding into the position of being highly dependent on fish for animal protein in spite of the fact that we are ranking low in per capita fish consumption (Chan and Phillips 2019). Chan et al. (2019) also confirmed that globally Africans are now in the second position to the Asians that rely on fish as the main animal protein source in their diet. Fish now represents over 20% of animal protein intake in 20 African countries (FAO 2017).

If the case of Nigeria is to be examined, currently fish production in Nigeria stands at 0.8 million metric tonnes with a deficit of 1.9 million metric tonnes of fish as local demand for protein is 2.7 million metric tonnes annually (Ukpe 2000).

Table 11.3 Projected population and fish demand/supply in 1997–2025

Year	Population (million)	Fish demand (million tonnes)	Fish supply in domestic production (million tonnes)	Shortfall (million tonnes)
1997	105.20	0.80	0.41	0.39
1998	108.20	0.82	0.45	0.37
1999	111.20	0.85	0.49	0.36
2000	114.40	0.87	0.53	0.34
2001	117.60	0.89	0.57	0.32
2002	121.00	0.92	0.61	0.31
2003	124.40	0.95	0.65	0.30
2004	127.90	0.97	0.69	0.28
2005	131.50	1.00	0.73	0.27
2006	135.20	1.03	0.77	0.26
2007	139.10	1.06	0.81	0.25
2008	143.00	1.09	0.85	0.24
2009	147.10	1.12	0.89	0.23
2010	151.20	1.15	0.93	0.22
2011	155.50	1.18	0.96	0.21
2012	159.90	1.22	1.00	0.22
2013	164.40	1.25	1.04	0.21
2014	169.10	1.29	1.08	0.21
2015	173.90	1.32	1.12	0.20
2016	178.80	1.36	1.16	0.20
2017	183.30	1.39	1.20	0.19
2018	189.00	1.44	1.24	0.20
2019	194.40	1.48	1.28	0.20
2020	199.90	1.52	1.32	0.20
2021	205.60	1.56	1.36	0.20
2022	211.40	1.61	1.40	0.21
2023	217.40	1.65	1.44	0.21
2024	223.50	1.70	1.48	0.22
2025	229.80	1.75	1.52	0.23

Source: FAO (2000)

Table 11.3 shows the projected population and fish demand/supply projection in Nigeria from year 2000 to 2025 as projected by the Food and Agriculture Organisation of the United Nations. It could be observed that while fish demand increased steadily from 0.87 metric tonnes in 2000, it has a projection of 1.75 metric tonnes by the year 2025. Fish supply via domestic production is estimated to rise to 1.52 metric tonnes by the same year 2025, leaving a deficit of 0.23 metric tonnes (Table 11.1). Unfortunately, Nigeria imports over 700,000 metric tonnes of fish per annum, and annual deficit of about 0.5 metric tonnes still exists (Amosu et al. 2017).

11.2.1 Present Challenges in Aquaculture and Fisheries in Africa

Aquaculture and fisheries production and management is an age-long profession that involves human activities that result in environmental disturbances and natural disequilibrium; hence, it is faced with a lot of challenges.

Different authors, different organizations, and stakeholders that are involved in the production, provision, and management of fish as food had identified numerous challenges that confront fish production in Africa. Generally, across Africa, there is a lack of adequately trained staffs that are needed to carry out all the necessary production process and programs. This starts from fish brood stock selection to rearing of frys and fingerlings, feed, and feed ingredients/fish feed formulation among others. It is very common to see that qualified employees are found mainly in universities and research institutions where they train low-level manpower for extension services. In addition, the necessary practical skills in fish farming are relatively low in some African countries and thus the expected high level of fish production eludes many African countries. This is not to say that some African countries cannot boast of high technical aquaculture centres of proven success. In the midst of these challenges, aquaculture is still a major sector of food production in Africa.

Across the African continent, aquaculture has some significant general challenges such as (a) successful integration of aquaculture with other farming activities and promotion of small-scale low-cost aquaculture in support of rural development; (b) improvements in environmental management including the reduction of environmental impacts and avoidance of risks to biodiversity through better site selection, appropriate use of technologies, including biotechnologies, and more efficient resource use and farm management; (c) the reduction of competitions with other agricultural activities and how to meet growing demands for fish seed, fish feed, and fertilizers, just to mention a few.

In a recent study, ECOWAS presented about four major challenges facing aquaculture and fisheries in West Africa. These include (a) poor governance in the management of fish stocks, threats to the marine environment exacerbated by poor fishing practices, (b) importance of illegal, unreported, and unregulated fishing, (c) low promotion of fisheries products, and (d) insufficient coordination and cooperation among regional institutions (ECOWAS 2021).

However, the summary given by Adeleke et al. (2021) in their study concluded thus: “Key challenges plaguing the pace of aquaculture development are access to credit facilities, adequate supply of required quantity and quality of inputs, land ownership and product marketing. The distribution of aquaculture products is exacerbated further by dilapidated and inadequate infrastructure and facilities.” The import of these two different but common assertions is that Africa is cumbered by challenges that need to be tackled and resolved, if all stakeholders and various African governments are ready to raise productions from both aquaculture and fisheries.

Perhaps, it will be of added advantage to the discussion on the challenges faced by this sector, if the observation of the Embassy of the Kingdom of the Netherlands, Lagos Office is noted and addressed. These challenges as observed include (1) limited technical and business management support systems; (2) ineffective data collection and management systems; (3) poor organization and trust amongst aquaculture value chain players; (4) no internationally accredited farms; (5) EU and US restrictions on Nigerian smoked catfish export; (6) lack of accredited facilities for promoting fish export, e.g., limited ISO certified laboratories for residue monitoring; (7) limited knowledge and technology for fish production resulting in low production efficiencies and profitability; (8) high cost of quality inputs like feeds, seeds, and equipment; and (9) limited knowledge and technology readily available in the country for other aquaculture species other than catfish and tilapia (Embassy of the Kingdom of the Netherlands 2019).

11.2.2 Potentials and Benefits of Aquaculture for Food Security in Africa

Aquaculture and fisheries have the potentials to improve the socio-economic status of many African countries in at least three important major areas. Firstly, supply and feed Africa with the required protein. Secondly, provide employment for the teeming population of the youths of Africa and thirdly increase the annual production of fish and fish products in Africa.

For example, Egypt produces over one and a half million tonnes of fish with an estimated market value of over USD 2 billion. With this, she ranks sixth among the leading aquaculture-producing countries globally in 2018 (FAO 2003–2020; Shaalan et al. 2018). In addition, Egypt contributes 77% of the total national fisheries production, employing over 580,000 workers (El-Sayed et al. 2015; FAO 2016; Shaalan et al. 2018).

Nigeria ranks second in Africa with an annual production output of about 300,000 tonnes and it is principally dominated by catfish culture (FAO 2016, 2018a; Ozigbo et al. 2014). Uganda is the third producer in Africa; she supplies fishery products in the form of feed, fish seeds, etc., to neighbouring countries mainly Kenya, Congo, and Rwanda (FAO 2004–2020; Safina et al. 2018).

So many reports and studies have shown that aquaculture has many benefits, most of which are encompassing in many phases of human livelihoods in Africa. For example, in a recent report of the Regional Agency for Agriculture and Food of the ECOWAS (Economic Communities of West African States) on aquaculture and fisheries production, it had this to say, and I quote, “In West Africa, fisheries and aquaculture contribute a lot to the revenue of the States through royalties and financial compensation within the framework of the various fishing agreements. They play an important role in meeting the nutritional needs of the populations with low purchasing power. They also generate an important source of job creation for more than 9 million full-time workers. Most of these jobs derive from the artisanal fishing sub-sector, where women represent more than half of the segment" (ECOWAS 2021). It concludes that in West Africa, fisheries and aquaculture contribute a lot to the revenue of the States through royalties and financial compensation within the framework of the various fishing agreements. They play an important role in meeting the nutritional needs of the populations with low purchasing power.

They also generate an important source of job creation for more than nine million full-time workers. Most of these jobs derive from the artisanal fishing sub-sector, where women represent more than half of the segment (ECOWAS 2021*)*.

11.2.3 Aquaculture and Fisheries: Satisfying the Pillars of Food Security

Food security is essentially built on four pillars. These pillars are (a) availability, (b) access,

(c) utilization, and (d) stability. It has been observed that at the individual level, ready and steady access to sufficient food of the right dietary quality is essential, while at the global level, food availability is supreme. If well planned and managed, aquaculture and fisheries production will go well to satisfy the four pillars of food security in Africa.

11.2.3.1 Availability

Fish can be produced in Africa throughout all the seasons of the year through efficient water use just as we do in plant/crop production. Efficient water use can be guaranteed through innovations and technological advancement. There are enough fish stocks in the oceans and seas if global and international rules and regulations are enforced in their harvests.

11.2.3.2 Access

Africa is well known for its class regulation and demographic alignment where a few rich can have access to fish and fish products in different forms at affordable prices; and quality in the midst of the poor access to fish and fish products can be enhanced through proper income distribution pattern, market pricing regime, and food distribution modes in both rural and urban climes.

Fish and fish products can be transported in various forms and sizes. Fish can be dried, smoked, or retained in the wet form during sales, thus enhancing equitable distribution. The marketing channels of fish are more and distinct compared to other plant farm products in Africa.

11.2.3.3 Utilization

Utilization is commonly understood as the way the body makes use of the most of various nutrients in the food (FAO 2016). Fish is a readily digestible commodity with low-fat high-quality protein. Fish has omega-3 fatty acids and vitamins such as D and B2. Fish is a great source of minerals and other essentials such as calcium and phosphorus. These essential nutrients keep our heart and brain functional and healthy.

11.2.3.4 Stability

The stability of the production and distribution of agricultural products right from the farm to the market is affected by many factors such as adverse weather conditions, political unrest, and economic vagaries such as unemployment; rising food prices are prevalent in Africa. However, fish production still remains one of the enterprises (and commodity) that can withstand some measure of stability in supply and access, due to its numerous production habitats (freshwater, brackish, and marine) and the numerous methods of operations. For example, in Nigeria, the demand for *Clarias gariepinus* (African Catfish) is non-seasonal.

There are no up and downtrends in this industry as there is always demand for catfish. Demands even go higher than normal during festive periods; in fact, there are no periods when demand is below normal as even during the Muslim fasting periods.

11.3 Practical Solutions for Improvement in Aquaculture and Fisheries Sector for Food security

There are series of prescribed and suggested solutions to improve and subsequently increase the current level of fish production both from aquaculture and wild fisheries sectors.

For fish as food to enhance food security, especially in Africa, many international and local organisations have come up with many suggestions.

Some focuses its research on the three interlinked challenges of (a) sustainable aquaculture, (b) resilient small-scale fisheries, and (c) enhancing the contributions of fish to the nutrition of the poor, in places where research and development can have the greatest impact on the livelihoods of the poor and vulnerable.

World Fish partners with relevant communities, research innovators, entrepreneurs, and investors to meet these challenges. This multidisciplinary and partnership-based approach supports the development and implementation of innovations that optimize the individual and joint contributions of fisheries and aquaculture for reducing poverty, improving food and nutrition security, and sustaining the underlying natural resources and ecosystems on which both depend.

However, I am going to approach this from a different angle, based on my experience as a researcher, academics, and field scientist. I will separate aquaculture from fisheries in the discussion, in order to be able to present the theoretical, practical, and laboratory actions and activities that are needed towards improvement.

11.3.1 Aquaculture

11.3.1.1 Repositioning and Re-defining the Relevance of Research Institutions

Most African research institutions (with mandates for aquaculture and fisheries development) are not well funded as it used to be. Some have lost focus due to underfunding and low budgeting and staff paucity. In other words, these institutions have gradually lost relevance. Aquaculture needs innovations and application of modern technology to improve and advance its focus as it is done in the developed countries.

Repositioning and redefining the roles of these institutions will assist the enabling environment for technology adoption and thus facilitating effective delivery of technologies to fish farmers.

11.3.1.2 Re-energising Extension Services and Activities

Agricultural extension activities and services were the prime mover of transfer of information, technology adoption, and innovations to the rural farmers in the early 1950s and 1960s. It is a known fact that agricultural extension is very important because it plays a crucial role in (1) boosting agricultural productivity, (2) increasing food security, and (3) enhancing rural livelihoods and promoting agriculture as an engine of economic growth.

Agricultural extension services offer technical advice to farmers and give all the necessary inputs and support to farmers. Aquaculture as an arm of fish food supply needs rigorous extension service. It is my belief that there is a need to create a viable aquaculture extension forum in all African countries. Production and marketing need to respect the wishes of the consumers and have good interpersonal relationships (Bolarinwa 2014). Not many African countries can boast of adequate extension services toady. Raising aquaculture production and productivity through identification and deployment of appropriate technologies through dedicated and enlightened extension agents will go a long way to increase aquaculture production.

11.3.1.3 Provision of Solution Bus Stops

For me, solution bus stops mean enabling environment for aquaculture and fisheries production to meet food security. Fregene (2010) encased these as follows: (a) policies to link fish farmers to institutions, government agencies and fish seed and feed producers with hatcheries and grain out-growers, respectively, aimed to reduce the cost of fish seed and fish feed; (b) facilitating access to aquaculture sites and lands, dams, and reservoir when required by poor and small-scale farmers; (c) outreach campaign for technology adoption; and (d) policies to reduce fish importation and certification standards.

Most importantly, there is also a clear need for initiatives to support and promote the growth of Youths in aquaculture and fish businesses and also the training of entry-level professionals in the aquaculture food sector. Some of these solution bus stops may be as simple as linkages to markets or complex as conditional-based access to resources such as meeting milestones. In Nigeria, for example, some of the key issues prevalent in aquaculture include fish fingerlings production from working hatcheries, fish feed production using adequate and ingredients, brood stock production to ensure reliable pedigree, fish farm supplies, credit for aquaculture farms, to mention but a few. These are some of the solution bus stops that the aquaculture and fisheries industry in Africa needs.

11.3.1.4 Bringing Aquaculture to the Youths

FAO (2018b) observed that the African youths especially in the sub-Saharan countries have not considered agriculture as a profitable venture that can improve their livelihood. In order to salvage this unfortunate situation, African governments must create avenues for information dissemination and youth-tailored agriculture extension services that will open up communication channels tailored towards agriculture as a profitable business. The participation of our youths in aquaculture can be improved through the following: (a) entrepreneurship development by the governments of African countries, starting from the schools' course curriculum; (b) provision of credit scheme for youths that are ready to engage in aquaculture; and (c) provision of agricultural production loan scheme for graduates and school leavers as a way of empowering them. In Nigeria, aquaculture is still carried out using some physical strength, which declines with age. Our youth amounts to about 80 million, representing about 60% of the total population of the country. With a reasonable percentage of this youth in aquaculture, considerable progress will be ensured in terms of production (Awogbenle and Iwuamadi 2010).

Some of the identified areas of aquaculture sector that the youths can explore include (a) fish feed supplies from mills to farmers; (b) fish processing, value additions marketing; (c) consultancy, especially practical transfer of knowledge and skills to rural fish farmers; and (d) fish marketers as wholesalers and retailers.

In the University of Agriculture, Abeokuta, the Centre for Entrepreneurial Studies, organises and trains youths in different areas of agricultural skills and trades.

11.3.1.5 Re-visiting Previous Regional and African Treaties and Programs

There are numerous regional and international organisations that are involved in agricultural developments in Africa. Many programs and initiatives were created and recommended and some implemented within the African countries. It has been suggested that some of these programs and initiatives need some re-visitation.

For over a long period, the Food and Agriculture Organization (FAO) is a specialised agency of the United Nations that leads international efforts to defeat hunger. African Development Bank (AfDB), West and Central Council for Agricultural Research and Development (CORAF), has been involved in World Bank and FAO projects in most of the African countries. The Southern African Confederation of Agricultural Unions (SACAU) is a Regional Farmers Organisation that also has a role to play in enhancing food production.

The Economic Community of West African States (ECOWAS) has an agriculture and environment unit that is saddled with (a) the promotion of strategic projects for food security, (b) the promotion of a global environment conducive to regional agricultural development, (c) the reduction of vulnerability and promotion of sustainable access to food, and (d) the governance, coordination and monitoring-evaluation of programs. Our governments should create a new impetus to revitalise these initiatives especially in aquaculture and fisheries production.

11.3.1.6 Infusing Research Findings into Industry and Field Activities

Universities and specialised institutions are often saddled with the task of finding solutions to numerous problems that militate against profitable and sustainable agricultural production, including aquaculture. In Nigeria, for example, at the national level, the responsibility of aquaculture research lies primarily with two major institutes. They are Nigerian Institute for Marine and Oceanographic Research (NIOMR), Lagos, and the Nigerian Institute for Freshwater Research (NIFFR), New Bussa. The financing for aquaculture research in Nigeria has been relatively poor because of the low priority attached to the importance of research for development.

In Tanzania, fisheries and aquaculture research are handled mainly by the Tanzania Fisheries Research Institute (TAFIRI). With four centres in Mwanza, Kigoma, Kyela, and Dar es Salaam, funding, staff salaries, and emoluments are very poor (FAO 1994).

In South Africa, the Department of Agriculture, Forestry and Fisheries (DAFF) handles the development of Aquaculture and thus it has been transformed into a viable government unit to manage aquaculture development and administration, (FAO 2011).

In the Federal University of Agriculture, Abeokuta, Nigeria, our mandates among others, include the provision of practical and theoretically sound manpower in fisheries who will not only be job creators but employers of labour; engage in fish production and purposeful research that will solve the country's fisheries development problems, and increase the contribution of fisheries to the gross national product. The Department of Aquaculture and Fisheries Management of the University of Agriculture in Abeokuta organises at least two training programs yearly in the following areas of aquaculture, viz. fish feed formulation, fish seed production and genetics, fish farm construction, etc.

Many universities in Africa have similar mandates for Aquaculture development. Numerous laboratory discoveries and innovations are still hanging on the shelves of many universities and research institutions of many African countries. Many fish seed improvement drive and fish feed improvement tests are still hidden in these laboratories. The challenges of demonstrating and up-scaling proven technologies to aquaculture value chain actors are not addressed based on finances and low transfer of discoveries to the field.

11.3.2 Wild Fisheries Production and Management

Globally, wild fisheries exist primarily in the oceans and particularly around coasts and continental shelves. They are also found in lakes and rivers where they are hunted and captured or fished as the case may be. Some seafoods are either farmed or hunted. Fish production from the wild (fishery) could either be (a) industrial, (b) small scale, (c) artisanal, or (d) subsistence depending on the intensity and level of technology. While industrial fisheries are capital-intensive using relatively large vessels with a high degree of mechanisation; they have high production capacity. Not many African nations are competitive in this sector.

Small-scale fisheries are labour-intensive using relatively small crafts if any with little capital and equipment per person on board. Most are often family-owned, and could be commercial or subsistence. The African coastal fishers are in this category. Catch per unit effort is usually very marginal. Since 2005, the Africa Program for Fisheries (APF) has focused on sustainable use of the marine resources, governance of the sector, and deep engagement with coastal communities. Consequently, the World Bank supports Africa's commitment to invest in sustainable fisheries as a way to build the resilience and improve the livelihoods of coastal communities. In addition, the African Union's Agenda 2063 declares the Blue Economy to be "Africa's Future" and recognises the key role the ocean plays as a catalyst for socioeconomic transformation.

11.3.2.1 Africa, Sustainable Fishing and Food Security

Africa is not among the ten fishing nations of the world. Foreign vessels harvest our fish to the detriment of our resources. Demand for seafood and advances in technology have led to fishing practices that deplete fish and shell fish populations around the world.

In order to maintain fish stock, there is a need to reduce overfishing through fisheries management. Nations are responsible for regulating, monitoring, and controlling of fishing in their coastal waters. Africa and African nations have to address the issue of illegal fishing and overfishing within their territorial waters.

11.4 Conclusion and Recommendations

In this chapter, efforts have been made to present the potentials and benefits of aquaculture and fisheries as cultured and captured food products that can be harnessed for human consumption and sustainable livelihoods in Africa. While aquaculture is an integrated production system which can be tested by laboratory scientific research, fisheries is more or less controlled by and from multi-faced dimensions. It could be observed that most of the research undertaken and presented is from aquaculture. Unlike crop and animal (ruminants and non-ruminants) where extensive large-scale and small-scale production levels abound, it is recommended that aquaculture, being relatively a most recent agriculture system, should begin to enjoy funding to improve its overall development.

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Chapter 12
Medicinal Plants: A Perspective on Their Application in the African Smallholder Aquaculture Farms

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Abstract This chapter reviews the role of medicinal plants as growth enhancers, immunostimulants, disease-controlling agents, anaesthetics, and sex reversal agents in aquaculture and perspectives on their application in African aquaculture smallholder farms. The statement that aquaculture is one of the significant contributors to global food security is unquestionable. However, increased intensification of this sector compromises its sustainability as some of the challenges such as increased fish

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stress, disease outbreaks, poor fish growth, and feed quality affect its performance. Therefore, effort has been made for the fish farmers to take advantage of the benefits associated with intensive aquaculture systems. Among the remedies, medicinal plants are believed to be one of the best innovations with the potential to contribute to a sustainable aquaculture sectors as they can be used as growth promoters, feed utilization enhancers, immunostimulants, anti-depressants, anaesthetics, sex reversal agents, antimicrobial agents, among others. Since they are usually cheap, readily available across the world, more biodegradable, and simple to use compared to pharmaceutical drugs, they are more appropriate for smallholder aquaculture farmers in Africa. However, for the African smallholder aquaculture farmers to take advantage of the benefits associated with medicinal herbs, more studies are needed to validate and optimize the effects of numerous herbs on African aquaculture species.

Keywords Aquaculture · Anaesthetics · Immunostimulants · Medicinal plants · Sex reversal

12.1 Introduction

Aquaculture is one of the fastest developing food-producing sectors across the world. In 2018, the sector contributed about 46% to the total seafood world production, and its total first sale value was estimated at USD 250 billion compared to USD 151 billion from capture fisheries (FAO 2020). The global success of aquaculture could partly be attributed to the escalated adoption of intensive production systems, which are associated with higher stocking densities (Kumar and Engle 2016). However, higher stocking density could be stressful to the fish, as it is allied with poor growth (Liu et al. 2016), poor health (Montero et al. 1999), increased susceptibility to diseases (Kibenge 2019), and in extreme cases mortality (Amal et al. 2018). Therefore, the prerequisite for a successful intensive aquaculture farm is mainly good health management.

In an attempt to economically benefit from intensive farming systems, fish farmers started using synthetic pharmaceutical drugs to maintain the good health of farmed fish. The adoption of these drugs in aquaculture was later shown to be unsustainable, as they cause fish pathogen drug resistance, immunosuppression, environmental pollution, and accumulation of chemical residues, which is potentially hazardous to public health (Heuer et al. 2009). For this reason, many nations such as the United States, countries in the European Union (Bulfon et al. 2015), and Asian countries (Ji et al. 2007) have a strict demand for aquatic products free from synthetic pharmaceutical drugs. Consequently, the need to replace pharmaceutical drugs with dietary supplements or ingredients or additives (immunostimulants) that are capable of strengthening fish health, and enhancing their growth, feed utilization ability, and ultimately ensuring safe and good quality of aquatic products from aquaculture has become increasingly imperative.

Recently, there has been an increasing interest in the use of medicinal plant extracts in aquaculture globally, including in Africa. This is because the use of medicinal plants could be more sustainable compared to synthetic drugs as they are locally available in most parts of the world, diverse in nature, inexpensive, and are believed to be more biodegradable in nature (Reverter et al. 2014). Medicinal plants contain several biologically active metabolites with various functions such as immune-modulating (Yilmaz 2019), growth-promoting, digestive enhancing, appetite-stimulating, antioxidant-enhancing, antidepressant (Pu et al. 2017), hepatoprotective effects in fish (Gurkan et al. 2015), increasing resistance against pathogens(Yilmaz 2019), and improving fish rearing water quality (Reverter et al. 2017). In addition, plant extracts have been reported to improve fish meat quality (Pu et al. 2017), control reproduction in tilapia (Gabriel 2019), and displayed anaesthetic functions in fish species (Aydın and Barbas 2020). Besides research, it is interesting to know that biological products (including plant extracts) have already been applied in aquaculture in countries such as Indonesia (West Java) (Caruso et al. 2013), Bangladesh (Ali et al. 2016), and China (Xie 2013) for various purposes. Caruso et al. (2013) discovered that about 46% of aquaculture farmers in West Java utilize plant extracts to improve fish rearing water quality, reduce fish stress, improve fish immunity, and manage fish diseases. Although African research institutes have also generated a significant amount of knowledge about the application of medicinal plants in aquaculture, to date, there are limited examples on their application in the African aquaculture industry. Therefore, this chapter reviews the role of medicinal plants as growth enhancers, immunostimulants, disease-controlling agents, anaesthetics, and sex reversal agents in aquaculture and their trends and perspectives on their application in African aquaculture smallholder farms.

12.2 Some Medicinal Plants Studied in Aquaculture in Africa

The African continent is characterized by an immense wealth of plant resources of about 50,000 different plant species of which 25% have been used for several 100 years as medicinal plants in the prevention and treatment of several ailments in humans (Iwu 2014). The implementation of medicinal herbs is a new concept in aquaculture all over the world, with China generating more research over the years (www.scival-com). A significant number of research on medicinal herbs in aquaculture has also been reported in Africa, dominantly in Egypt followed by Nigeria (www.scival-com) (Table 12.1). These herbs have been reported in different fish species for various functions and could be used as a whole or part (i.e. leaves, roots, or seeds) in a crude form or as extracted compounds from the whole plant or parts. Additionally, the effects of herbal extracts in farmed fish have been investigated either as individual extracts incorporated in the basal diet or in combination (mixture) with other medicinal herbs. Although positive benefits for individual herbs

Table 12.1 Growth performance and feed utilization response of fish fed diets enriched with some of the widely available medicinal plants that can be used in African aquaculture due to their wide distribution

Medicinal herbs	Function	Fish species	References
Green tea *Camellia sinensis*	Dietary *C. sinensis* significantly increased final fish weight (FW), weight gain (WG), specific growth rate (SGR), feed intake (FI), protein efficiency ratio (PER), decreased feed conversion ratio (FCR), and improved innate immune parameters in dose-dependent fashion, with 0.50 gkg^{-1} diet inclusion level being optimum	Nile tilapia (*Oreochromis niloticus*)	Abdel-Tawwab et al. (2010)
Tamarind (*Tamarindus indica* L.)	Dietary extracts significantly enhanced fish growth, nutrient digestibility, and utilization, villi height, and absorption area and conferred better protection against *Aeromonas hydrophila* in *O. niloticus*; and an inclusion level of 1.0% was found optimum	*O. niloticus*	Adeniyi et al. (2021)
Clove bud	Dietary supplements (5.0, 10.0, and 15.0 gkg^{-1} diet) significantly increased growth performance, intestinal villi height/width and absorption area	African catfish *Clarias gariepinus*	Adeshina et al. (2019)
Trigonella foenum graecum	Enriched diets significantly increased growth performance parameters and decreased feed conversion ratio in fish fed for 8 weeks	*O. niloticus*	Moustafa et al. (2020)
Aloe vera	Dietary supplements significantly increased growth and feed utilization parameters	*C. gariepinus*	Gabriel et al. (2019b)
Garlic *(Allium sativum)*	Dietary supplements significantly increased growth and feed utilization parameters	*C. gariepinus*	Gabriel et al. (2019a)
Spirulina platensis and Origanum vulgare	Dietary supplements improved growth performance, feed utilization parameters, antioxidants, and resistance of fish against *Vibrio alginolyticus*	*O. niloticus*	Abdel-Latif and Khalil (2014)
Mitracarpus scaber	Dietary *M. scaber* leave extracts improved growth performance, feed utilization, antioxidant, non-specific immunity parameters, and resistance of fish against *Gyrodactylus malalai* infestation	*O. niloticus*	Adeshina et al. (2021a)
Astragalus polysaccharides	Enhanced growth performance and immune parameters	*O. niloticus*	Zahran et al. (2014)
Psidium quajava	Enhanced growth, nutrient utilization, innate immune, antioxidant parameters, and survival of fish against *A. hydrophila*	*O. niloticus*	Omitoyin et al. (2019)
Miswak (*Salvadora persica*)	Supplemented diets improved growth, antioxidative response, and fish	*O. niloticus*	Abd El-Naby et al. (2020)

(continued)

Table 12.1 (continued)

Medicinal herbs	Function	Fish species	References
	histopathological damage induced by zinc toxicity		
Coffea arabica	Dietary supplementation did not improve growth and feed utilisation, it could only improve their immunity and reduce the impact of waterborne zinc toxicity and bioaccumulation in the fish body	*Common carp* (*Common carpio*)	Abdel-Tawwab et al. (2015)
Artemisia afra	Dietary supplementation at 3.0, 6.0, 9.0, and 12% could not improve growth and feed utilization; it could only improve fish immunological parameters and resistance against bacterial infection	*O. mossambicus*	Mbokane and Moyo (2018a)

have been widely reported in farmed fish, synergistic/additive benefits were also unveiled when herbs were studied in combination.

In Egypt, leaf crude powder from *Ziziphus mauritiana* (El Asely et al. 2020) *Camellia sinensis* (green tea) (Abdel-Tawwab et al. 2010), and *Rosmarinus officinalis* (Naiel et al. 2020) were added to the feed to ascertain for their effects on growth, health, and resistance against bacterial infection in *Oreochromis niloticus* (Nile tilapia), respectively. In south, growth, immune response, feed digestibility, and toxicity effects of dietary *Moringa oleifera* and *Pennisetum clandestinum* leaf powder extracts were investigated in three species (*Tilapia rendalli, O. mossambicus*, and *Clarias gariepinus*), respectively (Hlophe 2015). In addition to leaf extracts, dietary root powder extracts from *Panax quinquefolium* (Abdel-Tawwab 2015), *Salvadora persica* (Abd El-Naby et al. 2020), and *Withania sominefera* (Zahran et al. 2018) were studied in *O. niloticus* in Egypt. In the same fish in Nigeria, dietary *Psidium quajava* aqueous leaf extracts were investigated for growth, intestinal morphology, immune, and survival against *Aeromonas hydrophila* (Omitoyin et al. 2019). Furthermore, other medicinal plant extracts reported in African aquaculture includes essential oils (Abdelkhalek et al. 2020), seed powder (Nyadjeu et al. 2019), coffee powder (Abdel-Tawwab et al. 2015), ethanol leaf extracts (Abodahab 2015; Adeshina et al. 2021a), methanol extracts (Abodahab 2015), and herbal mixtures (Gabriel et al. 2021).

12.3 Mode of Administration

Generally, in aquaculture, plant extracts may be administered orally through diets, injection, or immersion. The oral administration method has been widely used to investigate for plant extracts' growth and immune response effects in different fish species (El Asely et al. 2020; Adeshina et al. 2021a). Immersion as a method of delivery is popularly used in herbal extract anaesthetic studies (Bodur et al. 2018;

Brandão et al. 2021), and parasitic infection (Yildiz et al. 2019) in fish, while the injection method has been reported in immune-related studies (El-Barbary and Mehrim 2009; Harikrishnan et al. 2009). Among herbal extract administration methods, oral seems to be more feasible as it is less labour intensive, cost-effective, does not need highly skilled operators, and could be applied at any scale of aquaculture when compared to injection and immersion methods (Harikrishnan et al. 2009; Gabriel 2019). Although oral administration sounds more appropriate especially for African aquaculture smallholders, unfortunately, the choice of the administration method depends on the intention of administration, types of extract, size and types of fish species, and aquaculture system as elucidated in Gabriel et al. (2015b).

12.4 The Effects of Medicinal Plants Extracts on Fish Growth and Feed Utilization Performance

The effects of medicinal plant extracts on fish growth and feed utilization performance in fish have been reported in aquaculture worldwide, and Africa is no exception. For example, a study from Egypt evaluated the effects of five dosages of *C. sinensis* (0.125, 0.25, 0.50, 1.0, 2.0 gkg^{-1} diet) on growth, feed utilization, innate immune parameters performance in *O. niloticus* juveniles, and resistance against *Aeromonas hydrophila* infection after 12 weeks' feeding (Abdel-Tawwab et al. 2010). This study reported that dietary *C. sinensis* significantly increased final fish weight, weight gain (WG), specific growth rate (SGR), feed intake (FI), protein efficiency ratio (PER), and decreased feed conversion ratio (FCR) in dose-dependent fashion, with 0.50 gkg^{-1} diet inclusion level being optimum (Abdel-Tawwab et al. 2010). In Nigeria, tamarind (*Tamarindus indica* L.) leaf extracts were incorporated in the diet at 5, 10, 15, and 20 gkg^{-1} diet to investigate their effects on growth, nutrient utilization, gut physiology, and susceptibility to *A. hydrophila* infection in the same fish species and for the same feeding duration (Adeniyi et al. 2021). These dietary extracts significantly enhanced fish growth, nutrient digestibility, and utilization, villi height, and absorption area and conferred better protection against *A. hydrophila* in *O. niloticus* and an inclusion level of 1.0% was found optimum for aquaculture application (Adeniyi et al. 2021). Similarly, the supplementation of clove bud extracts in *C. gariepinus* feed (5.0, 10.0, and 15.0 gkg^{-1} diet) significantly increased growth performance, intestinal villi height/width, and absorption area after 12 weeks' administration (Adeshina et al. 2019). *Trigonella foenum graecum* seed powder–enriched diets significantly increased growth performance parameters and decreased feed conversion ratio in *O. niloticus* fed for 8 weeks (Moustafa et al. 2020). Moreover, the supplementation of *Aloe vera* (Gabriel et al. 2019b) *Allium sativum* (Gabriel et al. 2019a) and their mixtures in an equal ratio (Gabriel et al. 2021) reportedly increased growth and feed utilization parameters in *C. gariepinus*. Growth performance and feed utilization parameters were also improved in

O. niloticus-fed diets enriched with *Spirulina platensis*, *Origanum vulgare* (Abdel-Latif and Khalil 2014), *Mitracarpus scaber*, and *Tridax procumbens* (Adeshina et al. 2021a,b), *Astragalus* polysaccharides (Zahran et al. 2014), *P. quajava* (Omitoyin et al. 2019), *S. persica* (Abd El-Naby et al. 2020), and in *O. mossambicus*-fed diets supplemented with *P. clandestinum* (Hlophe and Moyo 2014).

At present, there is limited information on how medicinal plant extracts improve growth and feed utilization in fish. Some studies explain that the enhancement of growth performance following the supplementation of medicinal herbal extracts in fish is ascribed by their broad range of nutritional constituents including proteins, lipids, vitamins, enzymes, minerals, sugar, saponin, and salicylic acids (Adesuyi et al. 2012; Gabriel 2019). In addition, their complex sugar such as polysaccharides are known to act as prebiotics that have the ability to sustain the homeostasis of the gut microbial community as well as the host's health (Zahran et al. 2018; Foysal et al. 2019), either by reducing the bacterial and viral infection levels (Chen et al. 2003) or by directly affecting pathogenic gut microflora (Sohn et al. 2000; Citarasu 2010; Yu et al. 2018). This, as a result, improves feed digestibility and availability of nutrients from feed and shortens the feed transit time, which might have a beneficial influence on digestive enzymes. It also minimizes the amount of feed substrate available for the proliferation of pathogenic bacteria (Citarasu 2010). The growth performance and feed utilization response of fish fed diets enriched with some of the widely available medicinal plants that can be used in African aquaculture due to their widely distribution are shown in Table 12.1.

12.5 Disease Control in Aquaculture

Fish farmers increasingly experience fish mortalities as a result of infectious diseases. Diseases caused by parasitic, bacterial, and viral pathogens are among the most limiting factors in the growth of aquaculture in Africa. This results in substantial economic losses which may explain the low investor confidence in the sector in most regions on the continent. The most commonly encountered bacterial pathogens in farmed fish include, among others, aeromonads, *Edwardsiella tarda*, *E. ictaluri*, *Streptococcus* spp., *Flavobacterium columnare*, *Francisella* spp. and *Shewanella putrefaciens*, *A.hydrophila*, *A. sobria*, *A. veronii*, and *A. jandaei*. Among these pathogenic bacteria, *Aeromonas* spp. are the most common and they cause a major disease condition in fish called haemorrhagic septicaemia. Fungal infections caused by the fungal species belonging to the *Saprolegnia* genus are also common in aquaculture farms. The industry also faces a threat from exotic fungal species such as the oomycete *Aphanomyces invadans* which cause a serious pathological condition known as Epizootic Ulcerative Syndrome (EUS) in both farmed and wild freshwater fish (Huchzermeyer and van der Waal 2012).

Small-scale aquaculture farmers are usually the most affected because they lack knowledge on basic fish husbandry practices or disease prevention techniques. The spread of infectious diseases or susceptibility of the host is governed by many factors such as poor nutrition, culture technologies, stocking density, and poor water quality, among others. Temperature is one of the most important environmental factors influencing disease outbreaks. Temperatures below or above the optimal limits of the cultured fish will create stress, compromising the health of farmed fish. In most cases, most farmers do not have knowledge of disease identification or access to diagnostic equipment. This usually results in many diseases being underreported. This may be the reason why the role of infectious diseases in aquaculture has attracted the attention of veterinarians and researchers on the continent. Thus far, there are several diseases which have no prescribed remedies.

A number of prophylactic and therapeutic measures have been suggested, but many have not been successful in containing most of the common pathogens in aquaculture. One of the well-known measures that successfully worked in the past, but now seem to have limited success, is the use of antibiotics. With increasing usage, several pathogens have developed resistance towards antibiotic treatments. Recently, their use has also brought into sharp focus the environmental and human health risks associated with antibiotics use in aquaculture. A number of synthetic chemicals have also been used, some are still being used, although many of the chemicals have now been banned in many countries due to their harmful effect on the environment and their possible role in compromising human health. Thus, fish health and disease prevention are now considered a priority in aquaculture and viewed from different angles that include diagnosis and prevention of diseases through improving the immunity of cultured fish.

12.5.1 Medicinal Plants as Disease Controlling Agents in Aquaculture

The application of medicinal plants in fish culture is now considered the best strategy to control diseases in aquaculture. Medicinal plants contain a range of biologically active compounds with various pharmacological functions such as antifungal, antimicrobial, antiviral, growth promoters, immune-stimulatory, anti-inflammatory, anti-stress, and appetite-stimulating capabilities (Van Hai 2015). It is for these wide ranges of activities that the use of medicinal plants is regarded to be the most effective alternatives to antibiotics, vaccination, and other synthetic chemicals (Harikrishnan et al. 2011). Plants with these pharmacological activities usually contain active compounds such as alkaloid, terpenoid, phenolic, polyphenolic, quinone, lectin, and polypeptide compound (Harikrishnan et al. 2011). The other advantage of considering the application of medicinal plants in fish disease is that they are relatively cheaper and readily available to fish farmers. Therefore, using medicinal plants to manage diseases in fish culture especially in the small-scale industry can provide a suitable alternative as little training is required for users.

Furthermore, they are biodegradable and thus not harmful to the environment and fish consumers.

There are over 60 different plants species that have been investigated for their potential benefit in improving fish health and disease resistance. Most of the investigated plants are mainly those used in traditional medicine in various countries. A significant number of these plants are mainly found in Asian countries such as China, India, Thailand, and Korea (Bulfon et al. 2015). However, there are several studies that have investigated plants that occur worldwide and they include plants such as garlic (*A sativum*), garlic chives (*A. tuberosum*), green tea (*C. sinensis*), cinnamom (*Cinnamomum verum* or *zeylanicum*), turmeric (*Curcuma longa*), Sundial lupine (*Lupinus perennis*), mango (*Mangifera indica*), peppermint (*Mentha piperita*), nutmeg (*Myristica fragrans*), basil (*Ocimum basilicum* and *sanctum*), oregano (*Origanum vulgare*), rhubarb (*Rheum officinale*), rosemary (*Rosmarinus officinalis*) and ginger (*Zingiber officinale*), wormwood (*A. afra*), and moringa (*M. oleifera*). These are plants that can potentially benefit the aquaculture industry in Africa as they have abilities to enhance health and disease resistance in fish species mainly cultured in Africa, including tilapia, carps, trout, and catfish (Bulfon et al. 2015). The use of medicinal plants to control diseases in aquaculture is relatively cheaper than synthetic drugs. Using medicinal plants can thus benefit the small-scale aquaculture industry the most. A farmer does not need sophisticated infrastructure to prepare plant-based diets. Diets can be easily manufactured on the farm as medicated feeds. There are different methods of using plants in fish diets and each method may affect the efficacy of the plant in fighting disease. For instance, plants can be used as extracts or in powder form, using different parts of the plant, i.e., seeds, bulbs, leaves. The level of biological compounds is known to differ in the different parts of a plant. In addition, there are different ways of obtaining extracts from plants which include the use of water and different organic solvents (ethanol, methanol, ethyl acetate, hexane, butane, acetone, benzene, petroleum ether, etc.), or distillation to obtain essential oils. The use of plant powder is the cheapest form for most farm holders and scientific proof has shown that it is as effective as the other methods. Obtaining extracts from plants is also relatively simple, but it must be known that the choice of a solvent influences the presence of phytochemicals as a particular solvent may only be effective to extract compounds belonging to a particular group. Therefore, the chemical composition of a plant (powder or extract) has a direct impact on its efficacy as an immunostimulant. The immune-stimulatory properties of some of the widely available plants that can be used in African aquaculture are shown in Table 12.2.

12.5.2 Medicinal Plants as Immunostimulants in Fish

In fish, the innate immune response provides the first line of defence that keeps the body from being overwhelmed by pathogens. It also plays a vital role in activating the adaptive immune response (Whyte 2007). Leucocytes, also known as (white

Table 12.2 Immune-stimulatory properties and response of fish against pathogens fed with diets enriched with some of the widely available medicinal plants that can be used in African aquaculture due to their wide distribution

Fish species	Plant name	Dose	Immune indicators	Pathogenic response	Reference
Oncorhynchus mykiss (Rainbow trout)	*Allium sativum* (Garlic)	0.5% and 1% of	Phagocytic activity and respiratory burst and humoral immune parameters (total protein, lysozyme, antiprotease, and bactericidal activities)	*Aeromonas hydrophila*	Nya and Austin (2009)
	Mentha piperita (Peppermint)	1%, 2% and 3%	Lysozyme activity, respiratory burst activity, total protein, total immunoglobulin and peroxidase	*Yersinia ruckeri*	Adel et al. (2016)
Hybrid tilapia (*O. niloticus* × *O. aureus*)	*Allium sativum* (Garlic)	0.5% and 1%	Phagocytic, respiratory burst, total protein, lysozyme	N/A	Ndong and Fall (2011)
Oreochromis mossambicus	*Zingiber officinale* (ginger)	1%	Phagocytic activity, respiratory burst, lysozyme activity, total protein, and globulin	*Vibrio vulnificus*	Immanuel et al. 2009
	Zingiber officinale	0.1% and 1%.	Phagocytosis and extracellular burst activity of the blood leukocytes	N/A	Dügenci et al. (2003)
	Citrus sinesis (sweet orange)	1, 3, 5 g/kg	Lysozyme, myeloperoxidase, total protein, globulin	*Streptococcus iniae*	Acar et al. (2015)
	Citrus limon (bitter lemon)	0.5, 0.75, 1%	Respiratory burst, lysozyme, myeloperoxidase, total protein	*Edwardsville tarda*	Baba et al. (2016)
	Citrus limon	1–5%	Red blood cell, white blood cell counts, haematocrit, mean cell haemoglobin, mean cell haemoglobin concentration, and immunological parameters, namely serum immunoglobulins, lysozyme activity, and respiratory burst.	*Aeromonas hydrophila*	Ngugi et al. (2017)

(continued)

Table 12.2 (continued)

Fish species	Plant name	Dose	Immune indicators	Pathogenic response	Reference
	Artemisia afra	3%, 6%, 9%, and 12%	White blood cells, lysozyme, and phagocytic activities	*Aeromonas hydrophila*	Mbokane and Moyo (2018a)
	Moringa oleifera	3%, 6%, 9%, and 12%)	White blood cells, lysozyme, and phagocytic activities	*Aeromonas hydrophila*	Mbokane and Moyo (2018b)
Clarias gariepinus	*Artemisia afra*	3%, 6%, 9%, and 12%	White blood cells, lysozyme, and phagocytic activities	*Aeromonas hydrophila*	Mbokane and Moyo (2020a, b)
	Moringa oleifera	3%, 6%, 9%, and 12%	White blood cells, lysozyme, and phagocytic activities	*Aeromonas hydrophila*	Mbokane and Moyo (2020b)
Oreochromis niloticus	*Aloe vera*	0.5, 1, 2, 4%	Lysozyme and total protein	N/A	Gabriel et al. (2015a)
	Camellia sinensis (green tea)	0.125, 0.25, 0.5, 1, 2%	Respiratory burst and bactericidal	*Aeromonas hydrophila*	Abdel-Tawwab et al. (2010)

blood cells), are considered as the back-bone of all immune responses. The most abundant leucocytes are phagocytes (monocytes/macrophages and neutrophils). When a pathogen invades a fish, it is faced by phagocytes which engulf it and initiate an inflammatory response. In addition, there is a repertoire of soluble molecules that also play a vital role in innate physiological defences in fish. These comprise the following molecules: complement, transferrins, interferon, anti-proteases, lysozyme, and C-reactive protein (Whyte 2007).

Medicinal plants are known to improve the innate (or non-specific) immune response in fish (Sakai 1999; Table 12.2). As shown in Table 12.2, dietary administration of medicinal plants or their extracts has been reported to enhance a wide range of cells involved in innate immune response including phagocytic activity, respiratory burst activity, nitrogen oxide, myeloperoxidase content, complement activity, lysozyme activity, total protein (globulin and albumin), and antiprotease activity in many fish species (Awad and Awaad 2017). Phagocytic cells kill pathogens by engulfing them and producing toxic or microbicidal oxygen forms and nitrogen reactive species (NOS) during a process called the respiratory burst. The release of these unstable molecules from phagocytes has been shown to increase in fish after administering an immunestimulant (Siwicki et al. 1994). Many biological activities from medicinal plants have been attributed to the several active compounds such as phenolics, tannins, saponins, polyphenolics, flavonoids, terpenoids, alkaloids, and flavonoids (Harikrishnan et al. 2011; Van Hai 2015). Some of these active compounds possess immunomodulatory, antifungal, antibacterial, and antiviral properties, which offers protection against many diseases in fish. The presence of compounds with anti-bacterial, antifungal, and antiviral properties in the fish's system may directly inhibit the replication of pathogens in the host (Awad and Awaad 2017). Moreover, most of these compounds have antioxidant properties and act as protective agents by preventing or delaying the oxidative damage as they effectively scavenge reactive oxygen species (ROS) (also known as free radicals) and other most oxidizing molecules responsible for compromising the immune system in animals and thus contributing to the occurrence of several diseases (Xie et al. 2008).

12.5.3 Medicinal Plants as Antibacterial Agents

Some of the biologically active compounds from medicinal plants possess antimicrobial, antifungal, and antiviral activities. That means their extracts can inhibit the growth of pathogens directly. While in most cases, studies have used different pathogens to assess the capacity of a fish's immune response after oral administration of medicinal plants, the response is usually attributed to the stimulatory properties of the medicinal plant being assessed. However, even in such studies where pathogens are used to challenge fish after feeding with plant-based diets, it is probable that the presence of compounds with anti-bacterial, antifungal, and antiviral properties in the fish's system may directly suppress the growth of the pathogen inside the host (Awad and Awaad 2017). Although there are relatively few in vitro studies that have been carried to evaluate the antimicrobial, antifungal, and antiviral activities of extracts of most medicinal plants used in aquaculture, there is some evidence showing that a number of microorganisms display different sensitivities to medicinal plants (Reyes-Becerril et al. 2021). Most of the studies mentioned in this chapter have investigated the response of fish fed with plant-based products against bacteria such as *A. hydrophila*, *Vibrio* (*Vibrio harveyi*, *V. anguillarum* and *V. alginolyticus*), *Streptococcus* (*S. agalactiae* and *S. iniae*), and *E. tarda*.

Numerous researchers have shown that compounds extracted from medicinal plants can inhibit the growth of both Gram-positive and Gram-negative bacteria. For instance, Reyes-Becerril et al. (2021) has recently shown that seed extracts from *M. oleifera* exhibited antibacterial activity against *V. parahaemolyticus* and *A. hydrophila*. In addition, the essential oil of *M. oleifera* has also been shown to have both antibacterial and antifungal activities. Chuang et al. (2007) found that the essential oil of *M. moringa* had antibacterial activity against two Gram-positive strains (*Bacillus cereus*, *Staphylococcus aureus*) and two Gram-negative strains (*Escherichia coli*, *Pseudomonas aeruginosa*). The oil further demonstrated antifungal activity against several pathogens, namely, *Trichophyton rubrum*, *T. mentagrophytes*, *Epidermophyton xoccosum*, and *Microsporum canis* (Marrufo et al. 2013). Dip treatments containing extract isolated from *A. indica* were shown to facilitate healing in *C. carpio* experimentally challenged with *A. invadans* (Harikrishnan et al. 2005). Abdul Kader Mydeen and Haniffa (2011) also observed that aqueous extracts from the same plant were effective against *A. hydrophila* infection in *C. carpio*. Similarly, aqueous extracts from *Solanum torvum* (Sundakai fruit coat) and *C. longa* (rhizome) inhibited the growth of *A. hydrophila* (Abdul Kader Mydeen and Haniffa 2011).

In vitro experiments undertaken by Harikrishnan et al. (2009) indicated that a mixture of medicinal plant compounds, azadirachtin, camphor, and curcumin yielded higher zones of inhibitions against *A. invadans*. Extracts from *Rosmarinus officinalis* were efficacious against *Streptococcus* infection (Abutbul et al. 2004). Chitmanat et al. (2005) showed that Indian almond extract (*Terminalia catappa*) had antibacterial activity against two strains of *A. hydrophila* from *O. niloticus*. Aqueous and alcoholic extracts of *Nuphar lutea*, *Nymphaea alba*, *Stachys annua*, *Genista lydia*, *Vinca minor*, *Fragaria vesca*, *Filipendula ulmaria*, and *Helichrysum plicatum* showed antibacterial activity against a number of pathogens isolated from fish, namely, *A. hydrophila*, *Yersinia ruckeri*, *Lactococcus garvieae*, *Streptococcus agalactiae*, and *Enterococcus faecalis* bacteria (Turker et al. 2009). Ravikumar et al. (2011) also reported that extracts from *A. indica*, *Cinnamomum verum*, and *Eupatorium odoratum* exhibited antibacterial activity against a number of bacterial pathogens from diseased ornamental fishes. Shangliang et al. (1990) reported the antimicrobial activity of extracts from five Chinese herbal plants, namely, *Stellaria aquatica*, *Impatiens biflora*, *Oenothera biennis*, *Artemisia vulgaris*, and *Lonicera japonica*, against 13 bacterial fish pathogens. Their findings showed that *A. salmonicida* and *E. ictaluri* were the most sensitive to the extracts of these five plants. Finally, Castro et al. (2008) found that methanolic extract of 31 Brazilian plants had antibacterial activities against fish pathogenic bacteria, viz., *S. agalactiae*, *F. columnare*, and *A. hydrophila*.

There is clear evidence suggesting that extracts from medicinal plants can be used to control bacterial infections in fish culture. There is, therefore, a greater need for researchers to test the anti-bacterial activities of extracts of the plants most investigated in aquaculture against the most common pathogens of fish. One of the easiest ways in which plant products can be used as antibacterial agents in aquaculture is through dips or baths. Baths are easy to effect on a small-scale farm, although the process can be labour-intensive and time-consuming depending on the size of the farm or the number of fish to be treated. For instance, separate treatment tanks may have to be setup and it may be absolutely necessary to ensure that baths are executed in water containing sufficient oxygen and fish are immediately transferred to clean and well-oxygenated water after treatment. Depending on the concentration of the plant extracts, baths could vary from a few seconds to a couple of minutes. It should be possible for smallholder farmers to master the different extraction methods as dips/baths will require that a plant extract be used. Some of the plant products are now available on the market in liquid form, albeit on a limited scale. The only disadvantage with baths is that the process could be stressful to fish due frequent handling of the fish and, therefore, it should be carried out with great care. Alternatively, fish farmers may be able to add appropriate dosages of a plant extract to their tanks or ponds and minimize stressful conditions for the fish. One of the advantages of using plants in fish culture is that their constituents are biodegradable and, thus, their addition into the water should have minimal negative effect on fish health, human health, and the environment. On the other hand, it can provide the fish with protection from a number of pathogenic bacteria. However, more studies are still required to investigate the effectiveness of plant extracts and associated dosages at farm level.

12.6 Medicinal Plants Application in Feeds for Small-Scale Aquaculture

It appears that more research is still required to determine which of the tested plants and the appropriate dosages can be considered for inclusion in the diets of different fish species. Literature indicates that some of the tested plants may be used to enhance growth only, while some may also be used to boost immune response or both in one fish species. In other cases, evidence strongly shows that a plant may improve growth in one fish species but fail to do the same in another fish species. So far, most of the plants have only been conducted at an experimental level, and few, if any, have been tested at a commercial level. Nevertheless, there is overwhelming evidence that certain plants can be incorporated in the diets of some fish species depending on the preference of a farmer. In the small-scale fish farming industry, this seems easily achievable. In terms of disease management, for example, it is possible for farmers to prepare medicated feeds on the farm because doing so is easy and requires little expertise. Using medicated feeds is easy and inexpensive in many circumstances. However, farmers may experience challenges using some of the plants for growth performance without sufficient evidence on a large scale or addressing some of the fundamental limitations associated with plant-based diets on growth performance in fish. For example, most plants usually do not have acceptable levels of protein and amino acids to meet the specific requirement for some fish. If high amounts of the plant were to be used to compensate for the low protein and amino acid profile, levels of ant-nutritional factors (ANFs) in the diet will increase and negatively affect the health and growth of fish. This has been one of the major challenges for scientists to resolve because the effectiveness of a particular plant largely depends on the dosage used. On the other side, the efficacy of a particular dosage of a plant is influenced by its chemical composition and their associated concentrations. Therefore, the chemical characteristics of a plant influence its toxicity and efficacy of chemotherapeutic treatment and a plant has to be assessed thoroughly before any large-scale application. It has been recommended to start with small dosages on a small number of fish and if the response is weak, then it may be necessary to progressively adjust dosage levels.

12.6.1 Medicinal Plants Application in Aqua Feeds

In recent years, researchers have focussed on searching for alternative protein ingredients for use in aquaculture feeds. Plants with high protein levels are preferred because dietary protein enhances growth performance in fish (Musuka et al. 2009). Research efforts have focused on the replacement of fishmeal with less expensive locally available sources (Enami 2011) especially meals from processed seedcakes. Most studies were carried out to determine the effects of replacing fishmeal with plant proteins in tilapia diets have focussed mainly on soybean meal (Wee and Shu 1989; Shiau et al. 1990; Webster et al. 1992). Other plant-based fishmeal replacers explored include maize gluten meal (Wu et al. 1997); lupins (Fontainhas-Fernandes et al. 1999); rapeseed (Davies et al. 1990), and distillers dried grains (Coyle et al. 2004).

There is a need to continually search for new sources of protein in fish diets because competition from other sectors has led to the commercialisation of some of the widely used plant protein resources (soybean meal, rapeseed meal, and sunflower meal). Leaf meals are potentially good sources of protein because of their rapid growth enabling several harvest times per growing season compared to seed meals. An appreciable amount of work has been done on the use of different leaf meals as inexpensive sources of protein in fish feeds such as cassava (Ng and Wee 1989); sweet potato (Adewolu 2008); alfalfa (Yousif et al. 1994); moringa (Richter et al. 2003); *Leucaena leucocephala* (Bairagi et al. 2004).

Replacement of fishmeal in fish diets without reducing the growth performance would result in more profitable aquaculture enterprises. The negative effects caused by plant-based diets on the digestive morphology and growth performance have been extensively studied in carnivorous fish (Krogdahl et al. 2000). However, the adverse effects of plant-based diets on the digestive physiology of herbivorous fish have been overlooked. Previous research done on fishmeal replacement diets fed to herbivorous fish has focussed on growth performance. Understanding the effect of plant-based diets on the digestive enzyme activities, morphology of the digestive organs and health of fish is pivotal in finding ways to reduce their adverse effects.

Some plants are known to possess high concentrations of (Anti-nutritional factors) ANFs. Anti-nutritional factors usually affect fish health when excessively applied in fish diets, but they are said to be beneficial when used in smaller quantities (Makkar et al. 2007). Anti-nutritional factors are organic compounds that interfere with food utilisation by negatively affecting palatability, growth performance, and health of animals (Makkar et al. 1993). They are naturally occurring chemical substances in plants. Most researchers have identified anti-nutritional factors as one of the main factors limiting the inclusion of plant ingredients in fish diets (Krogdahl et al. 2000). Anti-nutritional factors have been reported to result in poor palatability, chronic intoxication, poor feed intake, alteration of gut morphology, interference with the digestion, and utilisation of dietary nutrients of plant-based diets (Francis et al. 2001). The main anti-nutritional factors identified in plant protein sources used as fishmeal replacers in tilapia diets include saponins, tannins, fibre, and protease inhibitors.

12.6.2 How to Reduce the Effect of Anti-Nutrients?

The identification and destruction of anti-nutritional factors that inhibit nutrient utilization is imperative for the successful use of plant-based protein resources in fish feed. Several studies have been conducted to find effective ways of destroying anti-nutritional substances in plant-based diets and increase their utilisation. The use of exogenous enzymes may be the most effective way to inactivate anti-nutritional factors and enhance the nutritional value of plant-based protein in tilapia feeds (Dalsgaard et al. 2012). Hlophe-Ginindza et al. (2016) found that adding natuzyme, a mixture containing several enzymes (protease, lipase, amylase, cellulase, amyloglucosidase, b-glucanase, pentosonase, hemicellulase, xylanase, pectinase, acid phosphatase, and acid phytase) improves feed utilisation and growth performance in *O. mossambicus*. Lin et al. (2007) reported that supplementing a mixture of enzymes containing neutral protease, b-glucanase, and xylanase to a plant-based diet promoted the secretion of endogenous protease and amylase in the Nile tilapia. Phytase supplementation not only releases bound phosphorous from phytate but also releases amino acids and minerals, ensuring maximum utilisation of dietary nutrients. Supplementing with a combination of exogenous enzymes (phytase, protease and xylanase) showed increased growth performance, improved intestinal morphology, and a stimulating effect on serum lysozyme activity of *O. niloticus* (Adeoye et al. 2016). Supplementing with exogenous enzymes such as protease and amylase complements endogenous enzymes and enhances the digestibility of plant nutrients (Soltan 2009). The addition of enzymes containing cellulase, xylanase, and glucanase in plant diets with high fibre and high cellulose levels resulted in increased nutrient digestibility and nutrient utilisation (Tahir et al. 2008). Additionally, certain extracts can be used to reduce the amount of certain ANFs before a plant extract is used in fish diets. For example, saponnis can be effectively removed by aqueous or solvent extraction (Afuang et al. 2003). Tannins in plant-based protein resources can be inactivated by soaking in an alkaline solution (Ben Salem et al. 2005), fermentation (Mukhopadhyay and Ray 1999), or supplementation with a tannin complexing agent such as polyethylene glycol (Makkar 2003).

12.7 Medicinal Plant Extracts as Anaesthetics in Aquaculture

In aquaculture, fish are usually subjected to activities and routine procedures such as collecting broodstock from the wild, transporting fish from the wild and within the farms, performing sampling (biometry), artificial breeding, grading, among others. These activities are known to be stressful to the fish and to an extent may lead to increased mortality, if proper management practices are not considered (da Costa et al. 2019). It is for this reason that anaesthetic applications have become a common and essential practice in aquaculture (de Souza et al. 2019; Hoseini et al. 2019). There are a number of fish anaesthetics that have been developed for aquaculture operations such as methanesulfonate (MS-222), etomidate, benzocaine, propofol, quinaldine, and metomidate. These products are effective in their functions; however, they are associated with a number of shortcomings such as high cost, unavailability especially in most African countries, and/or have caused stress (i.e. inhibition of cortisol synthesis) and haematological disorders in fish (Zahl et al. 2012; Gressler et al. 2014). Hence, this calls for search in alternative fish anaesthetics that are more affordable, locally available, easily applicable, and with minimal effects on fish, humans, and the environment.

In this regard, essential oils (EOs) from medicinal plants have been recently reported as one of the potential anaesthetic alternatives in aquaculture (Bodur et al. 2018; Hoseini et al. 2019). This is because EOs are rich in compounds such as terpenoids, which have the ability to cross blood-brain barrier where they can modulate brain function/central nervous system (CNS) (Bianchini et al. 2017). This qualifies them to be used as ideal anaesthetics in fish as they are able to induce fast anaesthesia (3 min or less) with minimum hyperactivity or stress and rapid recovery (within 10 min or less) after fish transference to anaesthetic-free aquaria (Gilderhus and Marking 1987). Parodi et al. (2012) and de Souza et al. (2019) suggested the use of EOs from *L. alba*, *Aloysia triphylla*, and *Melaleuca alternifolia* as anaesthetics in aquaculture due to ease of access, availability, and the costs compared to synthetic anaesthetics. Benovit et al. (2012) used EOs from *A. gratissima* and *Ocimum gratissimum* L. (Lamiaceae) as sedatives in Brazilian flounder, *Paralichthys orbignyanus*, where 900 mg/L of *A. gratissima* caused a rapid anaesthesia (about 4 min). The ideal anaesthetic EOs from other herbs such as *Mentha piperita* (de Oliveira Hashimoto et al. 2016), *Thymus vulgaris* (Azad et al. 2014), *Ocimum gratissimum*, *Lippia alba* (Toni et al. 2014), *Coriandrum sativum, Bursera delpechiana*, and *Lavandula hybrida* (Can et al. 2019) were also reported in fish. The same was also reported for herbal EOs derivatives, i.e. carvacrol (Bianchini et al. 2017), methly eugenol (Khumpirapang et al. 2018), linalool (Mirghaed et al. 2016), and 1,8-cineole (Mirghaed et al. 2018). Most of these plants are found almost everywhere across the globe and the African continents. Therefore, it is a good thing for the African aquaculture smallholders and researchers to adopt plant EOs as anaesthetics in aquaculture to reduce stress, mortality and improve the welfare of their farmed animals during aquaculture operations.

12.8 Medicinal Plants as Sex Reversal Agents in Aquaculture

Fish farming has different challenges, ranging from the production of uneven sizes of fish, low growth, and low survival rate (Biswas et al. 2005). One of the methods adopted by fish farmers to address some of the challenges mentioned above is farming with a monosex population, where males are preferred over females as they grow faster and spend less energy in reproduction (Biswas et al. 2005). The above has led fish farmers to employ different sex-reversal methods, including the usage of medicinal herbs, to increase fish growth and ultimately yield and economic returns from their farming enterprises (Gabriel 2019). Medicinal plants have androgenic characteristics of phytochemicals, which can disrupt vertebrates' reproductive biology (Gabriel et al. 2015b). The phytochemicals influence the reproductive biology of animals similarly as that of testosterone or estrogens (Bradbury and White 1954). Phytochemicals that are found in medicinal herbs include alkaloids, flavonoids, saponins, and tannins (Kuete 2013). The phytochemicals work by blocking biosynthesis and the action of oestrogen (Gabriel et al. 2015b, 2017; Gabriel 2019).

Successful sex reversal effect in fish has been observed for dietary *A. vera* (Liliaceae) on Nile tilapia Fry (Gabriel et al. 2017); for pawpaw (*Carica papaya*) seed meal on three spotted tilapia (*O. andersonii*) fry (Gabriel et al. 2017); for *Basella alba* leaf on *O. niloticus* (Ghosal et al. 2021)*;* for *Tribulus terrestris* seed on *O. niloticus* (Ghosal et al. 2021)*;* for *Mucuna pruriens* seed on *O. niloticus* (Ghosal et al. 2021)*, Asparagus racemosus* root on *O. niloticus* (Ghosal et al. 2021)*; Gokshura (T. terrestris)* on *C. gareipenus*) (Turan and Çek 2007); *Hibiscus Rosa-sinensis* (Linn.) *O. niloticus* (Jegede 2010)*; and* crude extract of *Azadirachta Indica* saponin on *O. niloticus* (Obaro et al. 2012). Medicinal plants like red clover *(Trifolium pratense L.)* have also been observed to lead to the feminization of *C. gareipenus* (Turan et al. 2021). Sex reversal agents of plant origin could be appropriate for the African tilapia aquaculture smallholder farmers to improve yield by curbing the problem of early maturing, and stunted growth in tilapia species.

12.9 Conclusion and Future Perspectives

It is now an established fact that the widely adopted intensive aquaculture farming systems demands for a high level of management to support better fish growth, feed utilization, improve rearing water quality, reduce stress, and lower the incidences of disease outbreaks. This chapter has provided considerable proof that medicinal plants have the potential to improve feed nutritional quality and feed utilization, control disease outbreaks, enhance health and resistance against pathogens, and act as anaesthetics and sex reversal agents in fish culture. Besides, medicinal plants sound to be more appropriate for African smallholder aquaculture farmers for many reasons: (1) they are inexpensive, (2) readily available, (3) simple to apply, (4), diverse in nature, and (5) more biodegradable. Although there are thousands of research outputs on medicinal plants in aquaculture across the globe, the African continent is contributing little. The awareness about the potential benefits of medicinal plants in aquaculture on the African continent is only emerging in some countries (mainly Egypt and Nigeria). This could be a result of lack of awareness, well-equipped research facilities to perform trials across Africa, lack of research funds, and limited researchers in the field of aquaculture. Another challenge is that there is a lack of implementation of this innovation in aquaculture across Africa at all levels of aquaculture.

Going forward, there is a need to study the unstudied medicinal plants available in Africa and validate and optimize those studied elsewhere in the African aquaculture species and culture settings (i.e. in the lab and smallholder culture systems). In this way, African aquaculture farmers at all levels would be confident in adopting medicinal plants in aquaculture and take advantage of all the benefits associated with medicinal plants. In essence, medicinal plants have the potential to play an important role in the sustainable development of the aquaculture industry.

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Chapter 13
Application of Integrated Water Resources Management Towards Livelihood Improvement: A Case of Smallholder Farmers in Olushandja, Namibia

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Abstract Namibia is a semi-arid country, often affected by droughts and occasional floods in some of its regions. This forces smallholder farmers to battle with the challenge of water availability for productive agricultural use. To address the water challenges, Namibia developed and adopted Integrated Water Resource Management (IWRM) as per the Dublin Conference of 1992. The IWRM approach was implemented to provide an enabling environment for smallholder producers to increase food production such that food security and nutritional levels of all people in the country can be improved. In order to effectively implement IWRM, River Basin Organizations were used to foster water management at grassroots level. The Olushandja sub-basin is one such river basin, found in the larger Cuvelai-Etosha Basin (CEB). Smallholder farmers in the sub-basin are part of the Olushandja Horticulture Producer Association (OHPA) which aims to contribute to the agricultural sector in Namibia by cultivating crops for individual income, creating employment opportunities in the area and enhancing horticultural skills, thereby contributing to food security in the sub-basin. This chapter thus rests on the foundation that livelihood improvement and food security comes from effective management of water resources with a particular example on its application by

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smallholder farmers, found in Olushandja, in the north-central Omusati region of Namibia.

Keywords Integrated Water Resources Management · River Basin Organization · Water resources · Agriculture · Olushandja

13.1 Introduction

Smallholder farmers who constitute the majority of producers in sub-Saharan Africa still face challenges of accessing water for productive agricultural use (Williams et al. 2014). Since many households are dependent on subsistence agriculture, the lack of reliable water sources for productive purposes is the primary cause of food insecurity and lower standards of living in developing countries (Merrey et al. 2005). Food security is a global problem that receives developmental priority in many legal instruments, for example, Agenda 2030, Agenda for Sustainable Development (Conceição et al. 2016). With more than one in four Africans undernourished, and food insecurity remaining persistent (Besada and Werner 2015), ensuring food security depends on the adequate quantity and quality of water supply. This has become of paramount importance in many less developed countries of the world (UNEP 2012). However, water resources and agricultural production for smallholder farmers in sub-Saharan countries have become vulnerable to climate change (Tesfahunegn and Gebru 2020), that is, droughts and heat stress, which threatens fish and crop production and consequently food security (Nshimbi 2019). These limitations hinder the prospects of agricultural intensification by smallholder farmers, and consequently, compromises their ability to meet the demand for food (Giordano et al. 2019). Moreover, in Namibia, the agricultural sector consumes about 75% of water, with the commercial agriculture being the largest consumer and communal farmers being the least consumptive (Dirkx et al. 2008). Namibia's Vision 2030 highlights the need for increased agricultural productivity, in order to achieve food security by the year 2030. The Green Scheme Policy was devised in support of this national objective, with the goal of promoting increased investment and food production with irrigation. Having created 23% of the total employment in the country, the agriculture sector alone contributed more than 5% to GDP in the last 10 years (Nangolo and Alweendo 2020). Improving the productivity of agricultural production of rural communities thus provides opportunities for improving livelihoods and enhancing food security (GRN 2005).

13.2 Water Resource Use in Namibia

Water supply is becoming an increasing constraint for Namibia. Until the beginning of the 1990s, emphasis was placed on supply augmentation, and over the last 40 years, surface water dams have been built to collect run-off from ephemeral rivers (Christellis et al. 2001). However, augmenting water supply is becoming increasingly expensive as the country has to look further afield for water. As a result, Water Demand Management (WDM) was implemented, to reduce demand rather than continue to augment supply. Non-conventional supply schemes have thus also become important components in Namibia's Integrated Water Resources Management (IWRM) programme (Biggs and Williams 2001).

Additionally, water is supplied from three natural sources, namely, groundwater, perennial and ephemeral surface water. Perennial surface water is supplied by the rivers, which flow year-round and form the northern and southern boundaries of Namibia. Ephemeral surface water is supplied by rivers within the country that only flow after long rains. Groundwater is found throughout the country and is one of the most commonly used water sources (Christellis et al. 2001). Water supply is further divided into three categories: bulk water supply, rural water supply and the private water development, as controlled and managed by the state-owned Namibian Water Corporation Limited (NamWater) and the Directorate of Rural Water Supply and Sanitation Coordination (DWSSC) within the Ministry of Agriculture, Water and Land Reform (MAWLR). Water from these sources varies in terms of accessibility, quality, and reliability, and their use also varies depending on rainfall received (Lange 1997).

Furthermore, in north-central Namibia, traditional water supply techniques, such as *Oshanas* and excavation dams *(Omatale*), shallow dug wells (*Omuthima*), dug wells *(Oshikweyo*), and rainwater harvesting, play a crucial role in the livelihoods of local communities as they are used by communities for human and livestock consumption (Zimmermann 2010; Hartley 1997). These water sources are primarily important to rural communities, the main advantage being that water is free to use despite their poor quality, that is, highly saline (Kluge et al. 2008). Access to clean water is limited by the long distances between communities and available water points. It is assumed that about 15% of the population in the northern region live further than 2.5 km from clean drinking water (Liehr et al. 2017).

Smallholder farmers in the northern regions traditionally depend on naturally unreliable rainfall, which has become increasingly variable and scarce in recent years. The average annual rainfall is about 330–500 mm and surface water is scarce, making rain fed cultivation highly risky (FAO 2005). The regions are prone to flooding and severe droughts, further limiting crop productivity and threatening food security (Angula et al. 2014). Irrigation is only possible along the bordering perennial rivers and/or where dams either feed irrigation schemes or where sub-artesian water can be utilized (Christellis et al. 2001). This once again, in its entirety, demonstrates the country's unstable and unreliable food security situation.

The intensification of efforts to increase access to water, ensuring its efficient use and making water available for small-scale agricultural production (including livestock, fish, crops) in regions where rainfall is unreliable, becomes important. Given the fact that sociocultural and economic aspects in northern Namibia influence water resource management practices, and with the increasing competition for water across sectors, innovative systems will be required for water rights, allocation and management. One such system is the framework of Integrated Water Resources

Management (IWRM), which is crucial in meeting and managing the increasing water demand. The idea of IWRM is to optimize the use of water and provide vital impetus to reduce poverty (Biggs and Williams 2001). Against this background, this chapter seeks to highlight the importance of water resources management in addressing food security in Namibia.

13.3 A Brief Overview on Integrated Water Resources Management (IWRM)

The concept of Integrated Water Resources Management (IWRM) became popular because of the debate on sustainable development, as triggered by the United Nations at the beginning of the 1990s (Zimmermann 2010). Globally, the accepted definition of IWRM by the Global Water Partnership states that IRWM is “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (Babel 2005; SIWI 2020). IWRM does not only look at, amongst others, water supply and wastewater treatment, but combines many other functions, including flood control, poverty alleviation, food production, ecosystem conservation and drought management (Rahaman and Varis 2005). IWRM seeks to establish a path for sustainable development and management of water and related resources, while at the same time improving the livelihoods of people (Oremo et al. 2019). As a management practice, IWRM emphasizes the decentralization of water management to the local level, by increasing the participation of local communities in the decision-making process (Hu et al. 2014).

Following the International Conference on Water and Environment, held in Dublin, Ireland, in 1992, four guiding IWRM principles (also known as the Dublin Principles), which form the basis for implementing IWRM were formulated:

1. Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment.
2. Water development and management should be based on a participatory approach, involving users, planners, and policymakers at all levels.
3. Water has an economic value in all its competing uses and should be recognized as an economic good.
4. Women must play a central part in the provision, management and safeguarding of water (SIWI 2020).

At the regional level, the SADC region has embraced the IWRM approach and demonstrated the political will to decentralize the governance or management of water resources through River Basin Organizations (RBOs). The RBOs in Southern Africa are well capacitated to address issues regarding the conservation, development and utilization of water resources (Nshimbi 2019). This is essentially manifested through the principles of IWRM, which could pave the means through which water discussions amongst smallholder famers could be addressed.

13.4 Water Resources Management in Namibia

Since the early 1990s, numerous plans, strategies and water laws that aimed at achieving the sustainable use and integrated management of water have been developed. These included the development of national water policies and draft legislations (Table 13.1), to develop, manage and regulate activities in the water sector (Heyns 2005; Remmert 2016).

The process of implementing the principles stipulated in the Water Resources Management Act (WRMA) of 2004 began with the demarcation of the country into Water Control Areas (WCAs) and establishment of individual Basin Management Committees. These not only serve to protect, develop and control water resources in the respective catchment area, but to also develop plans for the use of water resources and to ensure the participation of local communities (Kluge et al. 2008).

IWRM was introduced in the north-central region through the Olushandja sub-basin, an administrative unit for implementing IWRM at grassroots level. The Olushandja sub-basin is one of four sub-basins in the larger Cuvelai Etosha Basin (Fig. 13.1). It is characterized by the western surface and groundwater flow regime of the Etosha Pan.

One of the major water sources found in the sub-basin is the Olushandja Dam (Department of Water Affairs 2004) which stretches about 20 km and covers a total area of about 30 km^2 with capacity of 42 Mm^3 (Kapalanga et al. 2020). A water quality analysis, pertaining to irrigation suitability, indicated that the water is suitable for irrigation (Department of Water Affairs 2004).

The Olushandja Dam currently has several direct users ranging from fisheries, smallholders' horticultural farmers and indirect users such as subsistence livestock farmers for grazing and livestock watering. IWRM is thus a key tool set out to reconcile multiple, competing uses for water, with legitimacy attained through river basin units that foster public participation (Smith and Jønch Clausen 2015).

Table 13.1 Applicable legal instruments relevant for water resources management in Namibia

Legal tool	Year developed
Water Act No. 54	1956
Namibia Water Corporation Act No.12	1997
National Water Policy White Paper	2000
Water Resource Management Act No. 24	2004
Water Supply and Sanitation Policy	2008
Integrated Water Resource Management Plan	2010
Water Resources Management Act No. 11	2013

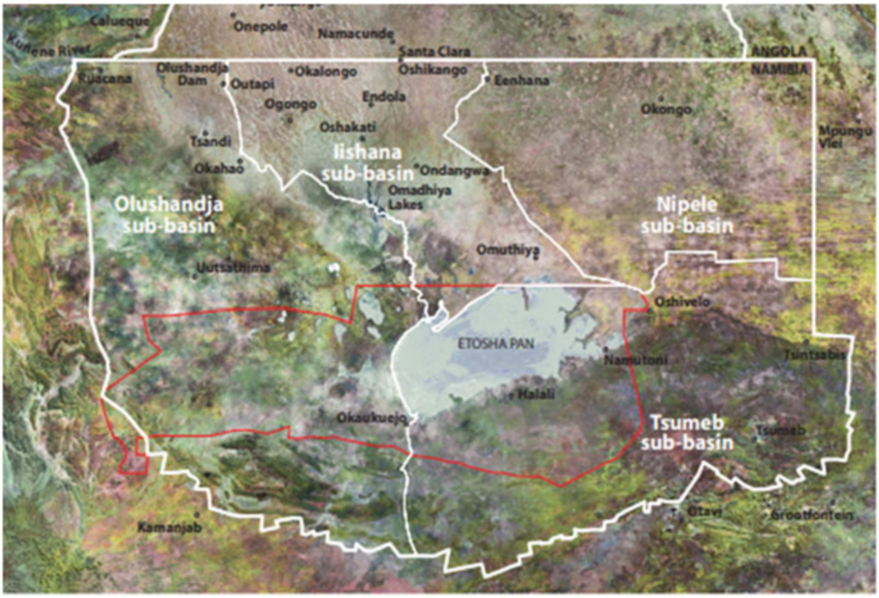

Fig. 13.1 Map showing the four sub-basins in the larger Cuvelai Etosha Basin. Source: JARO Consultancy 2021

The Olushandja sub-basin committee has representatives from various institutions, namely; traditional authorities, farmer's associations and government line ministries with a significant stake in the water sector. This allows for a holistic engagement and responsibility towards the promotion and coordination of IWRM at grassroots level (Besada and Werner 2015). Through the IWRM framework, the Olushandja sub-basin provides a platform for stakeholder participation and an opportunity to engage water users (such as the OHPA), not only to promote understanding of water sector reforms, but as means of building support for policies and sustainable water use practices (Oremo et al. 2019).

13.5 Addressing Food Security in the Olushandja Sub-Basin

Knowledge sharing and participation are identified as central tasks for optimized water allocation between the various sectors. Therefore, meeting the demand for improved agricultural production by small-scale farmers is possible, if industry players, such as producers, banking institutions, input suppliers (seeds, fertilizers, market researchers, etc.), electricity and water suppliers etc., form synergies that can contribute towards driving the ultimate goal of food security (MAWRD 1995).

In 2005, a group of smallholder farmers established the Olushandja Horticultural Producers Association (OHPA), consisting of more than 70 registered members, who farm along the Olushandja Dam (Van Wyk 2020). Through the sub-basin, various stakeholders were brought together. The OHPA are participatory stakeholders in the Olushandja sub-basin fostering a coordinated and inclusive decision-making process for the management of the limited water resources in the sub-basin. Moreover, their participation is covered by the second IWRM principle which encourages a participatory approach, involving users, planners, and policymakers, at all levels of water development and management (Rahaman and Varis 2005). Of relevance to the OHPA is the Namibia Agronomic Board (NAB). The NAB was established as an effort to support the agronomic and horticultural development by controlling the import of staple foods into Namibia (Frøystad et al. 2009). These efforts are further supported by the Green Scheme Policy of 2008, which forms part of the Government's commitment to attain food security in the country and support smallholder farmers to diversify agricultural production and products for the domestic and export markets in order to achieve Vision 2030. Namibia's Vision 2030 also seeks to ensure that the water resources are used to drive social well-being and support economic development as indicated in the Fifth National Development Plan (NDP5) (GRN 2004; NPC 2017)

Although the farmers still sell their produce to informal markets, the NAB provides collective forecasts for horticultural production of the north-central region from small-scale farmers (Table 13.2). Should there be a deficit in the local formal markets, the produce from the small-scale farmers relieve the deficit (Namibia

Table 13.2 Expected tonnage, yield and hectares of crops to be harvested July–November 2021 from North-Central Region

Controlled crop	Jul	Aug	Sept	Oct	Nov	Total forecasted yield	ha to be harvested
Butternut	55.37	13.77	49.98	0	0	119.11	8.89
Cabbage	215.4	197.54	168.73	28.9	8.5	620.08	17.31
Gem squash	7.65	7.48	5.78	3.4	0	24.31	2.41
Onions	7.65	7.48	5.78	3.4	0	69.62	7.10
Pumpkins	0	0	15.47	15.47	0	30.94	2.8
Tomato round	6.5	6.7	0	0	0	13.2	0.6
Tomato jam	83.3	154.7	1165.2	29.3	108	1540.5	20.4
Carrot	4	2.4	2.4	0	0	8.7	2.4
Green pepper	5	5.5	5.9	2	0.3	18.7	2.1
Sweet corn	1.8	1.8	0	0	0	3.5	0.5
Spinach	33.8	33.2	32.7	25	25	149.6	11.6
Beetroot	7.9	4				11.85	0.75
Sweet potatoes	125.2	58.9	25.7	18.4	30.6	258.76	14.16
Water melon	0	40.9	8.1	95.5	0	144.5	5.7
Sweet melon	0	0.7	8.8	0	0	9.5	0.73

Source: Namibia Agronomic Board 2021

Agronomic Board 2021) The Olushandja small-scale farmers are classified under the north-central region.

Traditionally, crops in the north mainly consisted of pearl millet (locally known as *mahangu*) (Liehr et al. 2017), maize with some veld (wild) fruits; however, the IWRM approach adopted for the Olushandja sub-basin has allowed the smallholder farmers of the OHPA to grow a wide variety of crops such as maize, tomatoes, peppers, onions, beetroots, spinach, butternuts, watermelons, cabbage and cowpeas, and there exists potential for other vegetables as the market develops. Albeit promising, horticulture production is still not fully developed in Namibia, and the current production remains at a small scale (GRN 2005). The produce from the smallholder farmers is mainly sold to a small formal market, through the association and to the informal market by individual farmers who cannot afford transportation to other markets. While smallholder farmers produce a marginal amount of cash and crops from small areas, their contribution to food security within their immediate families and local markets is commendable (Moyo 2016).

Since the inception of the Olushandja sub-basin, farmers became water-conscious and have responded by installing water-saving irrigation systems, that is, drip irrigation to ensure the efficient use of water. The farmers were also encouraged to only abstract the amount of water needed for production. Previously, no water allocation framework existed and farmers abstracted water based on the individual farmer's capacity to abstract, without permits. With the responsibilities for ensuring the sustainable use of water resources having being delegated to the basin level, this situation changed after the Olushandja sub-basin management committee came in place. Water users were now required by law to be in possession of a valid permit for the abstraction of water for irrigation purposes (Ihemba and Esterhuyse 2020). Water is a scarce resource in Namibia; therefore, water resource managers and users have to focus on improving efficiency of water resources through improved water demand management practices (Kluge et al. 2008).

Tillie et al. (2020) mentions that there are benefits that come along with investing in small-scale infrastructure to enhance productivity, that is, rain and flood harvesting technologies. These technologies can be applied by the Olushandja smallholder farmers in order to increase the resilience in agricultural production. This would then make irrigation farming possible during the dry season (Jokisch et al. 2016). This could also improve availability of vegetables in rural parts of Namibia. Improved farm output based on water access thus presents the potential to drive economic growth (Conceição et al. 2016), thereby improving the livelihood of these smallholder farmers. The IWRM approach set out to increase equitable access to potable water and freshwater for smallholder farmers, which contributes to the growth of agriculture in the region. Nevertheless, IWRM alone will not entirely improve productivity due to many other factors lacking (i.e. transport, cold storage, market access, etc.) (Fiebiger et al. 2010).

13.6 Conclusion

As Namibia's rural population grows aware of the importance of food security, and as smallholder populations continue to grow and develop the local economy, the application of IWRM initiatives should become more important in terms of conserving water, promoting efficient water use and livelihood improvement. Future water management approaches should also focus on decentralized and innovative water technologies to improve food production without stressing the already limited water from the Olushandja dam. Whilst some progress has been made in implementing IWRM at basin levels, and creation of awareness on IWRM, there is still a great need to increase and recognize the participation of women as smallholder farmers and decision-makers in water management. The IWRM framework recognizes that women are important stakeholders in water management; however, their presence in farming and decision-making in water resource management remains under-represented. The third IWRM principle primarily centres on women playing a central role, not only in domestic water issues, but for women to be included in all aspects of water governance. This is a challenge that needs to be addressed in the OHPA, whose members are primarily men. There is also a need for river basin organizations in Namibia to ensure that smallholder farmers in their hydrological areas are knowledgeable, willing and able to practice the basic principles of IWRM. Given the fact that the government of the Republic of Namibia sees significant potential for the production of horticultural fresh produce through irrigation farming in northern communal areas, more can be done to attain food security and attain livelihood improvement through IWRM efforts. Improving access to water, while removing economic and institutional constraints through IWRM, could henceforth empower smallholder farmers and successfully grow their way out of poverty.

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Part III
Climate Change and Resilience

Chapter 14
Climate Change Impacts on Food and Nutrition Security on Smallholder Farmers in Southern Africa

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Abstract This chapter reviews potential impacts of climate change on food security and nutrition in Southern Africa. Southern Africa is warming at twice the global rate, and many countries are being affected by multiple shocks at the same time. The average number of climate-related disasters/hazards has increased by nearly 35% since the 1990s. More frequent and intense extreme events increase food insecurity and malnutrition by destroying lands, livestock, crops and food supplies in Southern Africa. In Southern Africa, climate change means a warmer and drier climate and greater exposure to multiple climatic hazards including droughts, floods, cyclones, and warmer, shorter growing seasons. The review shows that the four pillars of food security, that is, availability, access, utilization and stability are affected by climate change. The strategies to address climate change impacts on food security are discussed and suggestions to improve them are analysed. Climate change is changing the dynamics of pests and diseases of both livestock and crops. In Southern Africa, new pests like fall armyworms, *Tuta absoluta* have negatively affected the productivity of maize and tomato crops.

Food access and stability may be affected through disruption of market prices, infrastructure, transport, manufacturer and retail as well as direct and indirect changes in income and food-purchasing power of low-income consumers. Food utilization may be directly affected by climate change due to increase in mycotoxins in food and feed. Increase in water-borne diseases under climate change such as cholera which has been rampant in Southern Africa can reduce food utilization. Extreme weather events, such as droughts, floods and cyclones, which have been on the increase in Southern Africa recently will affect the stability of food supply directly through disruption of transport and markets. Although climate adaptation, mitigation and resilient building will take many years, in the meantime,

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humanitarian food assistance is vital to address the impacts of climate change on food and nutritional security in the short term.

Keywords Nutrition burdens · Food systems · Adaptation · Resilience · Climate hazards

14.1 Introduction

Addressing food security and malnutrition are priorities within the African Millennium Development Agendas in Africa (FAO, ECA, and AUC 2020a). This is in line with UN Decade of Action on Nutrition that calls for coordinated response for a wider group of actions in addressing the world nutrition issues towards attaining Sustainable Development Goals. The African continent has made some improvements, but like the rest of the world needs to strengthen efforts to achieve food security and nutrition target of SDG 2 to end hunger, food insecurity and all forms of malnutrition by 2030. An estimated 256 million people in addition to 44 million since 2014 are hungry in the Africa continent. Apart from hunger, regular access to sufficient and nutritious food remains a challenge where an increase in the number of people over half 57.2% of the population within sub-Sahara Africa (SSA) are consequently experiencing moderate or severe food insecurity (FAO, ECA, and AUC 2020a).

Many countries will face malnutrition challenges of undernutrition and macronutrient deficiencies that are associated with higher risk of infectious and poor childhood development and cognitive outcomes. The number of stunted children has increased over time to 58.8 million in Africa, and in 2019, 36%, 144 million under 5 years who were stunted globally were in SSA (United Nations 2020). In 2018,14 million (7.1%) of children in Africa experienced wasting childhood resulting in adult obesity and overweight are emergency burdens of malnutrition that increases risk for non-communicable diseases. Adult obesity has increased in Africa in all regions and upward in the trend in overweight children particularly evidenced in certain regions of Africa. Several countries have progressed in reducing malnutrition, but the pace is still slow, and there are variations across African sub-regions (FAO, ECA, and AUC 2020a).

Small-scale producers who constitute a significant percentage of food production in many African countries still have significantly lower productivity and income levels than their large-scale counterparts. This is largely due to challenges regarding access to resources, information, markets, financial services and other opportunities. Increase in food prices mostly focussed in SSA is another notable factor that has affected access to proper nutrition (United Nations 2020). There is an urgent need for interventions to end and address key challenges such as economic factors, climate shocks and conflict that prevent progress towards food security in Africa by affecting the availability, access, utilization and sustainability of food security and nutrition outcomes particularly in children (Table 14.1). More recently, the health and

Table 14.1 Impacts of climate change on four pillars of food security

Food security dimension	Impacts of climate change
Availability Food production and exchange	Reduced production in Africa can affect dietary diversity Changes in land suitability for crop production Changes in precipitation patterns could affect suitability of rainfed agriculture
Access Ability to obtain food regularly through own production or purchase	Lower yields in some areas can lead to higher food prices Loss of income due to damaged crops
Stability Risk of losing access to resources to consume food	Instability of food supplies due to increase in extreme events Instability of income from agriculture
Utilization Quality and safety of food including nutritional aspect	Food security and health impacts include increase in malnutrition Ability to utilize food might decrease when changes in climate increase diseases Impact of food safety due to changes in pest and diseases

Source: FAO, IFAD, UNICEF WFP, and WHO (2020b)

socio-economic impacts of the corona virus (covid 19) pandemic have added a strain to food supplies and economies and such effects especially on vulnerable populations (FAO, IFAD, UNICEF WFP, and WHO 2020b). Food security and nutrition is part of the ten priorities of the African Science Technology and Innovation Priorities (ASP) programme. The objective of this chapter is to summarize the current state of knowledge and the impacts of climate change on food security and nutrition for smallholder farmers in Southern Africa.

The most vulnerable people cannot access enough of the major macronutrient (carbohydrates, fats and proteins). Another one billion are thought to suffer from hidden hunger in which important macronutrients (such as vitamins and minerals) are missing from their diets with risks of physical and mental impairment (Foresight 2011). Undernutrition remains one of the serious but least addressed socioeconomic and health problem (Horton et al. 2009). The human and socio-economic risks of undernutrition are enormous, falling harder on the poorest, especially women and the children (Horton et al. 2009). Millions of people around the world who have experienced undernutrition early in life face many challenges as they grow up. They encountered an increased risk of illness and death when they were young, experienced difficulties in world and often not able to make a full contribution and economic development of their household communities, notably, when they become adults (Nabarro 2010).

Climate change threatens and exacerbates existing threats to food security and livelihoods due to a continuation of factors that include frequency and intensity of climate hazards and diminishing agriculture yields and reduced production in vulnerable regions, rising health and sanitation risks, increasing water scarcity and intensifying conflicts over scarce resources, which would lead to new humanitarian crisis as well as increasing displacement (IPCC 2007). Climate change is expected to affect all of the components that influence food security: availability, access, stability and utilisation. The overall availability of food is affected by changes in agricultural yields as well as changes in arable land. Changes in food production together with other factors could impact food prices which could affect the ability of poor households to access food markets and could reduce dietary diversity. Decreased water availability and quality in some areas result in increased health and sanitation problems; diarrhoea and vector-borne diseases increase malnutrition and negatively affect food utilization. Extreme weather affects or disrupts the stability of food supply as well as people's livelihood. Increase in extreme weather events such as floods and droughts are as a result of climate change. This could have a negative effect on livelihoods that depend on climate-sensitive activities such as rainfed agriculture and livestock rearing (Schmidhuber and Tubiello 2007).

Understanding the specific impacts of climate change on food security is challenging because vulnerabilities are unevenly spread across the world and alternately depend on the ability of communities and countries to cope with risks. Projections suggest that the number of people at risk of hunger will increase by 10–20% due to climate change, with 65% of their population in SSA. The number of malnourished children could increase by 21% (24 million children) with the majority being in Africa (Parry et al. 2004; Nelson et al. 2009).

14.2 Long-Term Climate Change

Temperature rise: Global temperature is expected to rise as a result of climate change, and the expected pattern of rise is such that all areas will see an increase in the temperature. By 2050, the global average is projected to have risen between 2 and 4 °C above the pre-industrial climate. In general, the land will see greater increase in temperature than the oceans. The largest increase in mean temperature is projected for the higher latitude regions of the northern hemisphere with lesser increases in the tropical and subtropical areas. More significant warming is going to be experienced in Canada and Russia. South Asia and Southeast Asia are the regions where the lowest increases in mean temperature are projected (Christensen et al. 2007).

14.3 Changes in Precipitation Pattern

There is less coincidence in the climate model projections of change in precipitation patterns than changes in temperature. However, there is less certainty in regions projected. Rainfall records in many parts of the world, for example, in Africa and the Middle East are sparse. In general, increases in temperature will result in a more active hydrological cycle, meaning more rainfall overall. But changes in the pattern and seasonality of rainfall regionally means that some areas will see less rainfall and changes in the timing and intensity of rainfall events could have a significance locally.

14.4 Changes in Other Variables and Weather Patterns

Changes in climate will be felt not only through increasing temperature and changing rainfall pattern, but also through rising sea levels. There are changes in storms and storm tracks, glacier melt, large-scale circulation changes in seas, droughts, storm surges and damage and land loss. These changes will be negative for some areas; there will be a positive change, especially for low levels (Parry et al. 2004).

14.4.1 Seasonal Climate Patterns

The seasonal cycles of hunger and undernutrition are generally strongly correlated with climate-related factors, especially in rural areas. In the Sahel and in the horn of Africa, climate-related factors strongly influence crop and animal production and diseases. In Bangladesh, floods and cyclones tend to follow seasonal patterns with important food and nutrition security implications; seasonal peaks of hunger and undernutrition are shaped by human or socioeconomic factors, such as huge food prices on low-income opportunities. Rural communities across the world report that the timing and the pattern of seasonal rains are changing dramatically. It is reported rainfall is more erratic with shorter, heavy, drier spells, and unusual storms and temperature fluctuations are increasing. Meteorological droughts resulting from insufficient rainfall are expected to increase in duration, frequency and intensity (Burke et al. 2006). Droughts result in agricultural loss and are a major driver of food insecurity. In Africa, about 650 million are dependent on rainfed agriculture in environments that are affected by water scarcity, land degradation, recurrent droughts and floods. The trend is expected to exacerbate under climate change and population growth (FAO 2008). The areas of major crop production (maize, barley, rice, sorghum, soyabeans and wheat) have all experienced an increase in the area affected by hydrological drought that renders them sensitive to weather variability in the future (Li et al. 2009).

Food security may be affected by excessive rainfall. The impact of climate change on flood events is less certain. However, models suggest that there will be more rainfall events as the climate worsens (Held and Soden 2006). In the context of food security, heavy rainfall leads to floods which can destroy the entire crops over wide areas, as well as destroying food stores, assets such as farming equipment and agricultural land due to sedimentation. Climate variability studies in the UK (Kettlewell et al. 1999) showed that heavy rainfall in August can be linked to lower grain quality due to fungal infections. Tropical cyclones can have impact on food security and nutrition. Gray (1990) suggests that tropical cyclones may become more intense in the future with stronger winds and heavy precipitation but regional variation in cyclone formation are less understood. Tropical cyclones can have the potential to devastate a region causing loss of life and widespread destruction to agriculture crops, land, infrastructure and livelihoods (Meehl et al. 2009).

14.5 Climate Change and Food Production (Availability)

Climate affects food availability in many complex ways. Direct impacts include changes in agro-ecological conditions, indirect impacts include changes in economic growth and distribution of income, which in turn affects demand for agricultural produce. Empirical evidence suggests that increases in temperature in the period 1980–2008 have already resulted in average global maize and wheat yield reduction of 3.8% and 5.5%, respectively, compared to a non-climate scenario (Lobell et al. 2011a). To date, climate trends have been largely affected by gains derived from technology and other factors (Lobell et al. 2011a). Future changes in climate patterns coupled with population dynamism could result in higher vulnerability. In tropical countries, where much of the current food security problems are predominant, increases in temperature are expected to be predominantly detrimental. The quality and quantity of crop land available is projected to decrease under climate change in SSA, especially land for double-cropping could decline by between 10–20 million ha and land suitable for cropping could decline by 5–ten million ha (Fischer et al. 2002). Further region analysis collaborates these findings in West Africa; for example, crop yields could decrease approximately 11% due to effects of increased temperature and lower precipitation.

More specific country-level analyses show that adverse climate trends could reduce the quantity of land available for crop production in some countries. In Kenya, for example, a long-term study by FEWS NET (2010) notes that long rain has declined more than 100 mm since the mid-1970s, and this trend could continue. If this trend continues, food security would be affected due to a reduction in available prime land, which could affect critical surplus maize growing area in central Kenya (Williams and Funk 2010). Crops and climate models have also been used to assess the potential impact climate change on the availability of food (Lobell and Field 2007). Generally, the results indicate that changes in temperature and precipitation due to climate change will affect land suitability and crop yields. The research suggests that higher temperatures will predominantly benefit agricultural production in temperate latitudes as the area for potential production expands, the growing season length increases, and cold weather events are reduced and for many areas precipitation increases (IPCC 2007). However, increases in local temperatures can generate devastating agricultural levels and can be critical if they coincide with key stages of crop development (Wollenweber et al. 2003).

The yields of many crops can be drastically reduced by temperatures above 32 °C during flowering stage, for instance, grain sterility in temperatures in the mid-30 °C

(Hatfield et al. 2011). Mohammed and Tarpley (2009) similarly suggest that rice yields were reduced by 90% when ambient temperatures increased from 27 to 32 °C and temperature above 35 °C resulted in zero yield. These results are supported by experiences (Cheke and Tratalos 2007). European heatwave affected crops and resulted in yield losses of up 36% in Italy for maize (Stott et al. 2004). Empirical studies using historical crop trial data have highlighted the adverse impacts of temperature on maize yields in Africa (Lobell et al. 2011b). By combining crop production diets for 20,000 maize trials with meteorological data, Lobell et al. 2011b show that for each degree-day spend above 30 °C the final maize was reduced by 1% under optimal rainfed conditions and 1.7% under drought conditions. In addition, Lobell et al. 2011b suggest that approximately 65% of maize-growing areas could experience yield losses for 18% of warmer under optimal rainfed management, whereas 100% of areas would experience significant losses under drought conditions. The results highlight the role of moisture in improving ability of maize crops to cope with heat. Similarly shifts in mean precipitation patterns affect vulnerable rainfed agricultural production; globally over 80% of agriculture is rainfed and in Africa around 95% (Wani et al. 2009).

Water resources are predicted to be strongly impacted by climate change with wide-range consequences for human societies and ecosystems. Hundreds of millions of people risk being exposed to a growing scarcity of water. Climate change-related alteration in rainfall, surface water and water quality will impact on the incidence of water-related diseases. Closely interlinked with water scarcity, agricultural food production would become riskier in developing countries as the climate continues to change.

14.6 Climate Change Impacts on Food Access and Livelihoods

Climate change could affect food accessibility of individuals, communities and countries to obtain sufficient quantities of good quality food. Over the last 30 years, falling real prices for food and raising real incomes have increased purchasing power in many developing countries. However, recent market volatility has highlighted the vulnerability of poor and marginal households to price shocks.

The relationship between climate change and food access are complex, especially, because it is difficult to quantify and model the impact of economic growth. Moreover, any benefits associated with income growth might be affected by increases in price. If income levels rise moderately but remain low and the evidence of income spent on food remains high, increase in food prices level exacerbate food insecurity trends. Empirical evidence suggest that climate variabilities can impact livelihoods, for example, historical evidence in Ethiopia suggests that there is a strong correlation between economic growth and rainfall variability. Wetter years are associated with higher SDP growth whereas drier years are associated with lower negative growth (Conway and Schipper 2010).

While correlation does not causation, this relationship suggests that climate could affect livelihoods in the absence of adaptation measures. Some studies have quantified the potential impact of rising temperatures and food prices (Fischer et al. 2002; Nelson et al. 2009). Increases in food prices reduces dietary diversity, which reduces dietary quality and increases malnutrition, in particular, stunting and macronutrient deficiencies (Brinkman et al. 2009). Some studies have quantified the prolonged impacts of rising temperatures on food prices (Fischer et al. 2002; Nelson et al. 2009). The studies suggest that food prices are expected to rise moderately with moderate increase of temperature after 2050; however, food prices are expected to increase rapidly. Studies of Nelson et al. (2010) suggest that by 2050 real price might increase by 87–106% for maize, 55–78% for rice and 54–58% for wheat relative to 2010 baseline as a result of adverse climate change impacts. Further research suggests the potential for much larger food prices in the near term, with the price of major staples rising by 10–60% by 2030 and increasing poverty levels by 20–50% in some parts of South Asia and SSA (Hertel et al. 2010). Climate change could also have an impact on rural incomes given that agriculture is highly sensitive to climate patterns. Changes in temperature and rainfall can reduce agricultural output and, therefore, reduce rural incomes (Morton 2007). Mendehlsohn et al. (2007) also show that historically climate data is highly correlated to agricultural increases in particular regions with moderate and sufficient rainfall with rural incomes. Under climate change, upper optimal temperatures and erratic rainfall are likely to result in higher rural poverty and, therefore, lower income for food security.

14.7 Climate Change Impacts on Nutrition and Utilization

Undernutrition is a consequence of inadequate dietary and disease, which in turn results from household food insecurity, inadequate care, unhealthy environment and lack of health service. These three underlying causes of undernutrition are determined by environment, economic and sociopolitical contextual factors. For example, reduced calorie intake due to lower food availability could affect nutrition outcomes. Inadequacy of these practices could be exacerbated due to difficulty in accessing clean drinking water. Potential food prices increase due to climate change and could reduce diet diversity and hence reduce nutritional value of the diet which impacts on nutritional status. Finally, the health will be impacted through changing disease patterns as a result of climate change.

14.8 Climate Change and Health

Some scientists argue that climate change is the biggest global health threat of the twenty-first century and is already contributing to the global burden of disease and premature death (Costello et al. 2009). Important future trends for human health include an increase in the number of people suffering from death, disease and injury from heatwaves, floods, storms and droughts and changes in the range of infectious disease vectors, and an increase in the burden of diarrhoeal diseases (Confalonieri et al. 2007). Climate change impact on health eventually both increase nutrition needs and reduce absorption of nutrients and their utilization by the body. Climate change will have an impact on sanitation system and water quality and availability though changes in precipitation patterns. Further climate change might impact a different disease including diarrhoea and vector-borne diseases through changes in habitat suitability (IPCC 2007).

The link between increasing temperature and malaria incidents have been relatively well studied (Simon et al. 2002); increase in temperature and humidity can increase the risk of malaria transmission by mosquitoes. This in turn can expose a large number of people to malaria transmission. Some studies have quantified the impact of increased temperatures on common forms of food poisoning such as salmonella incidence would increase linearly for each degree increase in temperature (Kovats et al. 2004). Similarly increase in temperature have been associated with increased episodes of diarrhoea in adults and children (Singh et al. 2001). Diarrhoea, acute respiratory infection, measles and meningitis are all major food security and nutrition-related diseases. These increase the nutritional needs of affected people while simultaneously reducing the absorption of nutrients and their utilization by the body. Increasing poor health in a community also leads to loss of labour productivity and a larger dependency ratio (Mao 2009). Climate change could also put harder strain on the already heavy workload of women, will negatively impact on their ability to provide proper care to infants and young children, heightening the risk of undernutrition (UNSCN 2010).

14.9 What Farmers Can Do to Adapt to Climate Change

The IPCC (2007) defines adaptation as: Initiatives and measures to reduce the vulnerability of natural and human systems against existing and expected climate effects. Various types of adaptation exist: anticipatory and reactive, private and public, and autonomous and planned.

In addition to being a source of general stress to the food systems, climate change will manifest itself in specific ways to which smallholder farmers will need to adapt (Fischer et al. 2002). As the climate changes, the average weather experienced by smallholder farmers will alter as well as the frequency and distribution of more extreme events (Gornall et al. 2010). Individual farmers will need to adopt a suite of measures to adapt to these changes, the details of which will be contingent on individual circumstances. Nevertheless, broad adaptation themes can be identified and smallholder farmers will need to consider the different adaptation options (Lobell et al. 2008).

14.10 Options for Adaptation to Climate Change

Farmers should plant different varieties of species of crops or rear different breeds or species of livestock or fish in aquaculture. These varieties or breeds with different environmental optima may be required for those with broader environmental tolerance. The use of currently neglected and underutilized crops and breeds should be considered.

In the face of growing weather variability, we need to consider increased diversification of varieties or crop to hedge against risk of individual crop failure. Famers must make use of integrated systems involving crop/livestock or aquaculture to improve resilience.

Farmers must alter agronomic practices. Changes in rainfall may favour reduced tillage to less water loss. The inclusion of other agronomic practices such as animal manure and agroforestry practices and cover crop cropping will increase soil organic matter and increase water retention. Farmers must be prepared for increased frequency and intensity of extreme weather events. General water conservation techniques are valuable at times of drought with strategies such as improved soil organic matter helping to store water after storms.

There is need for farmers to adapt to pest, weed and disease management strategies; different crops and livestock diseases and pests will respond differently to climate change. However, farmers have different expertise in coping with existing pest and diseases and that the natural regulation of potential pests by natural enemies may be disrupted by a changing climate; farmers on balance are likely to face more rather less challenges of this type.

There is a need for farmers to change post-harvest practices to reduce grain contamination by fungi and other threats to food safety. There is also need to adopt weather-indexed insurance schemes against extreme events. Many countries are evaluating crop/livestock insurance schemes for smallholder farmers. There is need for farmers to consider the effects of new weather patterns on the health and well-being of the farmers and their agricultural workers.

In addition, farmers must engage with other farmers to share best practices and experiences so as to enhance community-based adaptation and resilience building. Many people, especially in SSA countries, use the extensive range of wild plants and animals to supplement their diets (Barucha and Pretty 2010). These species too will be affected by climate change, in ways difficult to predict. Autonomous and reactive adaptation will occur in these communities, but policymakers should be aware that climate change may (though not will) negatively affect these important ecosystem services.

14.10.1 How to Support Smallholder Farmers to Adapt to Climate Change

Farmers alone cannot adapt successfully to climate change. They need assistance from governments, private sector and third sector (NGOs), and there is also an important role of civil society organizations. These actions and policies that could reduce vulnerability to climate change are needed.

14.10.2 Undertake Regular Assessment of Climate Change Risks and Vulnerability

Anticipatory adaptation to climate change requires assessment of both risks and vulnerability (Howden et al. 2007). Most countries in SSA are increasingly carrying out regular assessments but nations without the capacity need external assistance. Careful communication of the inevitable uncertainties to policy matters more broadly is of great importance.

14.10.3 Modernize Extension Services

Of great importance is that smallholder farmers have access to the skill base, human capital that is needed for climate adaptation. Improving the information and training available to farmers through modernized extension services based on different friendly models (that can involve the public, private and civil society sectors) has also been highlighted as means of increasing general resilience. These extension services themselves must be equipped to provide the appropriate climate change adaptation advice (in some cases building on existing successful models in managing weather risks) taking into account the special needs of women and of disadvantaged groups. In addition to formal extension services, there are initiatives such as farmer-field schools that allow best practices and knowledge to be shared among farmers and allow food-producing communities that can help facilitate autonomous adaptation. Though national planning for adaptation is essential, great emphasis should be placed on involving and engaging with the communities where changes actually have to occur.

14.10.4 Improve Access to Genetic Resources

Effective and efficient adaptation will require access (both physical and legal) through appropriate intellectual property rules to genetic resources, both of existing crops, livestock and their wild relatives, as well as varieties that may be used in the future (Blakeney 2011). Crop genes for drought and flood tolerance should be identified and shared. Yield stability traits of species under variable conditions are particularly important areas where more understanding research is needed.

All that is possible must be done to minimize genetic erosion in the remaining biodiversity both in situ and in gene banks. Farmers, public and private sector institutions, research communities, and governments need to increase cooperation and ensure dissemination, distribution and creation of knowledge and transfer of technologies to conserve and curate genetic resources in gene banks, germplasm stores and related facilities and support the adaptation to climate change. Adaptation by all countries of the International Treaty on Plant Genetic resources for Food and Agriculture, as well as urgent implementation of its articles 5 (conservation), 6 (sustainable use) and 9 (farmer rights) would be positive steps in this regard.

Increasing agricultural biodiversity measures to develop markets for underutilized species and educating consumers about the importance of dietary diversity would help. The Commission on Genetic Resources for Food and Agriculture could consider identifying priority measures and developing a plan of action on the conservation and use of genetic resources for adaptation to climate change.

There is on ongoing debate on whether the current intellectual property rights regimes support or hinder development and use of improved plants and animal varieties and agricultural biodiversity. The issues of genetic resources, including intellectual property rights and farmer's rights, is a topic which needs global consideration and attention.

14.10.5 Exploit the Growing Availability of Information Technology

One of the challenges of climate change is likely to be coping with more vulnerable patterns of weather. Access to weather forecasting can improve farmer's ability to cope with increased variability and extreme events provided the information can be disseminated in time to those who need it. The near ubiquitous reach of mobile phones and related technology in even the poorest countries offers novel means of providing information and advice to farmers. Suitably resourced and designed information and communication technology (ICT) can provide this link to national meteorological services.

14.10.6 Facilitate Investments by Smallholder Farmers

The consequences of climate change will be more and more apparent as time passes. Adaptation to climate change requires investment that begins before the consequences occur. In that sense, adaptation requires investment in both material and immaterial (knowledge) forms and for farmers to have access to financial capital. Access to capital in less developed countries is more problematic. It is a general problem that can be approached in various ways including reprioritizing national budgets, refocusing development assistance or by private and civil society financial initiatives such as microfinance, especially targeted at smallholder farmers in vulnerable areas; investment in climate change adaptation (including new varieties and breeds, irrigation, food storage and infrastructure) will require increasingly high priority. Transparency and protection of rights of smallholder farmers need particular attention.

It is also important to ensure that those measures attend to the special needs of women in agriculture and are nondiscriminatory to vulnerable groups.

14.10.7 Explore the Potential of Innovation Insurance Schemes to Manage Weather Risks

The nature of food production means that cash flow varies over time and is at risk when adverse weather events occur, such as droughts, floods and sea water incursions. Climate change will increase the likelihood of such extreme weather events and the risk of crop and livestock loss, and will make it more important for farmers to have adequate risk-coping investments.

In developing countries, the insurance to protect smallholder farmers against uncertainty are usually absent or inefficient or still nascent. Experiments are underway in developing countries, especially in SSA with weather index-based insurance programs that have identified benefits and issues in their implementation (Giné and Yang 2009; Giné et al. 2007).

Research is needed on how best to provide poor farmers with financial security for building a program that pays out automatically when certain weather criteria are met, rather than needing complex loss adjustment.

One likely consequence of climate change is that weather shocks have greater frequency and extent affecting the whole region of the country, which could significantly raise costs of weather index schemes. Innovative solutions designed specifically for those challenges such as sovereign insurance covering the state could be investigated. The increased likelihood and type of extreme events associated with climate change should be taken particular note of in disaster management planning and in designing the provision of emerging relief to people affected by severe food security.

14.10.8 Ensure People Are more Resilient to Climate Change-Enhanced Water Availability Risks

Low-level and irregular precipitation that already affect the livelihood and production of large number of rural farmers is expected to be worsened in the face of climate change. Agriculture sector consumes about 70% of freshwater resources. Worldwide, 40% of agricultural production comes from irrigated lands (Bruinsma 2008). Future production will rely heavily on irrigation; however, freshwater supply for irrigation is definite and showing sign of vulnerability just as we are about to become dependent on it.

Many of the major rivers and major groundwater acquirers throughout the world are suffering from overexploitation. Access to water and use of water in relation with food and nutritional security are multidimensional problems. Semi-arid regions need water policy which contemplates four major dimensions: provision of water for domestic use, the use water for production, the use of water in rural areas and small communities, and the use of water in cities.

There should be a participatory water management system involving farm families so that local communities have a stake in both water conservation, sustainable use and equitable use. Participatory methodologies and communities' leading role should be part of building up of alternative means of collecting, storing, managing and distributing good quality water in a way that respects and protects ecosystems, preserves natural resources and stimulates degraded areas.

14.11 Conclusion

There is emerging consensus that changes in temperature and precipitation can have detrimental impacts on food and nutrition security of vulnerable people in Africa in the absence of adaptation. Aggregate impacts of climate change on food security are not well understood. Several impacts are difficult to quantify and depend on a number of assumptions. The available evidence to date suggests that climate change will reduce crop yields and land suitable for agricultural production with the greater impacts in SSA and Southeast Asia. Several studies show that food prices will increase as a result of climate change, thereby affecting ability of vulnerable people to purchase food. In the short term, the greatest gain in food access will be in South Asia and Latin America, with marginal gains in SSA. The link between climate change and food stability and utilization are well understood; less is known about how quantities impact. Climate change and variability, extreme weather events are likely to pose greater challenges for food stability. Climate impacts on pest and disease patterns will also affect the ability of the body to access and utilize nutrient needs. Climate change could also increase the number of malnourished children, especially in SSA countries. The evidence suggests the impacts of climate change on food security will be spread unevenly in SSA, affecting the population that are currently most at risk of hunger. Ultimately, how strongly the impacts of climate change are felt will depend on the ability to adapt to changes. Although, climate change adaptation, mitigation and resilient building will take many years, in the meantime, humanitarian assistance is vital to address the impacts of climate-related effects on food and nutrition security.

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Chapter 15
Climate-Smart Agriculture: Perspectives for Subsistence Crop Farming in Namibia

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Abstract Namibia is the most arid country in southern Africa, though agriculture still plays a great economic and social role in the arid country. Throughout the country, agriculture is mainly dominated by animal production with crop production being mainly concentrated in the north-east parts of Namibia, where smallholder farmers practice subsistence farming of cereals and grain legumes. Due to the aridity of the country, these smallholder farmers mainly grow small grain cereals such as pearl millet and other grain legumes, which are drought-tolerant. Though these farmers mainly practice subsistence farming, their productivity is critical in achieving national food security. With the advent of climate change, these smallholder farmers are increasingly being exposed to extreme weather conditions such as flooding, droughts, and high temperatures, which threaten their household food security. This chapter presents aspects of climate-smart agriculture that is being promoted in Namibia to increase the resilience of these smallholder farmers. Aspects that are limiting the greater adoption and effective research on climate-smart agriculture are also highlighted. With smallholder farmers being significant in national food security, localized research informed by indigenous knowledge systems must be promoted in Namibia to increase the adoption of the identified climate-smart technologies.

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15.1 Introduction

Climate-smart agriculture (CSA) is a concept that was formally defined and adopted by the Food and Agriculture Organization (FAO) in 2010 as an approach that supports the attainment of agricultural development for food security under changing climate in a sustainable manner. CSA helps to guide actions needed to transform and reorient agricultural systems to effectively support the development and ensure food security in a changing climate. CSA rests on three pillars of (a) increasing productivity and income (b) adapting and building the resilience of farmers to climate change (c) mitigating greenhouse gas emissions where possible (Food and Agriculture Organisation [FAO] 2013). The concept of CSA is a location-specific, knowledge-intensive holistic approach to managing cropland, livestock, forests, and fisheries through addressing the challenges of food security and climate change (Food and Agriculture Organisation [FAO] 2014). FAO estimates that food production will need to increase by 60% to meet global food demand by 9 billion people by 2050 (Food and Agriculture Organisation [FAO] 2013). As the population increases, there is a greater need for increased food production; however, with increased threats of global warming impacts, yields of crops are estimated to decrease by more than 2% (Intergovernmental Panel On Climate Change [IPCC] 2014). In already semi-arid countries like Namibia, it is projected that there will be a 5% decrease in cereal crop productivity at 1.5 °C increase in the global warming threshold and a 10% decrease in cereal crop productivity at 2 °C increase in the global warming threshold (Bouwer et al. 2018). The events of the past decade starting with 2013 which resulted in the least rainfall in 30 years causing 300,000 people to be food insecure, as well as consecutive years of drought leading to the 2019 drought year which caused 500,000 people to be food insecure, demonstrate the impacts of climate change on Namibia as well as its vulnerability (https://haanready.com/blogs/journal/the-consequences-of-decades-of-drought-in-namibia). Crop production decreased by 48% in the 2013 season making the majority of people dependent on drought relief. Such events have become common, and it is now imperative to implement CSA practices with urgency in Namibia, especially among the resource-poor smallholder farmers.

Namibia is regarded as the most arid country in Southern Africa and is prone to intermittent drought and floods (Ministry of Environment and Tourism [MET] 2010; van Rensburg and Tortajada 2021; Iijima et al. 2018; Awala et al. 2019). Although Namibia is richly endowed with natural resources, water is in short supply. The mean annual rainfall ranges from less than 50 mm per annum in the western region along the coastline to a maximum of 700 mm per annum in the north-eastern Zambezi. Only 8% of Namibia's total land area receives rainfall of 500 mm per annum or above, and in general, the rainfall is erratic throughout most of the country (Kaurivi et al. 2010). According to the Namibia National Farmers Union [NNFU] (2008), only 2% of Namibia's land receives sufficient rainfall for growing crops. There is a high dependency on rain-fed agricultural production, especially by smallholder farmers in Namibia who are located in fragile environments that are vulnerable to water scarcity and environmental degradation. This increases the vulnerability of farming systems and predisposes rural households to food insecurity and poverty. The reduction in crop yields has devastating impacts on food security at both national and household levels. Namibia thus needs to adapt its agricultural practices and increase the farmer's resilience for them to be able to withstand the challenges posed by climate change so that there is sustained development and growth of the country.

Despite high vulnerability to climate change impacts, Namibia's response has made some inroads to adaptation. Although Namibia is a Non-Annex I Party to the United Nations Framework Convention on Climate Change (UNFCCC) with no commitments under the Convention, it has instituted policies and measures to address the adverse effects of climate change (Mapaure 2011). In response to this, Namibia established the Namibian Climate Change Committee (NCCC) in 2001 to advise and make recommendations to the government on issues of climate change and produced the Intended Nationally Determined Contributions (INDC) to the UNFCCC which highlights targets on emissions and adaptation measures. Policies put in place to address climate change include the National Climate Change Policy (NCCP) and the National Climate Change Strategy and Action Plan for 2013–2020 which guides the implementation of the NCCP (Ramirez-Villegas and Thornton 2015).

The agricultural sector sustains more than 70% (MAWF 2015a, b) of the population directly or indirectly and employs 23% of the workforce (Namibia Statistics Agency [NSA] 2019), and support to the sector would greatly improve productivity and livelihood options. According to the Ministry of Agriculture, Water and Forestry of Namibia, the sole dependence on rain-fed agriculture significantly increases the vulnerability of farming systems, especially rural households, to food insecurity. Considering the current population growth within the country, Namibia needs to expand its agricultural productivity by about 4% a year to be able to meet the food requirements of this increasing population. This, therefore, highlights the need for extensive research into climate-smart technologies that can allow the exploitation of Namibia's unique climatic environments and resources to enhance food production in the arid country. Of the various regions of Namibia, CSA practices have been introduced in Omusati, Ohangwena, Kavango East, Kavango West, and Zambezi Region.

Climate-smart agriculture offers options to support the agriculture sector on the three pillars mentioned previously. The crop sector specifically benefits directly from CSA practices as farmers navigate the challenges they find themselves in to ensure food security and build the resilience of the sector. Therefore, our chapter presents research that has been done and analyses the influence of policies and programmes in Namibia highlighting the climate-smart technologies that are being promoted and their impacts on crop productivity. The chapter also highlights areas where Namibia needs to improve in terms of evaluation of CSA practices that are adaptable in the Namibian context.

15.2 Agriculture in Namibia

Namibia is the most arid country in southern Africa, though agriculture plays a critical role in the GDP of the country. In agriculture, 90% is animal-based though crop-based agriculture is particularly very important for food security within the country. According to the Government of the Republic of Namibia (GRN) (2015) agriculture, fisheries, and forestry accounted for 7.1% of the GDP in 2013. And despite its modest contribution to the GDP, agriculture impacts directly on the livelihood of about 70% of the population. Shifeta (2015) reported that agriculture contributed between 12 and 15% to the National Gross Development Product (GDP) in 2015. Subsistence agriculture constitutes a large portion of the livelihoods of families in Namibia, of which most are situated in the northern parts of the country's communal areas. Crop production in the smallholder farming areas of Namibia remains based on mainly cereal crops like pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*) and maize (*Zea mays*), with a few legume crops also being grown which include Bambara nut (*Vigna subterranean*) and cowpeas (*Vigna unguiculata*). The three cereal crops represent the staple crops of Namibia and are grown by subsistence farmers mainly in north-eastern Namibia. Pearl millet plays a critical social-economic role in Namibia, though the yield per hectare is low due to infertile soils, drought, and seasonal floods. Small-scale farmers in northern regions intercrop pearl millet with cowpea as a cheaper alternative for household protein consumption (Horn et al. 2015). The production of these crops entails minimum risks in terms of household food security and, therefore, emerges as a strongly preferred option in all efforts to reduce the impact of climate change and variability (Kaurivi et al. 2010).

Namibia's agriculture is divided into two main production systems, based on large private commercial farms (14.5 million ha) and smallholder subsistence farming in the communal land (17 million ha) areas, respectively (MAWF 2015b). Traditional cultivation techniques in Namibia are characterized by cultivating the same kind of crops persistently on the same piece of land, using a plough with minimal to no fertilizer application. Communal crop farming is confined mainly to the Zambezi, Kavango East, Kavango West, Ohangwena, Oshikoto, Omusati, and Oshana regions, while commercial crop farming is largely concentrated in the so-called maize triangle in reference to the triangle shape created by the neighbouring towns of Grootfontein, Otavi, and Tsumeb (see Fig. 15.1). Commercially, maize is the most important crop grown both under rain-fed and irrigated conditions, although wheat is grown under irrigation on about 200-400 ha annually at various irrigated sites around the country (NEWFIU 2015; Taapopi et al. 2018). The maize triangle towns are situated in regions that receive rainfall above 400 mm annually. Communal areas of Namibia have the highest variable drought episodes

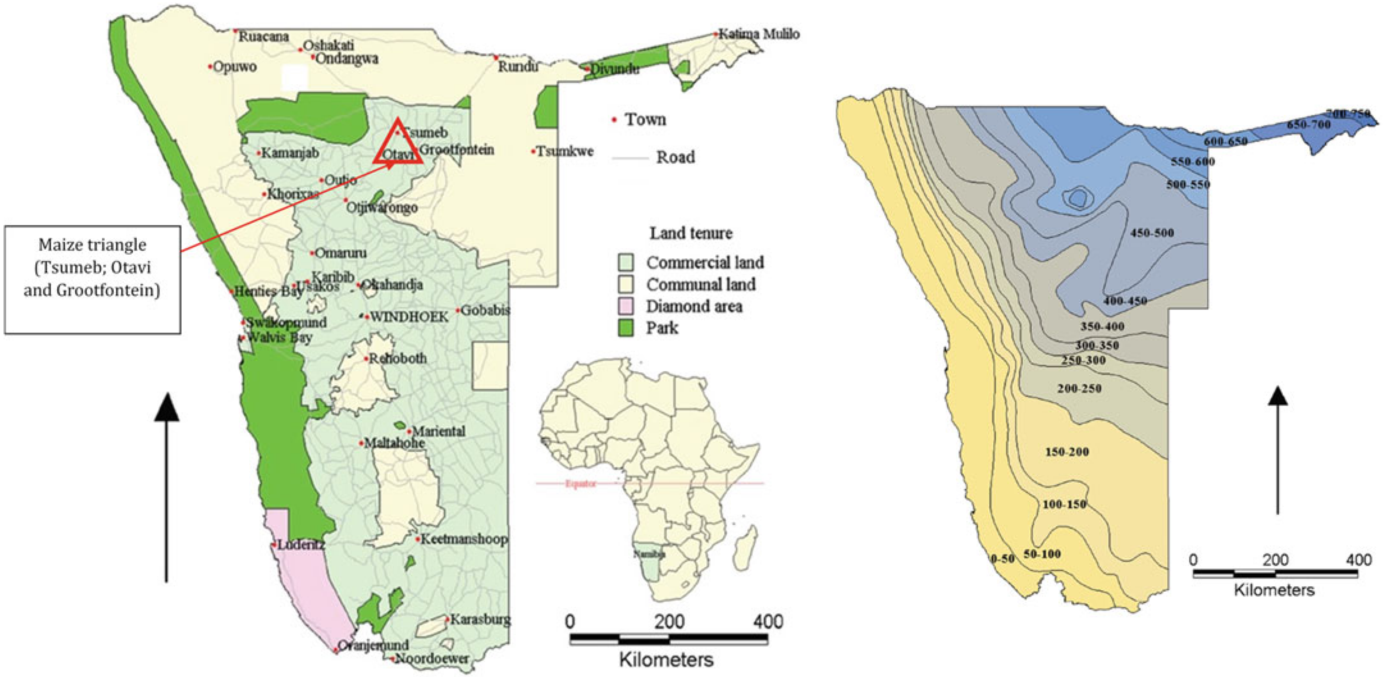

Fig. 15.1 Maps showing Namibia and the various land tenure systems and the distribution of annual rainfall (mm) across the country. Maps adopted and slightly modified, copyright belongs to Patrik Klintenberg, PhD thesis (Klintenberg 2007)

with very low rainfall. Crop yields (cereals and legumes) in these communal areas are extremely low compared to those obtained in the commercial sector, mainly due to the erratic rainfall and non-application of good agricultural practices (GAP). Mudamburi (2016a) refers to these GAPs as timely operations, quality seed, and integrated nutrient and water management techniques, including integrated weed management options as effective measures to reduce the risk of crop failure caused by erratic rainfall, while increasing and stabilizing yields.

15.3 Policies and Programmes that Support Climate-Smart Agriculture (CSA) in Namibia

Namibia, like many other countries that are faced with challenges of declining productivity, impacts of climate change, and looming food insecurity, has produced an overarching country CSA programme that is aimed at building the resilience of the agricultural farming systems as well as enhancing food and nutrition security. This programme has a duration of 10 years (2015–2025) and has six programme result areas, namely, (i) improved productivity and incomes through enhanced public-private partnerships and support, (ii) building social and environmental resilience and associated mitigation co-benefits, (iii) value chain integration, (iv) research for development and innovations for scaling up CSA (v) improving and sustaining agricultural extension services (vi) improved policy and institutional coordination (Ministry of Environment and Tourism [MET] and Ministry of Agriculture Water and Forestry [MAWF] 2014). Several programmes and projects that support CSA in Namibia were implemented to achieve these programme result areas and have a direct bearing on the subsistence cropping sector, and these are summarised in Table 15.1.

These policies and programmes have enabled the implementation of several projects with varied success across the different projects. Efforts towards addressing the three pillars of CSA in Namibia are high on the agenda of national development through the enabling policy environment as well as projects that are implemented to address the challenges of climate change and food insecurity.

A lot has been done regarding support to farmers in Namibia, and there is a need to tap on all that has already been done and upscale where necessary. To mitigate the lack of financial resources for smallholder subsistence farmers to produce, the government introduced seed, fertilizer, and tractor subsidies. The seeds are improved varieties that are produced under local conditions and available at a subsidized price. This ensures that most farmers produce every season even when they have little financial resources with seeds that are meant for limited rainfall. Moreover, fertilizers are also subsidized in recognition of poor soil fertility that often leads to poor harvests. As droughts also lead to a reduction in the draught animals available for these resource-poor farmers, tractor services are also subsidized to ensure that households with no draft power produce food for themselves instead of waiting

Table 15.1 Policies and programmes addressing and enabling climate-smart agriculture in Namibia

Policy/programme	Main objective (s)	References
Comprehensive Conservation Agriculture Programme of Namibia (2015–2019)	The programme is based on the premise that the future of food security relies not only on higher production and access to food but also on the need to address the destructive effects of production practices on the environment and the devastating and negative impacts of climate change. The programme addresses challenges crop and livestock farmers face in production.	MAWF (2014)
Dryland crop production Programme (DCPP) (2010-on-going)	The programme aims to promote food security at the household level through the provision of improved seeds and fertilizers as well as ploughing and weeding services to communal farmers at subsidized prices.	MAWF (2009)
Namibia agricultural policy (NAP) 2015	The NAP aims to (1) ensure food security and improve nutritional status; (2) create and sustain viable livelihood and employment opportunities in rural areas; and (3) improve the living standards of farmers and their families, as well as farm workers.	MAWF (2015a)
Namibia Food Safety Policy (2014)	The overall objective of the policy is to ensure food safety for all consumers in Namibia and provide sufficient food safety guarantees on all food products traded nationally or exported to other countries.	MAWF (2014)
Vision 2030	The national long-term development goal outlined in the Vision 2030 commits the Government of the Republic of Namibia to devise programmes and projects to ensure food security at national and household levels.	Government of the Republic of Namibia (2004)
Harambee comprehensively coordinated and integrated agricultural development	The overall HACCIADEP model is aimed at facilitating market access to small and	MAWF (2018)

(continued)

Table 15.1 (continued)

Policy/programme	Main objective (s)	References
Programme (HACCIADEP) (2018)	medium-scale agricultural producers and agro-processors, as a means of stimulating sustainable agricultural production and productivity.	
National Policy on Climate Change for Namibia (2011)	The overall aim of the policy is to provide direction on responding to climate change in a timely, effective and appropriate manner through exploring adaptation and mitigation approaches relevant to different sectors at scale to improve the quality of life of the citizens.	Ministry of Environment and Tourism [MET] (2011)
National Climate Change Adaptation Strategy and Action Plan (2013–2020)	The plan focuses on operationalising the implementation of the NCCP (2011) to address climate variability, and climate change risks and impacts affecting Namibia's social, environmental, and economic developmental potential. It is a tool that offers guidance on the mechanisms, means, and way implementation can happen.	Ministry of Environment and Tourism [MET] (2013)
Namibia country climate-smart agriculture program	The program aims to build the resilience of agricultural farming systems for enhanced food and nutrition security.	Ministry of Environment and Tourism [MET] and Ministry of Agriculture Water and Forestry [MAWF] (2014)

for handouts. The various projects and programmes that are related to crop farming and implementing CSA practices in Namibia are listed in Table 15.2.

15.4 Climate-Smart Technologies Being Promoted in Namibia

15.4.1 Conservation Agriculture

There is no one agricultural practice or production system that can be considered a climate-smart agriculture practice, but rather a set of possible options that under the specific climate change, socio-economic and agro-ecological conditions can increase agriculture's capacity to support food security (FAO 2010). Since its introduction by the Food and Agriculture Organization, conservation agriculture has been promoted

Table 15.2 Projects and programmes that are related to crop farming and implementing CSA practices in Namibia

Program	Level within the country
National dry land crop production	National implementation
CONTIL (conservation tillage) project	North-central regions
Micro and small poly bags drip irrigation	Omusati, Ohangwena, Kavango, Oshikoto, Erongo, Hardap (in 6 out of 14 regions)
Drought-tolerant and early maturity variety (pearl millet, sorghum, beans)	National implementation
Seed and fertilizers subsidy	National implementation
Tractor service subsidy	National implementation
Green scheme projects the National Horticulture Development Initiative (NHDI), aimed at increasing local agricultural production.	Regional (northern communal areas, Karas and Hardap)
Rice research project	Zambezi and Omusati regions
The Namibia agricultural mechanisation and seed improvement project (NAMSIP)	National implementation

as a panacea to most of the productivity challenges faced by smallholder farmers. Conservation agriculture is among the key practices being promoted in Namibia as a climate-smart farming system that has the potential of driving sustainable intensification of crop production among the smallholder farming sector (MAWF 2015a, b; Namibia Statistics Agency [NSA] 2013). Conservation agriculture (CA) is a form of ecological farming that is based on three principles, that is, minimum soil disturbance; permanent organic soil cover and diverse crop rotations (Taapopi et al. 2018). It aims to address the following challenges: (i) the low and declining productivity of the small-holder farming sector, (ii) vulnerability of small-holder farmers to climate change, (iii) continuing degradation and loss of the natural resource base, (iv) reduced emissions of the greenhouse gases from the land degradations, land use and sequestration of carbon in the soil. Conservation agriculture is grounded on protecting natural biological processes above and below the ground and offers economic benefits to the farmers by improving their soils and crop yields while conserving the natural environment. It incorporates a wide range of practices aimed at minimizing soil disturbance and minimizing bare, uncovered soils (Blanco and Lal 2008). FAO includes crop rotation as an essential component of conservation agriculture. Reduced or zero tillage plus incorporation of residues or other mulches reduces wind and soil erosion, increases water retention, and improves soil structure and aeration (Blanco and Lal 2008). Reduced erosion, improved soil structure, and greater water retention reduces yield variability due to weather events in general. Thus, conservation tillage practices can increase farm system resilience and improve the capacity of farmers to adapt to climate change.

Conservation agriculture technologies are being practiced by selected farmers in some of the communal crop-growing regions of Namibia. Technologies being practiced in Namibia on-farm and on-station include minimum soil disturbance, that is, basin method, ripping, rip furrow, tine cultivation. This is followed by crop rotation or intercropping of crops such as maize or pearl millet with cowpea or bambara nuts. Lastly, there is mulching with stover from the various crops. Fertilizing and manuring are also important for soil amendments using inorganic and manure and compost. What is also important to note is that various farmers practice the various aspects of CA selectively or as a complete set of the three principles.

Few studies have been carried out on the adoption of CA practices in Namibia to increase agricultural productivity (Taapopi et al. 2018; Mudamburi 2016b). Taapopi et al. 2018 highlighted limited success stories from the African countries with regard to research on CA, for example, with only positive results being reported at experimental sites that are researcher managed. They reported low adoption of CSA technologies and practices at the community level (Taapopi et al. (2018)). The use of sustainable agricultural practices such as CA has a huge potential to increase crop yields and at the same time preserve the environment (Taapopi et al. 2018) There is little evidence so far of positive yield effects of CA in southern Africa including Namibia, but these reports mainly include experimental plots (Thierfelder and Wall 2010; Thierfelder et al. 2015). Mudamburi (2016b) research outlined that farmers are aware of CA and know that it can increase yields. Most of the farmers noticed differences between crops grown under CA and crops grown under conventional agriculture methods. The most noticeable difference is the high yield on CA fields, rapid growth and better root development, deep root growth and high yield, rapid growth, and strong stems. Crops under CA do not dry easily and moisture conservation on CA fields. Farmers also noticed improved soil fertility, reduced soil erosion, improved water penetration or infiltration, whose ridges do not break easily, and noticed soils becoming dark under CA fields.

15.4.2 Improved Stress-Tolerant Seed

Whilst various programmes are being promoted as indicated above, it would have been best if farmers used improved stress-tolerant seeds by smallholder farmers to improve their adaptation to changing weather conditions. Togarepi et al. (2020) also reported that there are very few seed producers in Namibia as there was only one seed multiplication cooperative that was identified at Omahenene Research Station and these are the only ones currently processing seed in the country. There is also a lack of flood and drought-tolerant crops, that is, drought, heat and flood-tolerant varieties, early maturing, high nutritional value, high-value crops, and pest-resistant crops (Davies et al. 2019). Pearl millet is preferred among many smallholder communal farmers in Namibia, due to its low water requirements, drought tolerance, higher productivity under stress, and consumer cultural preference (Mudamburi 2016a). To enhance productivity among these farmers, the government has also distributed improved pearl millet seed varieties such as Okashana 1 and 2 which are high-yielding, short season (early maturing) but most importantly drought-resistant; these can reach harvest maturity in a short time with limited rainfall. However, there are still some farmers who will still grow the local landrace which is late maturing and not drought-resistant which leads to crop failure in some instances. There is a need for increased extension services that can encourage farmers to adopt the use of these improved varieties as an important climate change adaptation strategy.

15.4.3 Irrigation

Irrigation could very well solve the problem of poor rainfall and frequent droughts that Namibia faces. A situational analysis indicated that irrigated agriculture in the communal subsistence agriculture is limited to small gardens mainly for vegetable production, and to a limited extent for commercial purposes by emerging small-scale farmers who reside along a canal, river, or dam, for example, around the Olushandja dam and along the Calueque-Oshakati canal. The major impediment to irrigated agriculture seems to be inadequate infrastructure development, know-how for irrigation, and affordability for most of the farmers (Lasaroff et al. 2021. Moreover, there are limited water bodies that limit most farmers from irrigated agriculture; especially in northern Namibia there are very few dams and wetlands (locally called *oshanas*) that hold water after the rains dry up in drier months and cannot hold water for long periods. The existing and thriving irrigated agriculture is mainly done along the main rivers such as Kavango, Orange, Fish, Kunene, Zambezi and around man-made dams such Hardap, Naute, Olushandja, among others. Most of the irrigated agriculture belongs to the government through the green scheme projects and others are owned privately. The Green Scheme project encouraged the development of irrigated agronomic production with a target reaching approximately 27,000 hectares along the perennial rivers bordering Namibia. In addition, green scheme projects are operated by Agribusdev to ensure skills transfer for small-scale farmers who enter into a contract to produce for several years so that they can use the skills after leaving the project. The Green Scheme has not met many of its initial goals as several of the Green Scheme projects struggle financially (Agricultural Sector update of 2020-08-29 n.d.). There is limited irrigated agriculture using underground water usually done by private commercial farmers in the central high grounds of Namibia. Due to the unaffordability of technology and possibly lack of knowledge, the available irrigation methods are not very efficient as they are wasteful, and the use of drip and other water-conserving technologies are limited. Zimmermann (1999) and Haidula (2016) highlighted that some farmers use flood irrigation systems that waste water compared to other systems such as sprinkler and drip irrigation. Haidula (2016) went on to report that there was a lack of technical and production efficiency information such as water use, on irrigation systems, and the ability to be easily adapt by small-scale horticultural farmers in north-central Namibia.

According to the country CSA programme for Namibia and in terms of irrigation and water management, there is overdependence of agriculture on poor and erratic rainfall (rain-fed agriculture). There is inadequate infrastructural development and know-how for irrigation, maintenance, and drainage; high water wastage leading to low productivity on existing irrigation systems; and poor water management exacerbated by poor water harvesting and on-farm storage facilities (Davies et al. 2019). According to Togarepi et al. (2020), mechanized irrigation is still incredibly low across all 14 regions of Namibia. Given the recurring droughts and the effects of climate change, efficient use of water resources is a critical factor in adaptive crop production, especially by smallholder farmers.

15.5 Challenges with the National Adoption of CSA Practices in Namibia

15.5.1 Knowledge Management

Namibia has limited national agricultural research institutions that can spearhead climate-smart agriculture research (Ipinge et al. 2011). Therefore, agricultural R&D is carried out by several government agencies and higher education institutions under the relevant ministries. The lack of centralised and coordinated research may hamper the efforts of policies and programmes being implemented to improve the livelihoods of farmers. There is limited research information for the benefit of users and there is poor management and sharing of agricultural research information in most parts of the country, lack of appropriate platforms for researchers and users to interact and share knowledge and experiences. This results in poor uptake of CSA technologies and practices. There is a lack of a CSA knowledge management system across the country. There is limited upscaling of best practices, lessons learned from projects, community awareness, mobilization, and actions focused on controlling soil erosion and reforestation to conserve degraded agricultural landscapes and watersheds. There is limited awareness and training for small-scale farmers to bounce back after experiencing extreme weather events and climate variability in addition to raising awareness on varied innovative crop and livestock weather-indexed insurance packages.

15.5.2 Lack of Dedicated CSA Funding

Most CSA activities are pilot in nature and donor-funded which is good but ends as soon as donor funding ends. It was also observed that there is a weak collaboration between relevant ministries and agencies to ensure CSA is scaled upwards and the high dependency on rain-fed agriculture which is affected by the increasing frequency of extreme weather events such as droughts and floods need to be addressed. Results from a study conducted in north-eastern Namibia by Lasaroff et al. (2021) limited finances were cited as the biggest challenge by subsistence farmers. A limited number of subsidies to ensure farmers adopt the technologies. Namibia also lacks climate change-related insurance and other safety nets, states the Country CSA programme report. There is a lack of financial institutions to act as agents to deliver innovative crop and livestock weather-indexed insurance packages; raising awareness within the insurance industry of extreme weather and climate risks and communicate actions and opportunities, and undertaking farmer education to address their concerns regarding insurance products to get buy-in. There is limited involvement of the youth and marginalized groups in the application of ICT in CSA agribusiness and extension services.

15.5.3 Ignoring Indigenous Knowledge Systems

To make maximum use of scarce research resources, it is important to introduce a systematic research planning process, in which farmers themselves have a major input since they own a lot of indigenous knowledge. There is a lack of scientific and indigenous knowledge into the contingency planning process to improve the accuracy of models for predicting weather and improving seed varieties. The indigenous people in Namibia have long traditions of applying indigenous knowledge (Jussi et al. 2017). Indigenous knowledge is complementary to science-based knowledge. Indigenous knowledge is the main asset indigenous people use to invest in the struggle for survival, to produce food, shelter or to achieve control of their own lives amidst the climate change crisis. Indigenous knowledge is the basis for local-level decisions on agriculture, management of resources, food preparation, and even education in many Namibian rural communities.

15.6 Conclusions

This chapter presented aspects of climate-smart agriculture that are related to crop farming in Namibia and it's important to highlight that the country has made some in-roads in addressing climate change mainly at the policy level. With most of the crop farming being concentrated in the north-eastern parts of the country, where smallholder subsistence farmers are located, it is important to note that these farmers are critical in driving national food security. With climate change, several national and private institutions have established several experiments, mainly focusing on conservation agriculture, irrigation, and improved seed systems, as climate-smart technologies. However, the adoption of these technologies has been limited by factors such as lack of effective knowledge sharing, lack of dedicated funding, and disregard of indigenous knowledge systems during research. For Namibian farmers to be more resilient in the face of climate change, there is need for a well-coordinated multidisciplinary research that involves government agencies, universities, non-governmental organizations, and the farmers, which will allow for the development of successfully adoptable technologies.

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Chapter 16
Smallholder Farmers' Adaptation Strategies and Food Security: Experiences from Zimbabwe

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Abstract The reliance of African smallholder farmers on rain-fed agriculture exposes farmers to the deleterious effects of climate change. Climate change has become a tangible threat to agricultural production with negative effects on household food security. Frequent droughts in Africa have led to extremely low crop yields in crops and mortality of livestock. There are various strategies which have been identified to have potential to offset the negative impact of climate change within smallholder farmers' conditions. Adaptation prepares farmers to adjust to current or future changes in climate thereby reducing their vulnerability to climate change. Prominent adaptation practices include shifting planting dates; adopting improved land management practices such as adopting tree planting, changing crop cultivars, zero tillage, and crop diversification. Despite these wide range of choices of adaptation strategies, smallholder farmers continue to get very low yields, thus resulting in food insecurity. This chapter discusses adaptation strategies used by smallholder farmers across Zimbabwe and their bearing on food security. In addition, the chapter also highlights key challenges faced by farmers in adopting these adaptation strategies and suggests new adaptation options that may address current gaps.

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Keywords climate change · incremental adaptation · transformative adaptation · vulnerability

16.1 Introduction

Approximately 60% of the world's population largely depends on agricultural production for survival (FAO 2018). Consequently, any negative impact on agriculture leads to food insecurity at both national and household levels. According to FAOSTAT (2005), globally, rain-fed agriculture is practiced on 80% of the arable land and produces 62% of the world's staple food. Madzwamutse (2010) reiterated that the majority of Sub-Saharan Africa's (SSA) population is dependent on rain-fed agriculture. Putting this into consideration, climate change, therefore, becomes a tangible threat to rain-fed agriculture in Africa (Simba et al. 2012). The vulnerability of developing countries to climate risks, especially those in SSA, is intricately linked to the sole reliance of most smallholder farmers on rain-fed agriculture (Jiri et al. 2015). Agricultural systems are highly susceptible to extreme events such as floods, droughts, and extremes in both temperature and precipitation (Global Framework for Climate Services [GFCS] 2014), making climate change a plausible threat to agricultural production for both the current and future generations (Jiri et al. 2015). This intricate link between climate change and agriculture, therefore, results in poor yields under rain-fed agricultural production, which subsequently affects food security and rural livelihoods (Cline 2007; Gornall et al. 2010; FAO et al. 2019).

There is sufficient evidence that indicates that climate change has compromised food security, particularly among rural smallholder farmers who largely depend on rain-fed agriculture. For instance, FAO (2007) highlighted that climate change is exerting immense stress on not only agricultural production and the biophysical, but also on political and social systems that are related to food security in Africa. Evidence from IPCC (2007) indicates that in several parts of the world, climate change has significantly altered the hydrological cycle and temperature patterns. In addition to the direct impact on agriculture and food security, climate change will disrupt access to clean drinking water, which negatively affects the health of poor people (Jiri et al. 2015). Scholars such as Conway (2011), Thornton et al. (2012), Beddington et al. (2012), Thornton and Herrero (2014) provided more evidence on the serious challenges posed by climate change on food security in rural SSA. One way to cope with the effects of climate change is through adaptation, which entails actions that prepare farmers to adjust to current or future changes in climate. In so doing, adaptation reduces the vulnerability of farmers to climate change. Notable adaptation practices include shifting planting dates; adopting improved land management practices such as adopting tree planting, changing crop cultivars, zero tillage, and crop diversification (IPCC 2007). While there is a wide range of adaptation practices available for smallholder farmers in Zimbabwe, several factors affect the adoption of key practices (Zamasiya et al. 2017). This chapter discusses key adaptation practices that have been adopted by farmers across Zimbabwe to address food security challenges caused by climate change. In addition, the chapter highlights key challenges that prevent both the adoption and effectiveness of these adaptation strategies and suggests alternatives to the current strategies.

16.2 A Global Overview of Food Security

According to UNDP (2012), food security is the basis of human development that enables people to live healthily with dignity. This makes food security a human right that should be accorded to everyone. The inclusion of food security in the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs) shows how food security is a crucial goal that needs to be attained globally. Unfortunately, food security continues to elude most countries with Africa facing the biggest challenge among all continents. Africa is the region with the highest prevalence of severe food insecurity followed by Latin America (more than 30%), then Asia (23%) and Northern America and Europe with only 8% (FAO et al. 2019). In addition, one in four people in Africa faces widespread and chronic malnutrition as well as a constant threat of acute food crisis and famine (Rukuni 2012; Bapolisi et al. 2021). For instance, Bapolisi et al. (2021) found out that, in 2018, close to 13.1 million Congolese were food insecure.

According to Porkka et al. (2013), meeting the future food requirements of the sharply increasing global population will become extremely challenging due to pressures caused by climate change. Food production needs to increase by twofold by the year 2050 to satisfy the increasing demand (Foley et al. 2011) with estimates showing that by 2030, 50% more food will be needed (FAO 2010). Climate change worsens the effects of increased competition for resources such as land, water and energy due to increase in population, which will in turn affect food security. By 2018, there were more than 820 million hungry people in the world, underscoring the immense challenge of achieving the Zero Hunger target by 2030 (FAO et al. 2019). These figures show how food insecurity has continued to plague the world with those in the developing world who largely rely on rain-fed agriculture being affected the most.

Food security implies that food is available at all times, that all persons have means of access to it, that it is nutritionally adequate in terms of quantity, quality and variety; and that it is acceptable within the given culture (FAO 2010; Boon 2002). There are four dimensions of food security, which are physical availability of food, economic and physical access to food, food utilization and stability of the other three dimensions over time (FAO 2008a, b). Global Framework for Climate Services [GFCS] (2014) explains these four dimensions in detail pointing out that food availability refers to availability of adequate quantity of food that meets basic quality standards. Food access means that individuals should have sufficient resources for attaining food while food utilization refers to access to an appropriate diet, clean water, sanitisation and healthcare (Global Framework for Climate Services [GFCS] 2014). Finally, food stability entails adequate access to food at all times at the national, household and individual level without risk of losing access to sudden economic or climatic shocks.

16.3 Climate Change and Food Security

According to Global Framework for Climate Services [GFCS] (2014), climate change will affect all the four components that influence food security. Most parts of SSA often experience severe food shortages, food insecurity, hunger and famine due to frequent droughts and floods (Ngigi 2009). Consequently, climate change exacerbates existing threats to food security and livelihoods by increasing occurrence of climate hazards, which weakens agricultural production especially in vulnerable regions (Global Framework for Climate Services [GFCS] 2014). The vulnerability of the SSA agriculture and all who depend on it for food security and livelihoods is well documented (IPCC 2007). Food insecurity remains pervasive in Africa with climatic conditions such as extremes in rainfall and temperature being some of the major causes (Ngigi 2009). Extreme weather, climate variability and long-term climate change have serious negative effects on crop yield and hence food security (Global Framework for Climate Services [GFCS] 2014). Poverty and food security are linked to low agricultural productivity that is being intensified by climate change and variability (Ngigi 2009). Consequently, climate change acts as a hunger risk multiplier, worsening the food security risk factors (Global Framework for Climate Services [GFCS] 2014).

There are direct and indirect linkages between food security and ecosystems services through food and resource provisioning, climate regulation and support services such as soil formation and nutrient cycling (Millennium Ecosystem Assessment 2005). Hence, the agricultural sector plays a strategic role in ensuring availability of food and attaining food security (Pawlak and Kolodziejczak 2020). It is, therefore, necessary for developing countries to invest heavily in agricultural research and extension systems in order to increase and sustain agricultural productivity (Pawlak and Kolodziejczak 2020). Improved support systems will ensure the survival of approximately 2.5 billion people who derive their livelihoods directly from agriculture (FAO 2008a, b). Smallholder farmers' livelihoods mostly comprises agriculture and livestock rearing leading to a link between smallholder farmers' livelihoods and food security. This dependence makes the farmers' livelihoods vulnerable especially for those farmers that solely depend on rain-fed agriculture. Farmers constantly face major risks such as limited water resources, drought, desertification, land degradation, erosion and natural hazards (Global Framework for Climate Services [GFCS] 2014). All these hazards put a strain on the livelihoods of smallholder farmers in SSA (Jiri et al. 2015). The problem of food insecurity caused by climate change and invariability has left smallholder farmers with no other alternatives but to adopt various adaptation strategies. According to Vermeulen et al. (2012), modifications and agricultural practices in order to acclimatize to a changing climate are, therefore, necessary in order to critically sustain the livelihoods and food security for millions of smallholder farmers. Without any adaptation, climate change and variability would cause a decline in food security among smallholder farmers especially in SSA where per capita food production has been declining (World Bank 2010). Therefore, households that seek to preserve food security have resorted to a number of coping strategies to gain access to food, and these include adaptation by means of innovative use of available resources (Boon 2002). According to Ngigi (2009), adaptation of smallholder farmers requires an exceptional level of both economic and political commitment. Adaptation in smallholding farming systems is crucial given the gravity of threats posed by climate change and demographic pressure on land and thereof food security levels (Douxchamps et al. 2016). Some of the adaptation strategies adopted by smallholder farmers include intensification of food production through better access to improved seed, soil fertility management, rainwater harvesting, smallholder irrigation, conservation agriculture, sustainable extraction of groundwater and improved on-farm water use efficiency (Ngigi 2009). These adaptation strategies, if implemented well, can enhance food security among smallholder farmers who are facing a decline in crop yields due to climatic conditions.

16.4 Challenges in Attaining Food Security in Zimbabwe

Smallholder agriculture is the major contributor to national food security in Zimbabwe (Mutekwa 2009). However, several challenges have hampered the capacity of agriculture to meet the food requirements of Zimbabwe's rural populace (Ignowski 2012), chief among which is climate change and global warming (Mushore et al. 2013). There has been severe drought from 2018 to 2019, economic deterioration, hyperinflation, and shortage of inputs, unavailability of hybrid seed, expensive fertilizers, shortage of labour, power shortages, poverty, HIV and the low agriculture production as drivers of the crisis (Muzerengi and Khalema 2019). Mashizha et al. (2017) noted that fluctuating rainfall patterns and a frequent occurrence of droughts and floods significantly affected yields of rain-fed crops and livestock productivity. Most smallholder farmers in Zimbabwe practice rain-fed agriculture and are thus vulnerable to climatic change (Dube et al. 2014). In addition to causing poor crop yields, decrease in rainfall resulted in deteriorating pasture conditions and drying water sources leading to the death of livestock (Mavhura et al. 2015).

In addition to poor agricultural productivity, the available food is usually priced well beyond the reach of most Zimbabweans, which in turn affects individual nutrition and health. The Zimbabwe Multi Indicator Cluster Survey (2019) noted that about a quarter of children below 5 years were stunted and had high chances of having impaired physical and cognitive growth. This can be partly attributed to several smallholder farmers focusing on cash crops such as tobacco and cotton instead of the maize staple (Rubhara et al. 2020). They noted that maize production dropped by about 46% nationwide in the 2016/2017 season; this could be attributed to the Grain Marketing Board providing late payments to maize farmers. Added to this, maize production dropped from 2019 because of climate change-induced shocks such as cyclones Idai and Kenneth. Consequently, the reduction in food crop production has resulted in some families reducing either the quantity of food per meal and/or number of daily meals, whereas others were forced to change their diets (Mavhura et al. 2015). Food insecurity might worsen with the spreading of the COVID-19 pandemic because of restricted access to markets. Border restrictions and lockdowns slowed down food production and disrupted supply chains. There has been an increase in unemployment rate, loss of income and a rise in food prices which in turn resulted in access for food being difficult. According to SADC (2020), about 7.7 million people in Zimbabwe were in urgent need of food assistance by July 2020. Consequently, there is a need for farmers to take up relevant adaptation practices to cope with climate change and hence improve access to food.

16.5 Zimbabwean Farmers' Experiences and Perceptions on Adaptation Strategies and Food Security

Most smallholder farmers solely rely on rainfall for their agricultural production, which is often erratic and poorly distributed due to climate change. This predisposes smallholder farmers to poor crop yields and food insecurity. It is, therefore, important for smallholder farmers to adapt to these challenges through implementation of crop management practices such as planting drought-tolerant crops (e.g. pearl millet, rapoko and sorghum), planting short season varieties, staggering planting dates (Stringer et al. 2009) and crop diversification (Makate et al. 2017). Farmers can also adopt soil moisture-retention techniques and conservation farming (Limantol et al. 2016; Mutunga et al. 2017) which can help mitigate the effects of climate change on agriculture (Nyakudya and Stroosnijder 2011; Gukurume 2013). Nhemachena and Hassan (2008) noted that some of these measures ensure that critical crop growth stages do not coincide with harsh climatic conditions in the season.

Whilst the vulnerability, coping and adaptive capacity and resilience of farmers to climate change and variability in semi-arid systems could be addressed through different adaptation strategies (Chivenge et al. 2015), farmers' adaptation decisions are guided by their perception to climate change and variability, and climate-related risks. Deressa et al. (2011) pointed out that adaptation to climate change is a two-step process, which requires that farmers perceive climate change in the first place and implement adaptive strategies as the next step. Also important is that farmer's perceptions and vulnerabilities are place-specific, which calls for numerous studies to capture and understand the problems facing farmers in their endeavour to deal with climate change. Studies on adaptation to climate change must be localised as different forms and levels of vulnerability exist, with serious implications for the adaptation measures most appropriate for specific locales (Brazier 2015). Generally, farmers in Zimbabwe do perceive that climate change is taking place and are implementing different adaptive strategies despite some challenges.

In response to the perceived changes in climate, some smallholder farmers have resorted to growing hybrid maize, which takes a shorter period to mature and yield more than traditional varieties (Mutekwa 2009). Unfortunately, most smallholder farmers had to resort to selling their livestock at very low prices so that they can afford to feed their families (Mavhura et al. 2015). Some families even resorted to supplementing their diets by increasing their consumption of wild fruits, mushrooms and insects (Rurinda 2014). Other smallholder farmers have resorted to collective farming action (i.e. working in groups); this helps in cutting costs when buying fertilizer and reduces transport costs as they buy as a group and share costs (Rurinda 2014). In addition, some have implemented the selection of local cattle breeds that are adapted to local conditions that would sustain cattle production (Rurinda 2014). Makuvaro et al. (2017) noted that in Lupane, elephants destroyed some farmers' crops and as a result, they have resorted to harvesting their crops early, followed by preservation. In Chiredzi, 26.8% of smallholder farmers have resorted to dry planting, 17.5% conservation agriculture and 12.4% planting short season varieties (Muzamhindo et al. 2015). Gukurume 2010 noted that in Masvingo use of contour ridges as a water harvesting technique has been adapted. These ridges help to decrease runoff to lessen the loss of soil nutrients through runoff. However, ridges have proven to be labour-intensive. However, some smallholder farmers in Gwanda have resorted to stream bank cultivation, which may have negative effects of water resources. Stream bank cultivation is deemed less labour-intensive and water could be accessed easily from the rivers (Dube et al. 2018). Some smallholder farmers in Gwanda moved their cattle to faraway places such as to Esigodini, Tuli and UMzingwane Rivers, which were believed to have good grazing lands and water. Most smallholder farmers adapted through collecting and storing crop residues, including those from maize, sorghum, millet, and groundnuts for cattle feeding while others migrate daily to better grazing lands (Dube et al. 2018).

Simba et al. (2012) showed that climate change is a reality in Masvingo Province. The study showed how rainfall in Masvingo is decreasing and how it has affected crop production. This is in line with UN sentiments that Masvingo Province will become a non-maize-producing region in the future. Farmers in the area perceive that there is climate change and should move to adaptive strategies that can assist them. In the study, the authors pointed out that farmers should grow small grains as an adaptive strategy. They point out that drought-resistant crops like most small grains guarantee food security and are worthwhile. The study also pointed out that farmers should incorporate early maturing seed varieties as an adaptive measure and underscored the extension support services, planting dates, suitable cultivars and soil nutrient management.

Muzerengi and Tirivangasi (2019) assessed the feasibility of small grain crops as an adaptive strategy to climate change in Mangwe District, Zimbabwe. The study identified the production of small grain crops as a dependable adaptive strategy to climate change, which can increase food availability, accessibility, utilisation and stability. The researchers noted that households in Mangwe who took up production of small grain crops have now realised food accessibility, as they are readily available in the district. There are, however, numerous challenges that farmers face in their endeavour to produce small grain crops. These include lack of government support, the problem of quelea birds, lack of markets and labour. Mugiya and Hofisi (2017) looked at the climate change adaptation challenges faced by small-scale farmers in Zvishavane District. Their study revealed that as farmers in Zvishavane are trying to implement adaptive strategies, they are experiencing some resource constraints. Some of their challenges include lack of finance, draught power, and lack of irrigation equipment. Most of the farmers in the study indicated that seeds of small grain crops were not available and resultantly farmers are growing maize, which is always available at the market.

Muzamhindo et al. (2015) looked at factors that influenced farmers' adaptation to climate change and variability in Chiredzi District, Zimbabwe. The study identified the following adaptation strategies: dry planting, conservation agriculture, planting short season crop varieties and crop diversification. The study found out that younger farmers were more likely to adapt to climate change and variability as compared to older ones. Older farmers were experiencing difficulties in implementing some adaptive strategies. This was attributed to issues related to education and to the labour associated with the strategies. The study also showed that larger households have a higher probability of adapting to climate change. This is mostly due to the labour associated with some adaptive strategies like small grain crop production and conservation agriculture. Mudzonga (2012), Gbetibouo (2009) and Nhemachena and Hassan (2008) all concur that households with large families can implement labour-intensive adaptive measures than smaller households. In several studies, it has been noted that farmers' efforts in implementing adaptive strategies is affected by their access to credit. Access to credit enables farmers to get the required crop seed varieties. The socioeconomic attributes and farmer's perception to climate change and variability considerably influenced the type of agricultural adaptation chosen by the farmer in response to a changing climate. In this regard, having credit is very significant as it enables farmers to adapt (Chivenge et al. 2015).

A study to determine the main drivers influencing adaptation to climate change in Chimanimani district, which is located in the south-eastern part of Manicaland Province, Zimbabwe, showed that the majority of farmers perceived that climate change has been occurring for over a decade (Mutandwa et al. 2019). The most popular adaptation strategies used were contour ridges (75%), crop diversification (63%), planting at different dates (62%), mulching (53%), rotation (42%) and zero tillage (33%). The least adopted options were agroforestry and multipurpose trees (9%) and migration to new places (9%). Farmers' prior knowledge of climate change was one of the most important determinants of adoption. Other determinants included the household head's education level, land tenure and access to public extension services. Consequently, knowledge dissemination is a very important determinant, hence the need for stronger educational and extension programs.

16.6 Moving beyond Incremental Adaptation Towards Transformative Adaptation to Climate Change

Climate change will result in up to 90% decrease in net crop revenues by year 2100 due to poor crop yields (AfDB 2012). There is, therefore, a need for smallholder farmers to adopt farming practices that ensure yield stability in the face of climate change. Adaptation has, therefore, been an important premise of a number of initiatives that researchers and policymakers have recommended over the years. Regrettably, smallholder farmers have low inherent adaptive capacity due to insufficient access to labour, inputs, markets, technology, financial credit, and technical support (von Loeper et al. 2016). Consequently, knowledge-intensive approaches such as conservation agriculture, which have been highly recommended by FAO and other related organisations, have had low uptake among smallholder farmers. Other barriers that limit the adaptation capacity of smallholder farmers include: inadequate information, knowledge, skills, lack of technical support, cultural factors, food preference, conflicting programs and priorities (Mugiya and Hofisi 2017).

The adaptation measures discussed above involve incremental adjustments that may allow short-term management of climate risks (Kates et al. 2012; Vermeulen et al. 2018). Whilst incremental adaptation measures are essentially individual farmer-oriented and in most cases aid farmers addressing climate change they may be insufficient in dealing with rapid shifts in conditions over larger areas (Vermeulen et al. 2018) because they drive minor adjustments to the prevailing system (Fedele et al. 2019). This is largely because the focus of incremental adaptation is at field and farm level, leaving out the rest of the farming system, ignoring processes such as storage, transport, processing and marketing (Kates et al. 2012; Grist 2014). Another characteristic of incremental adaptation measures is that they aim to maintain the status of system or processes constant, the proportion of change is very low with the general status remaining constant (Rickards and Howden 2012). The challenge with this is that these adaptation measures may fail to address severe or dramatic climate change shifts, which may occur at a greater scale, speed with severe impacts (Carter et al. 2018). These shortcomings call for the adoption of more robust, large-scale measures, which involve new adaptation innovations and involve different places and locations such as transformative adaptation (Grist 2014). There has been growing recognition of this approach across the globe over the last decade with countries such as Australia already recognising it as a priority (Rickards and Howden 2012; Kates et al. 2012; Carter et al. 2018; Gosnell et al. 2019).

Transformative adaptation is a system-wide approach that entails major changes to agricultural systems across large geographical areas. Most importantly, transformative adaptation challenges the underlying conditions that cause risk at a society level and not just at individual farmer or farm level, as is the case with incremental adaptation (Fedele et al. 2019); by so doing, whole communities benefit including extremely resource-poor individuals. The changes involved in transformative adaptation result in new economic, social and ecological systems and processes (Mapfumo et al. 2017; Fedele et al. 2019). Fedele et al. (2019) reviewed several

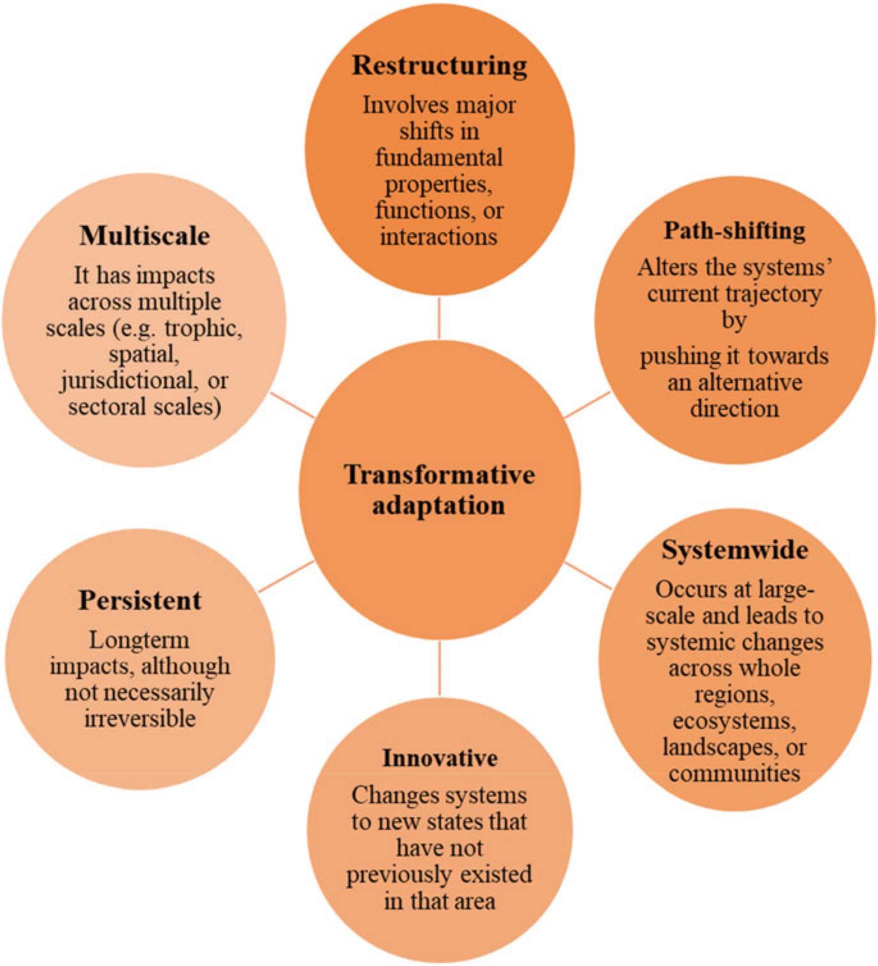

Fig. 16.1 Characteristics of transformative adaptation. Adapted from Fedele et al. (2019)

papers on transformative adaptation and identified six common characteristics as shown in Fig. 16.1.

One common example of transformative adaptation is the adoption of agroforestry in an area where annual cropping is no longer viable. Agroforestry in this case fundamentally changes the characteristics and properties of the land (Fedele et al. 2019). In this case, the benefits of adopting agroforestry meet all the six characteristics of transformative adaptation and have societal, ecological and economic benefits at a village level or beyond. Specific examples include Kenyan farmers who shifted from pastoralism to rain-fed cultivation and beekeeping due to severe drought in 1999–2001 (Vermeulen et al. 2018). In this case, there was a major change in inputs and outputs in that by 2010 almost 90% of all households were engaged in farming up from 0% in the 1980 whilst beekeeping increased from zero to 40%. This transformative adaptation influenced the livelihoods of about 133,189 people between the 1990s and 2010. This example shows that transformative adaptation could be the only viable solution in cases where climate change has caused acute ecological or social systems impacts (Vermeulen et al. 2018). Therefore, the integration of transformative adaptation into climate-related issues is very critical in order to ensure optimum food production and food security amidst climate change. However, there is a need for the involvement of researchers, policymakers and other stakeholders such as politicians and traditional leaders because of the scale of transformative adaptation, which may require significant investments.

16.7 Conclusions

Smallholder farmers in Zimbabwe have adopted several adaptation practices to cope with climate change. These adaptation practices include conservation agriculture, planting short season varieties, planting on ridges, crop diversification, planting at different dates, mulching, rotation and zero tillage. Whilst some yield and food security benefits have been realised, these incremental benefits are usually farm level focus, leaving out the wider system. Consequently, these incremental adaptation strategies have not resulted in meaningful yield and food security. Focusing on transformative adaptation, which addresses the wider system has more social, economic and ecological benefits that assists the wider society including those with an extremely low adaptive capacity. For instance, some of the studies reviewed showed that some farmers have moved to small grains production; however, they are facing challenges like unavailability of seed and birds that damage seeds. It would be beneficial in such cases to move from cereals to, for instance, an agroforestry system that may improve soil properties and sequester carbon, which will in the end improve soil properties.

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Chapter 17
Building Resilience to Climate Change by Adopting Conservation Agriculture in the Smallholder Farming Systems

Cosmas Parwada, Justin Chipomho, and Ronald Mandumbu

Abstract Continuous soil fertility decline, soil degradation and abiotic stresses caused by climate change and variability affect crop productivity in sub-Saharan Africa. Crop yields in the smallholder sector have continued to decline, and farmers whose livelihoods rely on agriculture are poor and food-insecure. Technologies to avert some of the challenges faced by these farmers have been developed, although adoption is low in some countries of southern Africa. This chapter provides a treatise review on how the farmers can build resilience to climate change through adoption of conservation agriculture (CA). Conservation agriculture is one such technology whose main objectives are to reduce soil erosion and degradation, stabilize crop yield and increase crop profits. This is achieved through minimum soil disturbance, use of mulch or crop residue and crop diversification. Conservation agriculture has several positive attributes, which enable crop productivity in semi-arid regions of southern Africa. Among other advantages, CA maintains or improves soil structure; reduces soil exposure to water and wind erosion; increases water infiltration and reduces loss through evaporation. Minimum soil disturbance slows organic matter breakdown and mineralization resulting in organic carbon build-up. Moreover, there is little disruption to the soil organisms which are responsible for the mineralization of organic matter, improvement of soil fertility and structure. Compared to the conventional tillage system, CA saves time, energy and money and enhances enterprise profitability. Crops grown under CA systems have demonstrated resilience to some abiotic stresses associated with climate change.

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17.1 Introduction

The human population in sub-Saharan Africa is projected to double from 856 million to approximately 2 billion by 2050 (Food and Agriculture Organization of the United [FAO] 2019). Increased crop and livestock productivity in the region is, therefore, vital to meet the food demands of the anticipated population growth and to ensure food security. Maize (*Zea mays* L.) is among the main staple cereal crops in southern Africa, constituting at least 50% of the diet of most people (Rodenburg et al. 2020). Besides maize, other main sources of carbohydrates in the human diet are rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L. Moench) and indigenous traditional grains such as rapoko (*Eleusine corocana* L.) and pearl millet (*Pennisetum glaucum* (L.) R. Br). Legumes and animal meat products are the main sources of human dietary protein (Muzangwa et al. 2019). Smallholder farmers play a significant role in crop production in the southern region and in Zimbabwe; more than 60% of grain deliveries to the national grain reserve (grain marketing board (GMB)) are from this sector. Despite smallholder farmers' contribution to national food security, crop productivity under rain-fed conditions is still low and, on average, maize yields of less than 1 t ha^{-1} are being attained and are far below varietal potential between 8 and 12 t ha^{-1} (Bhasera 2015). Crop yields are significantly reduced by poor inherent soil fertility (Chikowo et al. 2014), paltry external resource use (Chipomho et al. 2020), biotic factors such as insect pests, disease, nematodes, and weeds (Tibugari et al. 2019) and abiotic factors such as floods (cyclones), erratic rainfall, short cropping seasons and drought episodes (Kurwakumire et al. 2015).

In recent years, the frequency and length of dry spells during the cropping seasons has been high in the southern African region resulting in increased heat and water stress to agro-ecosystems (Mazvimavi et al. 2009). This ultimately affects agricultural communities whose livelihood depends on livestock and crop production (Nezomba et al. 2015). Smallholder farmers whose production system is mainly rain-fed (dryland) are at high risk, and adoption of strategies that increase crop resilience to abiotic forms of stress is vital. In southern Africa, rainfall is projected to decline by 30% while 2.6 °C temperature increases are anticipated by 2050 (Cairns et al. 2012). Resource-conserving management strategies that positively alter the soil-crop environment such as conservation agriculture are perceived to alleviate the adverse impacts of climate change on crop productivity (Nyamangara et al. 2014). Conservation agriculture is one such practice farmers can use to build crop resilience to climate change. This chapter, therefore, is aimed at reviewing literature on how the smallholder farmers in Zimbabwe can build resilience to climate change through adoption of conservation agriculture.

Fig. 17.1 Crop residue or mulch

17.2 Building Resilience to Climate Change by Adopting Conservation Agriculture

In Zimbabwe, the first version of conservation agriculture (CA) was implemented at a commercial farm in Bindura, Matepatepa area, Mashonaland Central in the 1980s (Zimbabwe Conservation Agriculture Task Force [ZACTF] 2009). The main objective of CA was to reduce soil erosion through minimum soil tillage and retaining crop residues, stabilize crop yield and increase crop profits (Rodenburg et al. 2020). The current version of CA is broader and is based on the following three principles: (i) farming system designed to prevent loss of arable land while regenerating degraded lands through promoting minimum soil disturbance (no tillage), (ii) maintaining permanent soil cover by using organic crop residues (mulch) or cover crops (Fig. 17.1) and (iii) crop rotations and or crop diversification, which include legumes (Thierfelder et al. 2015) (Fig. 17.2).

17.3 Conservation Agriculture (CA)

In Zimbabwe, conservation farming (CF) is described as digging of planting basins and following mulching and crop rotation principles while conservation agriculture is described as an agricultural system that encompasses minimum tillage techniques such as rip row plant and/or direct seeding. The principles of mulching, crop rotation and integrated pest management apply in conservation agriculture (Twomlow et al. 2008). Conservation agriculture (CA) has limited wastage as there is precise application of soil amendments and only the crops, and not the surrounding soil and weeds, benefit. This translates to increased yields and savings on production input

Fig. 17.2 Crop diversification (maize/bean intercrop)

cost, for example, farmers require 10–40 t of manure/ha in a conventional system (Mupangwa et al. 2016). Under CA, the same hectare requires significantly less to a minimum of 1.6 t equally, with the basal fertilizer requirements. The conventional systems need 200–350 $kg^{-1}ha$ compared to 80 $kg^{-1}ha$ in conservation agriculture (Mazvimavi et al. 2009).

Agriculture in Zimbabwe and throughout sub-Saharan Africa faces double challenges: to increase production while simultaneously preserving natural resources. This is not an easy task, but is key to fighting hunger and poverty in the region. Some of the pressing challenges for rural people are related to poor management of land and water resources (Nyagumbo et al. 2017). In many cases, the land is insufficient to sustain growing human and livestock populations resulting in overexploitation of the land. Lands once used for grazing are being cultivated and the remaining grazing lands overexploited, resulting in loss of local plants, soil erosion and the formation of gullies (Mazvimavi et al. 2009). This reduces land productivity leading to poverty and food insecurity among the farmers.

The average cereal yields in Zimbabwe have been declining sharply over the past 20 years (Nyagumbo et al. 2017), due to problems which include very low public and private investment in agriculture. Farmers faced with this situation usually try to expand cropping areas to compensate for poor yields, sometimes growing crops that are inappropriate to the area. Nevertheless, stretching the already limited resources (such as labour, fertilizer and draught power) further leads to high land degradation. In turn, soil degradation decreases average yields even more and farmers are food-insecure.

17.4 Minimum Soil Disturbance

Zimbabwe's farming land is divided into five distinct natural regions (NR) with varying climatic conditions, soil types, and area covered (Table 17.1). The minimum soil disturbance tillage practices have been implemented successfully in NR II, III, IV and V. Many organisations are promoting the minimum soil disturbance way of crop production mainly in the semi-arid zones III and IV where over 80% of smallholder farming land is located (Twomlow et al. 2008). The government of Zimbabwe adopted the Pfumvudza Programme in the 2020/2021 cropping season as a measure to address the problem of low levels of productivity and production, making the country's farmers and households more resilient to climate shocks and ultimately ensuring food security in Zimbabwe (Nyagumbo et al. 2017). The concepts is well-suited in the dry farming regions of Zimbabwe, for example, the NR III, IV and V as the Pfumvudza can improve the soil organic matter and soil hydro properties as it centres on permanent soil cover by using organic mulch, therefore raising crop productivity. It can also reduce the production costs through minimum soil disturbance, that is, digging holes for planting only, and increasing soil fertility by rotating crops and intercropping cover crops with main crops (Mazvimavi et al. 2009). Food security among the smallholder farmers is expected if these activities are timely done at standard and with limited wastage. The expected results of the

Table 17.1 The natural farming regions of Zimbabwe

Region	Soil type	Average rainfall (mm) per year	Rainy season	Area covered as a percentage of the total land size of the country
I	Red clay	>1000	Rain in every month of the year and relatively low temperature	–
II	Sandy loams	750–1000	Rainfall is mostly received in summer (October–April)	18.68
III	Sandy, acidic, low fertile	650–800	Infrequently heavy fall of rainfall. Subjected to severe seasonal droughts and severe mid-season dry spell. Rainfall is confined to summer with relatively high temperature	17.43
IV	Sandy, acidic	450–650	Rainfall is characterized by frequent seasonal droughts and severe dry spells during the rainfall period. Rainfall is confined to summer (October–April)	33.03
V	Sandy, acidic and infertile	<450	Very erratic rainfall confined to summer season (October–April). Very high temperatures during the summer	26.2

Fig. 17.3 Digging planting basins

Pfumvudza is to raise the national yield from 0.5 MT/Ha and achieve food security among the smallholder farmer (Nyagumbo et al. 2017).

The success of CA is hinged on the paying attention to detail and timely execution of operations such as land preparing, lime, manure and fertilizer application, planting, weed control, pest and disease control and final crop harvesting and post-harvest handling of the crop (Rodenburg et al. 2020). The first key principle of CA is minimum soil disturbance or little movement of soil as much as possible. In this case, soil is only manipulated where lime, manure, fertilizer, and seed are to be placed. Unlike conventional tillage system, which disturbs the soil profile layers, minimum soil disturbance has more benefits compared to conventional tillage system (Zimbabwe Conservation Agriculture Task Force [ZACTF] 2009). In practice, depending on the resource capacity of the farmer, the following options are available for land preparation under the CA farming system, manual hoeing out, hand-operated planters, oxen-drawn rippers, seed planters, self-propelled fuel-powered machines fitted with rippers or planters and tractor-drawn equipment for resource-endowed farmers.

Where manual hoes are used, which is a common practice by most smallholder farmers, land preparation is done before crop planting by digging out the planting basin. There was a 45% increase in maize yield for farmers who practice basin planting compared to the convectional tillage in the drier areas of Zimbabwe (Thierfelder and Wall 2009). The operation is normally done between the months of July and October before the onset of rains (Fig. 17.3). It is important to carry out this operation on time because it is time-consuming and laborious (Rodenburg et al. 2020). However, digging planting basin during this period in unprotected fields is at risk of being destroyed by animals. The animals usually graze freely during off cropping seasons, winter months in southern Africa between June and October (Zimbabwe Conservation Agriculture Task Force [ZACTF] 2009). Furthermore, heavy winds and early summer rainfall may close the opened planting basin, and

Fig. 17.4 Jab planter (Thierfelder and Wall 2009)

farmers may have to repeat the operation again. Alternatively, instead of digging planting basins, farmers may have to invest and buy jab planters (Fig. 17.4).

The equipment is used for direct seeding in moist soil or where the soil is loose enough for seed and fertilizer placement. The use of jab planters was found to be efficient and demands less labour than digging planting basins. Less number of people are required per hectare when using the jab planter than manually digging the planting basins using hoes (Mupangwa et al. 2016). However, the cost of buying the equipment may be out of reach to poor resource-constrained smallholder farmers.

17.5 The Principle of Permanent Soil Cover (Mulching)/Leaving Crop Residues on the Soil Surface

Permanent soil cover is probably the fundamental principle of CA that distinguishes it from the conventional tillage practice (Mupangwa et al. 2016). This principle requires farmers to apply mulch or leave crop residues on the soil surface and discourages farmers from burning crop residues. Mulching material in form of crop residues (stover), dry grass and leaves, and other dead plant material is spread in the field. Close to 30% ground cover should be attained for good results (Rodenburg et al. 2020). Mulch is applied before preparation of basins and planting.

Conventional farming system encourages 'clean' fields and believes crop residues interfere with crop emergence and also promotes insect pest and disease carryover. It is, therefore, a common practice that farmers either burn the crop residues, leave crop residue in the field for livestock feeding or remove crop residues from fields and store them in secure places for future livestock feeding during the dry off-season period (June to October) when grazing is poor and of low nutritive value. Contrary to the conventional farming system of 'clean farming', CA promotes the proper management of crop residues (Mupangwa et al. 2016). During land preparation, crop residues are carefully placed between planting rows. Proper use and management of mulch/crop residues in CA systems have the following benefits: mulch cushions the soil from direct raindrop impact, encourages infiltration and reduces runoff which causes soil erosion. The conserved soil moisture is available for crop uptake even when there is a dry spell. Mulch inhibits weed seed germination, reduces water loss through evaporation and conserves moisture for crop use. Applied organic mulch/crop residues in the long term increase soil microorganism activity and are broken down, increase soil organic matter content and soil nutrient status. However, there are competing interests in mulch use with livestock. Besides, if fields are not protected or fenced, free movement of livestock will graze crop residues. This is one of the major drawbacks of CA is the smallholder sector in southern Africa.

17.6 The Principles of Crop Diversification/Rotation

Traditionally, smallholder farmers practice multiple and/or intercropping in a bid to reduce the risk of single crop failure associated with a rain-fed (dryland) farming system. Mixing different crops in one field mimics the natural processes found in nature and brings about soil stability, maximizes plant nutrient recycling and the benefits associated with synergy between different crop species such as cereals and legumes. Conservation agriculture encourages crop combination that is both agronomically efficient and profitable to the farmer in the cereal and legume rotation or intercrop is encouraged or inclusion of a cash crop in the program (Muzangwa et al. 2019). Crop diversification through inter-cropping or rotation has several benefits such as replenishment of soil fertility by including nitrogen-fixing legumes in the program. Moreover, applied fertilizers are efficiently utilized in both intercrop and crop rotation systems (Kitonyo et al. 2018). Crop rotation helps break weeds, diseases and insect pests' life cycles, thereby reducing the risk of crop failure and saves crop protection costs (Muzangwa et al. 2019). However, smallholder farmers in Zimbabwe and other countries in southern Africa rarely practice crop rotation for a number of reasons. The small landholding per household usually forces farmers to give priority and focus on staple cereal crops for family food security. Legume seed is expensive, and at times, there are shortages of legume seed restricting planting. Furthermore, the legume crops are normally grown for local consumption only, and farmers may find it difficult to sell any surplus.

17.7 Crop Management under CA System

Success and benefits of CA is hinged on paying attention to detail and timely excursion of management operations. Timeliness of land preparation, correct lime rates and timing, use of livestock manures as an alternative source of crop nutrient and correct fertilizer type rate and timing is key to crop productivity under the CA farming system. The CA is applied to agroecosystem management that can improve climate resilience. Conservation agriculture promotes climate resilience by enhancing rainfall infiltration and soil moisture-holding capacity, reducing anoxia and other hazards related to excessive soil moisture, moderating soil temperature fluctuations, and improving soil nutrient cycling processes (Muoni et al. 2013). Generally, the resilience-promoting effects result from CA's impacts on soil aggregation and SOM concentration. Indeed, recent research showed that SOM is vital to crop yield stability (Hobbs 2007). The SOM should enable a given soil to sustain higher and more stable levels of crop production under adverse environmental conditions than the same soil with less SOM (Pan et al. 2009). The SOM can be increased by reducing tillage intensity, maintaining soil cover with crop residues or cover crops, and increasing agroecosystem crop diversity via crop rotation (Muoni et al. 2013). Reduced tillage practices such as zonal tillage significantly minimize soil disturbance compared with more intense practices such as mouldboard and chisel plough, allowing SOM accumulation or reduced SOM depletion in surface soil layers (Parwada and Van Tol 2018).

17.8 Impact of Conservation Agriculture on Crop Resilience to Climate Change

Conventionally cultivated fields are characterized by bare and loose soils, and in case of high rainfall intensity, more water is lost through runoff and large amounts of soil are prone to erosion (Mango et al. 2017). Moreover, intensive rainfall on bare soil leads to surface sealing and soil compaction, resulting in poor infiltration, localized waterlogging and more runoff (Parwada and van Tol 2020). Crop grown in such fields are prone to moisture stress in case of a dry spell. Unlike conventional tillage system, conservation agriculture manipulates tillage by reducing soil disturbance. Mulching or crop residue management that protects the soil surface from the raindrop effect encourages more water infiltration and reduces water loss through evaporation from the soil surface. The moisture conversation technique has shown a potential to substantially improve crop yields and soil conditions under rain-fed conditions in the semi-arid tropics (Rusinamhodzi et al. 2013). The use of mulch in semi-arid regions of Zimbabwe conserves soil water which will be available for crop use during dry spells, and this extends crop growth under moisture stress conditions (Rodenburg et al. 2020). In a study by Parwada et al. (2019), soil moisture content of Lixisol was increasing overtime by 20–30% under mulch cultivation. Conservation agriculture is also known to add mineral nitrogen to the soil as the organic matter decomposes. In a long-term study by Thierfelder et al. (2015) in Zimuto area near Masvingo, Southern Zimbabwe, CA system improved soil quality indicators over time by 64–96% and 29–97% for infiltration and soil organic carbon (SOC), respectively. The gradual increase in SOC resulted in an improved response to applied fertilizer and maize grain yields on CA systems compared to the conventional tillage system.

17.9 Benefits of CA to Smallholder Farmers

1. **Increase in grain yield**: Results from the survey carried by Mazvimavi et al. (2009) in 15 districts of Zimbabwe established that farmers obtained higher yields on average 1.5 t ha^{-1} from conservation agriculture compared to conventional tillage fields with 0.8 t ha^{-1}. Similarly, results from long-term experiment by Thierfelder et al. (2015) in Zimuto area in Masvingo, Southern Zimbabwe, demonstrated a significant increased maize productivity by up to 235% (1.76 t ha^{-1}) in conservation agriculture (CA) compared to conventional systems under low-fertility circumstances and erratic rainfall. Conclusions from the study by Thierfelder et al. (2015) were that CA is a potentially better farming option even in areas of low soil fertility and climate risk (dry semi-arid) region.
2. **Timeliness of planting:** Conservation agriculture enables early planting, as land preparation is simplified and can be carried out during the drier periods of the season, and planting can be done with or before the first effective rains (Nyagumbo et al. 2017). The early planting of field crop will ensure the crop benefits from low insect pest, disease and weed infestation. Parwada et al. (2019) noted that the sorghum grain yield was 40% higher on an early than late crop. It also results in more efficient use of heat units experienced beginning of season, and longer rainfall season length, thereby reducing the risk of crop failure in semi-arid areas, which receive below-average rainfall and rains are usually poorly distributed (Nyagumbo et al. 2017).
3. **Technology cater for resource-diverse households:** Conservation agriculture technology can be adopted by both resource-endowed farmers with such as draught animals and implements for use as well as resource-poor farmers who rely more on hand tools like the hoe and have no draught power or equipment.
4. **Soil protected against erosion**: Reduced soil disturbance practice and soil surface cover using mulch protect the soil against erosion by cushioning the soil surface from the raindrop impact which dislodges soil particle on bare soils, and it also increase soil water available for crop growth by reducing run-off, increasing infiltration and limiting water loss though evaporation.
5. **Increased infiltration and moisture retention:** The use of mulch in conservation agriculture, and more specifically, the use of crop residues as mulching material reduces water runoff and increases infiltration in southern Africa (Thierfelder and Wall 2009). The increase in water infiltration under CA resulted

in soil water availability, extend flowering period and increase the yield of cotton in semi-arid areas of Zimbabwe (Hobbs 2007).

17.10 Adoption of the Conservation Agriculture Technology in Zimbabwe and Challenges Faced by Smallholder Farmers

Studies in southern Africa have shown varying CA technology impacts on food consumption and adoption rate by smallholder farmers. A study by Mazvimavi et al. (2009) in Zimbabwe, Malawi and Mozambique found out that CA adoption had no significant impact in Zimbabwe and Malawi on the food consumption score of farmers. The possible reason highlighted was the small area devoted to CA per household and failure to implement the full complement of CA practices, thereby compromising on short- to long-term impacts of CA to farmers. However, in Mozambique, CA technology significantly improved the food consumption score of farmers. The possible reason for its effectiveness in Mozambique is that the program promotion is combined with better crop management practices such as improved seed varieties, timely weed management and fertilizer applications.

In a survey carried out by Mazvimavi in 2009, 89% of the farmers practicing CA have to dig planting basins, which is one of the CA component, while 11% is used direct seeding or rip row plant. However, the main reason why smallholder farmers who initially take up the technology eventually drop out was either input support withdrawal by NGOs or lack of government support to such program especially where the cost of inputs such as seed and fertilizer is beyond the reach of many smallholder farmers.

Besides access to crop inputs by farmers, other challenges associated with CA adoption by smallholder farmers in the region is the laborious digging of planting basins. The exercise is done manually using hoes, and in clay soils it requires more labour. In addition, farmers also find it difficult to prepare the planting basins on time, which ideally is supposed to be done between July and October but because most fields are not protected farmers start digging planting between September and October. There is a risk that the basin will be destroyed by wind and animals that roam freely in unfenced plots grazing. Moreover, early heavy rain could cover the basins, and farmers may have to reopen the basins again. However, jab planters were designed as an alternative planting method for vulnerable farmers, and it also saves on labour (Bishop-Sambrook et al. 2004). For resource-endowed farmers, the use of rippers and direct seeding equipment is a common practice.

17.11 Challenges Faced by Smallholder Farmers in Adopting CA

1. Basin digging is laborious and demands more labour in clay soils. This discourages most smallholder farmers who rely mainly on family labour. Most families comprise of school going children, men and women of old age, and the energetic members of the family usually migrate to urban cities in search of employment. With the HIV and AIDS pandemic, some of the sick family members usually received home-based care in the village, and this became an additional burden to family members who are also expected to be work in the fields.
2. Usually, planting basins should be opened between July and October. However, in unprotected field, famers face multiple challenges of destruction of basins by animals as they graze freely; heavy wind and early summer rains may close the dug basins.
3. The management of mulch in unprotected field is difficult because livestock destroys it. Moreover, for cattle owners, there is competing interest on the use of mulch, and this could be the reason why some farmers do not practice CA. However, use of mulching is not positive in all circumstances. Rusinamhodzi et al. (2013) reported that under incessant rainfall mulches have little effect on soil water status; instead it may cause waterlogging because of reduced evaporation, and this may be detrimental to the crop.

17.12 Conclusions

Agronomic benefits associated with the CA technology supports crop resilience to moisture stresses caused by variability in climate change in the dry areas of Zimbabwe. Success and realization of CA benefits are based on implementing the three key principles, paying attention to detail and timely execution of management operations. Timeliness of land preparing, correct lime rates and timing, use of livestock manure as an alternative source of crop nutrients and correct fertilizer type rates and timing are vital for crop productivity. A healthy crop offers tolerance to both biotic and abiotic forms of stresses; this increases crop yields and profitability to smallholder farmers. However, financial resource constraints, lack of mulch protection as well as competing mulch usage for farmers who own cattle are some of the drawbacks to CA adoption by smallholder farmers in southern Africa.

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Chapter 18
Contribution of Underutilised Indigenous Crops to Enhanced Food and Nutrition Security in the Advent of Climate Change

Thobeka Kunene, Samkelisiwe Hlophe-Ginindza, Vimbayi G. P. Chimonyo, Albert T. Modi, Sylvester Mpandeli, Luxon Nhamo, and Tafadzwanashe Mabhaudhi

Abstract The role of underutilised indigenous crops in food security has become crucial in this time of increased climatic variation as they adapt to local harsh climatic conditions. This chapter highlights the potential contribution of indigenous crops to food and nutritional security, especially in marginalised rural communities. The emphasis is on the distribution and agronomy of underutilised indigenous crops, as these result in improved production and nutrient-dense crops for enhanced food and nutrition security. We focus on a select number of African leafy vegetables (ALVs), including amaranthus (*Amaranthus* spp.), cowpea (*Vigna unguiculata),* sweet potato (*Ipomoea batatas*) and wild mustard (*Brassica juncea* L.) as some of the popular food plant crops for subsistence farmers in sub-Saharan Africa. These crops were selected because of their short growth period, low input requirements, morphological structure, and similarities in their phenology.

Keywords Food security · Sustainable development · Nutrition security · Resilience

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18.1 Introduction

Hunger and malnutrition are some of the most predominant challenges facing sub-Saharan Africa (SSA) despite the commitments made by many countries in the region to end nutrition insecurity at the International Conference on Nutrition (ICN) in 1992 (Van Rensburg et al. 2009). No SSA country has met a minimum rate of feeding 200 kg person $^{-1}$ year^{-1} of vegetables and fruits (Nyathi et al. 2018a). Although South Africa is generally food secure at a national level, about 30% of its population is still considered food and nutrition insecure at the household level. About four million people residing in marginal communities suffer from malnutrition and undernutrition (Govender et al. 2016). This is described as "hidden hunger" as it is a state of chronic lack of micronutrients such as iron (Fe) and zinc (Zn) and vitamins A and C. Hidden hunger is on the increase in rural, peri-urban and urban areas in South Africa (Pretorius 2014).

Agriculture is the main source of rural livelihoods on the African continent, providing food and nutrition security to over 60% of the population living in rural areas. However, agricultural productivity in most marginalised communities remains low and unsustainable due to lack of resources and low adaptive capacity to the prevailing rainfall patterns and shortened agricultural seasons (Govender et al. 2016). Previous studies have shown several biophysical factors affecting crop productivity (Shackleton and Shackleton 2012).

According to Snapp et al. (2010), marginal agricultural systems across sub-Saharan Africa (SSA) are characterised by low agro-biodiversity, making many cropping systems vulnerable to climate-associated risks. A significant proportion of agriculture (approximately 90%) is resource-constrained, subsistence-based and done under rainfed conditions and is susceptible to climate variability and change (Chimonyo et al. 2016). Pearce (2011) noted that many cropping systems are modelled on green revolution-type systems, making them unsustainable for a resource-poor farmer. Also, Padulosi et al. (2013) stated that promoting these systems has resulted in food and nutrition insecurity and increased vulnerability to climate risks such as drought. There is a need for a transformational change, an informed process that promotes a change from the norm and produces significant performance improvement, in the whole agriculture system if the sector is to meet the food demands of the growing population expected to reach 9 billion by 2050. The changing climatic and environmental conditions compound the challenges in the agriculture sector. The challenges are cross-cutting, affecting all sectors, hence the need for transformative approaches to inform a positive and smart change. According to Baldermann et al. (2016) and Mabhaudhi et al. (2019a, b), to improve resilience to climate risk while increasing food and nutritional security of farming systems, incorporating neglected and underutilised crops (Fig. 18.1) into marginalised systems can be useful.

Neglected underutilised crop species represent an important component of agro-biodiversity in South Africa. Most of these crops possess traits that best suit production under marginal agricultural systems that typify South Africa's rural

Fig. 18.1 Some commonly consumed indigenous leafy food crops consumed in Africa. Top row from left to right *Amaranthus cruentus* (pigweed), *Bidens pilosa* (blackjack), *Solanum nigrum* (nightshade), *Citrullus lanatus* (bitter melon). Bottom row from left to right *Vigna subterranean* (bambara groundnut), *Vigna unguiculata* (cowpea), *Abelmoschus esculentus* (okra), *Eleusine coracana* (finger millet)

landscape areas. Mabhaudhi and Modi (2013) and Oelofse and Van Averbeke (2012) assessed drought and heat stress tolerance and showed that many underutilised crop species are adapted to low water availability and high temperatures. These attributes suggest that these crop species should be promoted as drought adaptation strategies under changing climatic conditions. While much progress has been made on various aspects of agronomy (Manyelo et al. 2014; Van Averbeke et al. 2007; Van Rensburg et al. 2008), literature outlining their resource use and postharvest handling remains scanty.

To date, research on African leafy vegetables (ALVs) has covered some aspects of agronomy, agro-processing, and health co-benefits from their inclusion in diets. For instance, Faber et al. (2010) evaluated the social and health aspects of the inclusion of ALV in homestead gardens. van Averbeke (2008) accessed technological development for ALV to improve productivity and use of ALV. Oelofse and Van Averbeke 2012identified priority ALV and accessed their seed quality, nutrient and water requirements, and pest and disease management. Maseko et al. (2020) evaluated growth, physiology, and yield responses of three popular ALVs [*Vigna unguiculata* (cowpea), *Corchorus olitorius* (jute mallow), and *Amaranthus cruentus* (pigweed)] to varying water regimes. In addition to this, they evaluated the effect of different management strategies on the nutritional value of the priority ALVs. Van Jaarsveld et al. (2014) quantified the nutritional composition of eight ALVs and their potential contribution to dietary reference intakes. While the efforts to date are plausible, they have mainly been guided by the rapidly changing global dietary requirements and the realisation that there is potential for ALVs. The immediate response has been to increase production without proper planning of their mainstreaming (Chimonyo et al. 2020). Research has focused on generating agronomic information and not how production can influence the nutritional quality of

ALVs. This has inadvertently created a disjointed body of literature for these crops and no useable framework for transforming them from being underutilised to being utilised. This chapter aims to assess the status of popular ALVs in terms of research and to identify their potential contribution to household food and nutrition security. A key focus is the role that ALVs play as drought-tolerant and nutrient-dense crops, especially during drought periods.

Underutilised indigenous food crops constitute the basis for the diversity in the indigenous food systems of rural communities in developing countries (Akinola et al. 2020). Apart from being resilient to the prevailing harsh climatic conditions, the advantage of consuming underutilised indigenous food crops is that they have higher nutrient content than globally consumed food crops (Mbhenyane 2017). In addition, indigenous crops are less harmful to the environment and have a cultural connotation. This study highlights the contribution of underutilised indigenous crops in enhancing food and nutrition security in the advent of climate change. They are identified as a strategy for climate change adaptation and resilience, and nutritional security. The adoption of underutilised indigenous crops in the mainstream food systems also provides important pathways towards achieving Sustainable Development Goals (SDGs), particularly goals 1 (no poverty), 2 (zero hunger) and 3 (good health and wellbeing).

18.2 Pathways Towards Mainstreaming Indigenous Food Crops

Despite the known value of indigenous crops in achieving food and nutritional security, their mainstreaming into important food crops is still low and remains on the margins of agriculture (Akinola et al. 2020). This lack of competitiveness and adoption is mainly due to underinvestment in research and development efforts for their improvement (Mabhaudhi et al. 2017a, b).

The role of agriculture in improving nutrition is crucial; there is a need to clarify the required processes that occur between production and consumption (Fig. 18.2). The roadmap proposes linking mainstreaming of neglected and underutilized species (NUS) to sustainable agriculture, human health and nutrition, and environmental outcomes (see Mabhaudhi et al. 2019a, b). It further proposes that focus on a few priority NUS with potential could assist in profiling NUS. Several ALVs are also identified as priority NUS with such potential.

The transformational roadmap for mainstreaming NUS (Fig. 18.2) highlights the need for continuous priority setting, adaptive and knowledge management along the value chain, underpinned by human capacity development, policy, and market development. The process is underpinned on three important fundamentals: (i) human capacity development, (ii) political will, through targeted policy development, and (iii) market development. The three fundamentals pave the way towards the mainstreaming of NUS and are catalysed by crop genetic and conversion,

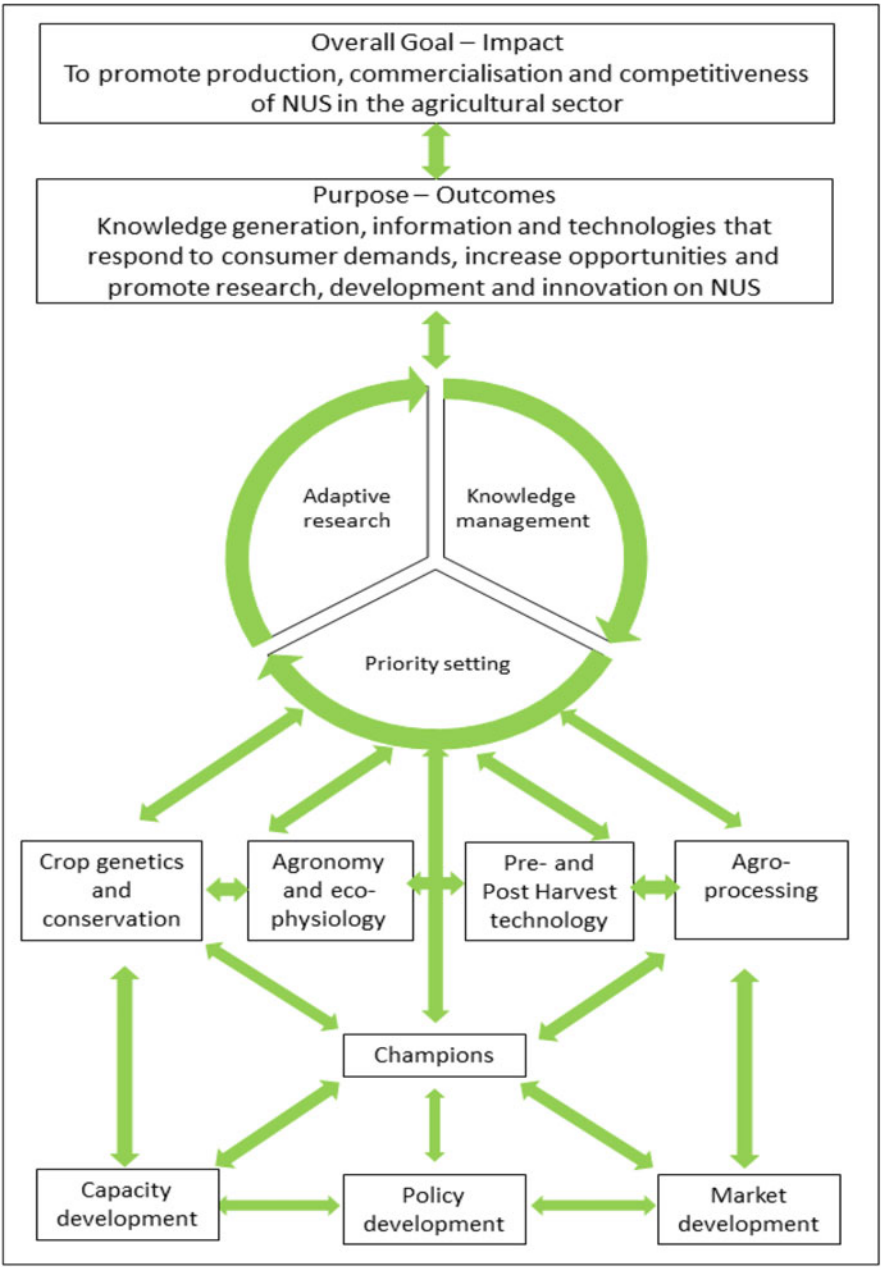

Fig. 18.2 A schematic illustration showing a roadmap for mainstreaming NUS

agronomy and eco-physiology, pre- and post-harvest technologies, and agro-processing. These are anchored on adaptive research to inform policy, knowledge management and priority setting. The whole transformational change process for the NUS (Fig. 18.2) culminates in informed outcomes that enhance the competitiveness of the NUS.

18.3 State of African Leafy Vegetable in South Africa

There are more than 100 different leafy vegetable plants known in South Africa. The most popular include *C. olitorius, A. cruentus*, *Citrullus lanatus*, *Vigna unguiculata*, *Cleome gynandra*, and *Cucurbita spp*. Terms such as imifino (isiZulu, isiXhosa) and morogo (Sesotho, isiPedi) are common names used to describe these leafy vegetables. Already by these terms, it becomes evident that these are local crops as they are known in their indigenous names. African Leafy Vegetables (ALVs) vary widely in their origin in this region. Similarly, their role in the food consumption patterns of South African households is erratic. It depends on factors such as time of the year, the status of poverty, distance or proximity to markets selling fresh produce, household income and level of urbanisation (Jan Van Rensburg et al. 2009; Mabhaudhi et al. 2017a, b). Farmers grow and harvest most of these leafy vegetables in summer; therefore, seasonal change is a major constraint on the availability of these vegetables.

African leafy vegetables (ALVs) form part of neglected and underutilised crop species (NUS). These are native to a given area in geological time (Raihana et al. 2015). They can also be crops introduced to that country and became naturalised over time (DAFF 2009; NRC 2006). South Africa holds one of the highest diversity of crop species globally (Senyolo et al. 2018). In general, ALVs are a vital source of genetic resources. They represent a significant part of agricultural biodiversity with a probability of subsidising climate change adaptation and food security (Chivenge et al. 2015). Research has shown that several ALVs are naturally adapted to low levels of water stress. They are drought-tolerant and can be cultivated in harsh climatic conditions, including arid and semi-arid areas (Mabhaudhi et al. 2017a, b; Pretorius 2014). The Department of Agriculture, Land Reform and Rural Development (DALRRD) also indicated that ALVs are tolerant to common pests and diseases DAFF (2009). These crop species are known to be nutrient-dense and have been recommended for use to improve food and nutrition security (Maseko et al. 2018).

The consumption of ALVs has decreased while exotic vegetables have increased (Njume et al. 2014). The utilisation of ALVs is mainly in smallholder communities where local people collect them from the wild or cultivate them in marginal fields. In very few cases, the seeds of selected species are broadcasted and cultivated in main fields (Maseko et al. 2018). Most popular leafy vegetables such as amaranth and spider flower grow naturally in the cultivated land. They are considered weeds by commercial farmers, whereas they are an alternative food source for smallholder farmers (Maseko et al. 2018; Njume et al. 2014). In smallholder cropping systems, women usually do most of the gathering, cultivation, and harvesting. They are often separated from other non-edible weeds when they emerge in cultivated fields.

In South Africa, the use of ALVs is further reduced because ALVs are mostly sold as dried products mostly by street vendors. Even though they have a well-recognised quality, their value chains have not been mainstreamed and are not easily found in major supermarkets. This is due to poor postharvest storage systems for these crops. This ultimately contributes to their low consumption, mostly in urban areas, as most fresh products are highly perishable (Van Rensburg et al. 2009; Maseko et al. 2018). Recently, there has been an upsurge in the interest in indigenous crops in South Africa. The Vegetables and Ornamental Plants Institute (VOPI) division of the Agricultural Research Council (ARC) is the key role player in the research and training of wild vegetables in South Africa (Maseko et al. 2018). Even at the policy level, the growing interest in leafy vegetable crops has reduced their negative reputation, especially among young consumers in the urbanised areas of South Africa. The consumption of ALVs has been associated with poverty and low social status. Thus, there is low utilisation of these crops amongst the youth. Additionally, the youth may not know how indigenous vegetables are collected as they tend to mix them with poisonous species (Van Rensburg et al. 2009; Maseko et al. 2018).

With the projected population increase to 65.5 million by the year 2050 in South Africa, the proportion of people suffering from hunger and malnutrition is also expected to increase. An increase of more than 50% in food production is required to alleviate this challenge. Focusing on the neglected, underutilised crop species may be a possible solution to improve agricultural production (Mabhaudhi et al. 2017a, 2019a). Underutilised indigenous crops create an excellent opportunity to develop new value chains supporting food security and rural agricultural development. According to Mabhaudhi et al. (2017b), the development of new value chains may require targeted research, including crop improvement, plant breeding, agro-processing, production and marketing. The contribution of indigenous crops to food security could be fully exploited and enhanced by analysing the upstream and downstream information along the value chain. It is also imperative to identify actors and significant role players to translate indigenous crops to commodity crops successfully.

18.4 The Potential of ALV in Addressing Food and Nutrition Insecurity

Although ALVs have great potential, they are primarily under-exploited due to limited information regarding their agronomy and the subsequent effect of different practices on nutritional value. To improve their usage and utilisation, there should be coordinated and cross-sectoral efforts at a local scale to facilitate the availability of information about their agronomy and how these agronomic practices will affect the nutritional value (Baldermann et al. 2016). With the current climate change and diet preferences, ALVs have become an important climate change adaptation strategy for ensuring food and nutrition security at the household level (Mayes et al. 2012). The limited knowledge on indigenous crops production, mostly water and nutrient requirements, has become a significant hold-up on their promotion as choice crops (Nyadanu and Lowor 2015) for food and nutrition security in marginal communities. There is a need to generate information or data about growth, development, and agronomic requirements (Nyathi et al. 2018a; Šimůnek and Hopmans 2009).

The attention given to the sustainability of food and diet systems has highlighted the need for special attention to the role of biodiversity. Previous research has shown gradually increasing evidence that small changes in food cultivated on a larger scale can significantly impact dietary choices (Powell et al. 2015). According to Chadwick et al. (2013) and Powell et al. (2015), it is essential to realise that knowledge alone is not enough for the human diet. However, eating behaviour is the product of rational decision-making and conscious process, and many nutritional interventions designed to improve the quality of the diet depend on education (Powell et al. 2015). Therefore, the rising promotion of underutilised indigenous crops will help people shift their attention towards a healthier way of living, thus improving their diets. Food choices and diet can have a massive impact on greenhouse gas emissions and the associated energy required to provide human nutrition. The shifting of people's food choices can reduce greenhouse gas (GHG) emissions (Shekhawat et al. 2009). Mabhaudhi et al. (2019a) outlined the mitigation co-benefits of underutilised crops under climate change, and that NUS adoption could reduce GHG emissions. This is because most NUS are adapted to low input forms of agriculture, hence lowering the high usage of external inputs such as pesticides and fertilisers (Mabhaudhi et al. 2019b).

African leafy vegetables are a good source of micronutrients such as vitamins, iron and other nutrients (Lewu and Mavengahama 2010; Table 18.1). Some indigenous crops, such as cowpea and sweet potato, produce nutrient-dense leaves (Suarta 2018). As poor households in sub-Saharan Africa mainly consume ALVs, their mainstreaming could face challenges as they could continue to be described as food for the poor.

18.5 Barriers to the Integration of Indigenous Crops into Food Systems

Despite the increasing knowledge on the role of indigenous underutilised crops, various barriers (Fig. 18.3) have hindered their mainstreaming into the main food systems. There has been a lack of policies favouring the mainstreaming of indigenous underutilised crops as current policies only promote the main cereals despite their high input costs (Mabhaudhi et al. 2019a). Policies that favour major cereals

Table 18.1 Nutritional value (based on raw 100 g) of selected neglected underutilised vegetable crops

Crop name	Species name	Energy (kcal)	Protein (g)	Fat (g)	Fibre (g)	CHO (g)	Ca (mg)	P (mg)	Na (mg)	Mg (mg)	Cu (mg)	Zn (mg)	Fe (mg)
Amaranthus	*Amaranthus spp*	49.00	4.00	0.20	2.87	7.86	1686.00	487.00	347.00	82.00	3.00	56.0	25.00
Nightshade	(*Solanaceae spp*)	55.00	3.00	0.60	2.42	9.03	2067.00	478.00	431.00	3.00	6.00	23.00	85.00
Blackjack	(*Bidens pilosa*)	39.00	5.00	0.60	2.92	3.72	1354.00	504.00	290.00	21.00	10.00	22.00	17.00
Mallow	(*Corchorus olitorius*)	392.00	20.90	5.20	45.61	55.50	1760.00	490.00	801.20	15.50	11.30	12.40	53.30
Wild mustard	(*Sinapis arvensis*)	26.00	2.70	0.20	1.10	4.90	0	0	0	0	0	0	0
Bottle gourd	(*Lagenaria siceraria*)	14.00	0.62	0.02	0.50	3.39	26.00	13.00	2.00	0.09	0.03	0.70	0.20
Chinese cabbage	(*Brassica rapa subsp. Pekinensis*)	21.00	9.00	1.00	1.00	22.00	152.00	32.00	29.00	42.00	0.07	0.30	1.40
Sunberry	(*Solanum retroflexum*)	38.00	5.80	0.80	1.40	5.00	442.00	75.00	0	0	0	0	4.20
Wild watermelon	(*Citrullus Lanatus L.*)	296.00	3.50	0.40	3.80	13.10	212.00	119.00	9.00	59.00	0.20	0.74	6.40

Source: Mabhaudhi et al. 2019b

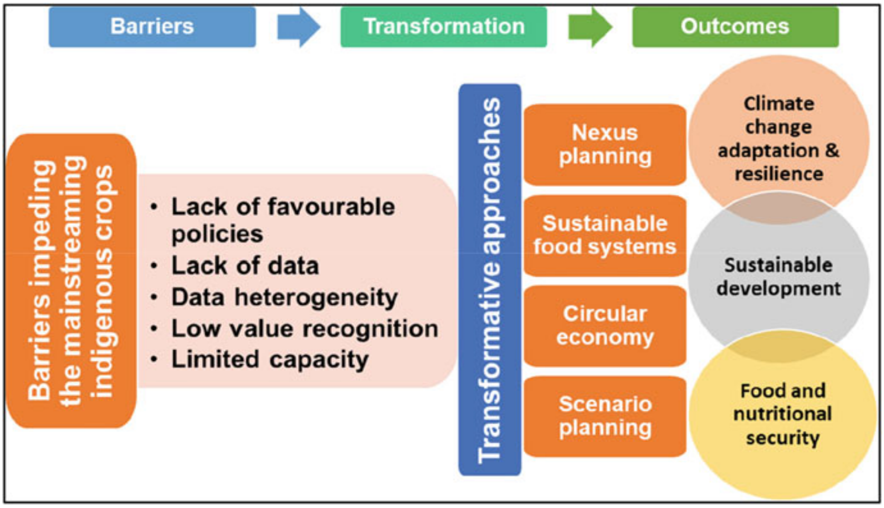

Fig. 18.3 A conceptual framework illustrating the key barriers to the mainstreaming of indigenous crops into food systems as well as the pathways towards transformational change and sustainability

have reduced the dietary role of diverse and nutritious indigenous crops. Of major concern is the strict food safety regulations that make it difficult for these traditional crops to enter the wider food market (Van der Meulen 2010). This is compounded by the emerging middle class that undermine indigenous crops, classifying them as food crops for the poor. One other major barrier to the mainstreaming of indigenous food crops is the lack of data that shows their diversity, resistance to climate change and nutritional value (Mabhaudhi et al. 2019b; Van der Meulen 2010). Most of the available data is localised and scattered.

The barriers impeding the mainstreaming of indigenous crops need to be addressed through integrated and transformative approaches, particularly now when the production of major cereals is under threat due to climate change (Mabhaudhi et al. 2019a). Recent and novel transformative approaches such as scenario planning, circular economy, nexus planning and sustainable food systems are widely used to guide policy and support decision-making to formulate coherent strategies that lead to sustainability (Fig. 18.3) (Mensah and Ricart Casadevall 2019; Nhamo and Ndlela 2020). Mainstreaming indigenous underutilised crops through transformative approaches can result in climate change adaptation and resilience, sustainable development and food and nutritional security (Fig. 18.3).

18.6 Effects of Drought on ALVs

Water and food and nutrition security are intrinsically linked. There must be an acceptable quantity and quality of water for health, livelihoods, ecosystems, and production to attain food security. Currently, agriculture is the biggest user of freshwater in Africa, with an estimated 85–90% of all freshwater sources. Future demands for water for food are threatened by climate change, technological development, and urbanization, rising global population and incomes. This has intensified competition for water within agriculture and across agricultural, domestic, and industrial uses. The challenge is to produce more food to meet the growing population demands using less water and other resource inputs in an environmentally friendly manner.

South Africa is considered a dry country (Donnenfeld et al. 2018). The country is ranked as the 30th driest country out of 193 countries (Donnenfeld et al. 2018). The challenges of water scarcity are expected to worsen as the country's population increases, and there is a continued increase in the number of industries. There is currently overexploitation of more than 60% of water resources in this country, and only one-third of the country's main rivers are in good condition (Donnenfeld et al. 2018). Considering this, the use of drought-tolerant crop species such as ALVs can result in the most productive use of the dwindling resource. However, the mechanisms that allow for drought tolerance in these crops is poorly understood.

Plants are regularly exposed to biotic and abiotic stresses. Water stress or drought is one of the significant adverse types of stress as it can trigger a lot of other plant responses, such as changes in growth rates, cellular metabolism, and yield. The effect of water stress on whole plant function is manifold. It can influence germination, emergence, leaf, root, stem and tiller development and growth, dry matter production, floral initiation, panicle exertion, pollination, fertilization, seed growth and development, yield, and seed quality (Prasad et al. 2008). Low soil water potential can result in seeds failing to imbibe a significant amount of water needed to drive the germination process (Bullied et al. 2012). When stress occurs after germination, Alves and Setter (2004) observed a reduction in cell division and expansion in cassava resulting in smaller leaves. Loss of cell turgidity results in reduced leaf area, a reduction in leaf photosynthetic efficiency, and ultimately low yield (Munns et al. 2000). Since most ALVs thrive well in the wild or under adverse environments, the current belief is that they possess several strategies/mechanisms to deal with drought stress. According to Maseko et al. (2020), ALVs response to drought stress is a function of plant species and stress severity.

Early drought screening for *Amaranthus cruentus*, *Beta vulgaris* var. cicla, *Citrullus lanatus, Cucurbita maxima*, *Solanum retroflexum* and *Vigna unguiculata* (cowpea) showed that seedlings were able to withstand water stress conditions (Oelofse and Van Averbeke 2012). The authors attributed the observed response to a build-up of anthocyanin in the leaves, indicating acquired drought tolerance. Water stress was shown to reduce plant height, leaf number and area in ALVs such as wild mustard (Mbatha and Modi 2010) and wild melon (Zulu and Modi, 2010).

Then again, Maseko et al. (2020) did not observe any significant differences across growth parameters for *A. cruentus*, *Corchorus olitorius*, *V. unguiculata* and *B. vulgaris* grown under limited water availability. According to DeSoto et al. (2020), meristem and organ differentiation are somewhat resilient to water stress than expansion growth. According to Blum (2011), determinate plants exposed to drought stress will nearly always maintain the same number of leaves, but leaves become smaller. However, Maseko et al. (2020) pointed out that shallow rooting ALVs like *C. olitorius* may be susceptible to water stress. To manage water stress, farmers have been encouraged to adopt management practices that minimise competition for the resource. It is important to optimise planting dates and plant populations.

18.7 Nutritional Water Productivity (NWP)

One of the significant challenges faced by sub-Saharan Africa includes water scarcity, which is a complex issue that is often associated with climate change and variability. The population pressure also adds to this issue in terms of malnutrition and food insecurity. Resource-poor households in rural areas are most affected, lacking micronutrients (iron and zinc and vitamin A (Nyathi et al. 2018b)). Indigenous crops can reduce food and nutrition security in resource-poor households (Nyathi 2019; Nyathi et al. 2018a).

Studies by Chibarabada et al. (2017), Mabhaudhi et al. (2016) and Nyathi (2019) indicate that water use efficiency and nutritional yield are often high when crops are grown under optimum conditions. This would suggest that plant nutrient yield and resource use are interlinking aspects in agriculture that cannot be assessed separately. Therefore, to successfully study the contribution of crops to water, and food and nutrition security, the nutritional water productivity (NWP) index was developed by Renault and Wallender (2000). This index accounts for water use, crop production, food access and human nutrition and can be represented in an equation as [NWP = (Yield or biomass/actual evapotranspiration) × (nutritional content of a product)]. NWP = [(above ground edible biomass/ET)] × NC (Nyathi 2019). NWP data may provide useful information regarding crop productivity, crop water use, nutritional productivity, and human nutritional requirement of indigenous crops.

18.8 Conclusions and Recommendations

It is necessary to study factors affecting the growth and productivity of ALVs to provide new bases for their development. Analysing these factors will also help in understanding the concentration of nutrients in different environments. For example, protein content tends to decrease where there is less water available for growth due to less nitrogen in dry leaves – in this way, minimizing challenges faced when modelling NWP. Lastly, nutrient concentration and nutritional water productivity must be assessed under various sample treatments (cooked, raw, blanched, etc.), requiring efforts from different disciplines.

There is a wide variety of indigenous leafy vegetable crops found in South Africa. These are most popular in poor-rural communities and can be grown for health benefits as well. The remarkable potential in contributing to food security is why more attention in crop production must shift towards developing and popularising these crops, especially in these significantly changing environmental conditions.

African leafy vegetables (ALVs) are nutritious and versatile (can be consumed in different ways); they also have many potentials in the marginal communities since they can contribute to their food and nutrition security. Thus, they can contribute extensively to the improvement of human health. However, data unavailability creates a considerable gap in understanding ALVs' nutritional characteristics or content. The studied ALVs are underutilized crops, and the information on their agronomy is limited.

This chapter also confirmed that several ALVs contain most of the essential nutrients necessary for growth and development in humans, and these nutrients are found in relatively high amounts. Therefore, it is suggested that for a proper understanding of these crops' contribution, nutritionally, more characterization or in-depth analysis of "essential nutrients" must be conducted in future for a coherent conclusion. Therefore, upscaling nutrient profiling of these crops by adding more nutrients and researching the ones characterized would be essential for understanding and developing these crops.

Considering the prevailing environmental and climatic changes, it is imperative to document indigenous crops and transform them from localised traditional and cultural beliefs to conventional utilisation and agronomic practices. There is a need for an awareness of the importance of underutilised crops, particularly highlighting their value in production areas where they are most suitable. This should be aided by exploring further the opportunities to extend their production, consumption, and nutritional value.

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Part IV
Farmer Knowledge: Indigenous Knowledge Systems

Chapter 19
Liquid Gold: Harnessing the Potential of Digestate to Enhance Smallholder Farmer Food Security and Livelihood

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Abstract Smallholder (SH) farming systems drive many economies in Africa and are one of the main sources of food and income to the poorest in both urban and rural areas. Improvements of the farming system is imperative to ensure food security and poverty reduction. A holistic SH farming approach that promotes resource recycling will ensure sustainability and productivity of SH farms. Anaerobic digestion (AD) is important to a holistic SH farming system. Anaerobic digestion aids in waste management and results in the generation of biogas as well as a nutrient-rich digestate. The value of the generated biogas has been widely publicised; however, the importance of the produced digestate is less known. This chapter aims at revealing the myriad of applications of digestate that are relevant to SH farming systems. These applications include its use as an organic fertilizer, in seed priming, as irrigation water, as a biopesticide, in aquaculture and livestock management as well as in several bioprocesses. Simple digestate post-treatment methods will also be highlighted. Overall, this chapter is aimed at improving understanding of the potential of digestate to promote its utilisation, together with the generated biogas, in a holistic farming approach thereby maximising benefits associated with AD.

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Keywords Anaerobic digestion · Digestate · Applications · Organic fertilizer · Smallholder farmers · Biogas

19.1 Introduction

The success of any farming system is closely related to the availability of several resources, including nutrients, energy, water, carbon, labour as well as finances, that collectively drive farming activities. Holistic farming systems promote the optimal reuse of such resources to maximise sustainability, efficiency and productivity of the farming process (Orskov et al. 2014). With the current projections of an increase in the population in sub-Saharan Africa (SSA) to approximately 2.5 billion by 2050 (Worldometers.info 2021) and the gradual decline in the productivity of SSA farmlands (Masso et al. 2017), it is imperative that urgent efforts, such as holistic farming, be implemented to ensure food security. Considering that smallholder (SH) farming systems contribute to as much as 80% of the food that is consumed in SSA, it is pertinent that SH farmers receive the necessary skills, technology and guidance to sustain and improve food productivity (Kamara et al. 2019). Holistic farming approaches are of particular importance in resource-poor SH farms where recycling of the limited resources is imperative to meet the ever-escalating food requirements. More so, such farming approaches may aid in transitioning SH farmers from subsistence to commercial level.

The integration of biogas digesters on SH farms may form a central component to the transition to holistic farming. Biogas digesters enable the provision of energy to households, along with the recycling and cleaning of wastewater and the production of a digestate, which could potentially be utilised for several applications, including as an organic fertilizer (Orskov et al. 2014; Roopnarain and Adeleke 2017; Roopnarain et al. 2019; Roopnarain et al. 2020). Smallholder farmers globally have adopted the process of anaerobic digestion (AD) for the treatment of organic waste such as animal manure and plant residues in small-scale biogas digesters constructed on their farms. Anaerobic digestion involves the breakdown of organic matter (feedstock) by anaerobic microorganisms in an oxygen-free digester into biogas and digestate (Groot and Bogdanski 2013). The process occurs in four stages, that is, hydrolysis, acidogenesis, acetogenesis and methanogenesis (Fig. 19.1) (Roopnarain and Adeleke 2017). Much attention has been placed on the product of methanogenesis, methane, due to its elevated energy content (50–55 MJ/kg) (Rajendran et al. 2020). On SH farms, methane produced during the AD process can be combusted for cooking, heating and lighting purposes, amongst others (Fig. 19.2). However, methane is not the only valuable product of the AD process, another oftentimes overlooked product of the process with immense value is the digestate, which is the organic matrix that remains after AD that has substantial agronomic potential (Nkoa 2014).

During the course of the AD process, not all of the components of the feedstock are converted to biogas. Easily transformable carbon compounds are converted to

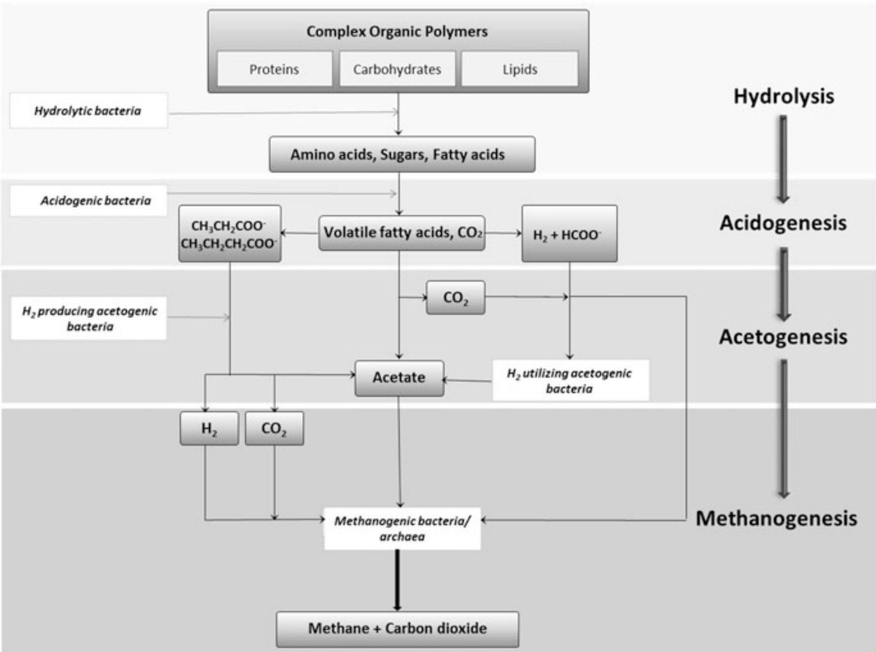

Fig. 19.1 Main stages of anaerobic digestion of organic matter (Adapted with modifications from Roopnarain and Adeleke (2017))

methane and carbon dioxide, whereas more recalcitrant carbon compounds remain in the digestate. Moreover, nitrogenous compounds are converted to ammonium-nitrogen, which remains in large quantities in the digestate along with other macro and micronutrients (Głowacka et al. 2020). When comparing the products of AD with regard to volume, the volume of digestate produced surpasses that of biogas. Approximately 50–85% of the feedstock input into an AD system is released from the system in the form of digestate (Primmer 2021). The large amounts of digestate produced during the AD process justifies its valorisation to ensure that a circular economy and sustainable development is achieved (Czekała et al. 2020). Moreover, valorisation of all AD products may aid in accelerating the payback period for the AD system thereby promoting technology adoption by SH farmers and urban households alike.

The composition and quantity of digestate is a function of the feedstock that is introduced into the digester as well as the digester configuration and fermentation process implemented during AD (Nkoa 2014; Czekała et al. 2020). The properties of the digestate in turn dictate potential applications. For example, liquid digestate that is produced upon digestion of poultry litter, which is rich in N, is more suited for the cultivation of vegetables, cereal crops and grasses. Whereas, liquid digestate derived from AD of cattle manure is more applicable for the cultivation of leguminous plants or crops that are in the blooming or reproductive phase, as it is rich in K and P

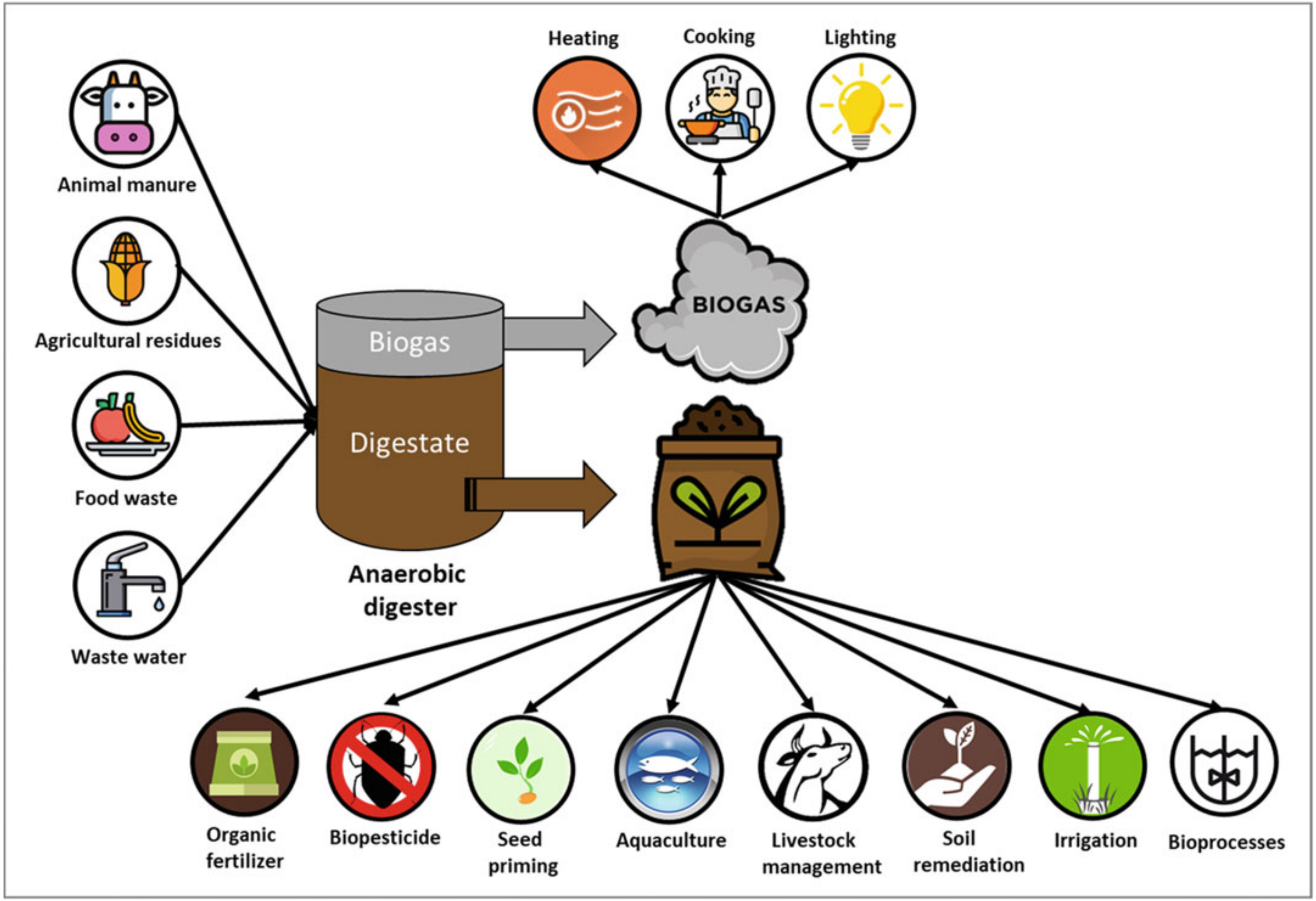

Fig. 19.2 Overview of potential applications of biogas and digestate in smallholder farming systems (Adapted from Nkoa 2014 and Baştabak and Koçar 2020)

(Clemens and Morton 1999; Nkoa et al. 2001; Nkoa 2014). Overall, the properties most times indicate that digestate can be successfully utilized as a fertilizing agent (Tambone et al. 2017). However, due to its nutrient-rich nature, several additional applications of digestate exist (Fig. 19.2).

With the increase in the number of household biogas digesters being constructed across Africa as a result of several national domestic biogas programmes (Orskov et al. 2014), it is imperative that the full potential of such systems be harnessed to ensure that system abandonment is minimised and the overall outlook of the technology is not tainted. Harnessing the full potential of AD technology requires the valorisation of all products, that is, biogas as well as the digestate. The value of the generated biogas has been widely publicised; however, the importance of the produced digestate is less known. Hence, this chapter seeks to highlight the properties of digestate as well as the multitude of applications and benefits associated with digestate use. Moreover, low-cost digestate treatment methods that are applicable to SH farming systems will be elaborated on and recommendations on how to maximise digestate use will be provided. Ultimately, this chapter is aimed at improving understanding on the potential of this valuable resource by integrating its use in holistic SH farming systems, thereby equipping SH farmers that possess anaerobic digesters with the necessary tools to improve their food security and potentially transition from subsistence to commercial level.

19.2 Physico-Chemical and Biological Properties of Digestate

Digestate, the solid-liquid residue of AD, consists mainly of macronutrients (N, P and K), micronutrients (B, Fe and Mn), as well as undigested organic matter (OM) (Plana and Noche 2016; Tampio et al. 2016; Mukuna et al. 2021). Consequently, digestate is commonly land applied as a nutrient-rich organic fertilizer when both the quality and characteristics are adequate for field application (Tambone et al. 2010). The composition, physico-chemical and biological properties of digestate presented in Table 19.1, are major indicators of its quality and key determinants of its possible end use (Teglia et al. 2011; Nkoa 2014; Tampio et al. 2016). These properties are dependent on several parameters including type and composition of feedstock (Tambone et al. 2010), AD process parameters (temperature, inoculum used and hydraulic retention time (HRT)) as well as digestion type (dry, wet, single- or multi-stage). For instance, the digestate recovered from wet AD contains low dry matter (DM) content; hence its characteristic liquid consistency in comparison to that which has undergone dry digestion (Logan and Visvanathan 2019), since dry AD promotes the production of digestate with elevated DM content (Momayez et al. 2019). No less important is the influence of feedstock on digestate characteristics (Sogn et al. 2018). With a wide range of feedstock or mixtures of feedstock being employed as substrates for AD, a high level of inconsistency is expected in the

Table 19.1 Physico-chemical properties of digestate derived from anaerobic digestion of various feedstock

Feedstock	DM (%)	OM	pH	C/N	TN	P	K	NH_4-N	Reference
Cattle manure and clover/grass	10.7	–	8.21	8.5	47, 31.4 mg/g DM	–	–	15.5 mg/g DM	Barduca et al. 2021
Cattle slurry, maize silage and haylage	5.83	–	8.53	–	31.4 g kg^{-1} DM	11.7 g/kg DM	55.9 g/kg DM	–	Barłóg et al. 2020
Food waste	1.9–7.8	12.3–63.7 g kg^{-1} FM	7.6–8.3	1.5–3.3	4.7–8.7 g/kg FM	0.11–0.33 g/kg FM	1.9–3.2 g/kg FM	1.7–4.5 g/kg FM	Tampio et al. 2016
Agricultural residues (corn silage and grass silage)	6.6–9.3	4.8–6.9%	7.6–8.0	–	3.6–4.9 kg/t	–	–	1.3–2.4 kg/t	Drosg et al. 2015
Crop residues	6.2–8.6	4.8–6.2%	7.4–7.9	–	3.9–5.2 kg/t	–	–	1.5–2.5 kg/t	Drosg et al. 2015
Agricultural waste	4.3–6.6	–	7.8–8.5	11.3–17.19	2.0–3.1 g/kg	460–1090 mg/kg	1155–1225 mg/kg	–	Głowacka et al. 2020

DM dry matter, *OM* organic matter, *C/N* carbon to nitrogen ratio, *TN* total nitrogen, *FM* fresh matter produced digestate imparting varying qualities, which ultimately dictates its application. Thus, a sound knowledge of the defining characteristics of every digestate is required to establish digestate quality and assess its potential use. Quality assessment will in turn aid in maximizing agricultural and environmental benefits and minimizing limitations, as depicted in Table 19.2, and eventually alleviate environmental impacts of unfit products (Beggio et al. 2019).

19.2.1 Dry Matter Content of Digestate

Due to the degradation of OM during the AD process, digestate has lower DM content compared to the feedstock (Drosg et al. 2015). The DM content of digestate varies widely from 1.9 to 10.7% (Table 19.1) (Insam et al. 2015; Tampio et al. 2016; Barduca et al. 2021). Variations in DM concentration of digestate can be attributed to factors related to the reactor configuration (wet or dry digestion), process parameters (HRT and loading rate) and feedstock type (Teglia et al. 2011; Tampio et al. 2016). For instance, DM of wet AD and dry AD digestate differs greatly from each other as DM of the former can be as low as 1.5%, whereas DM content of above 15% has been reported for digestate obtained from high solid content feedstock (Drosg et al. 2015). Since SH farmers have surplus diverse agricultural wastes, including crop residues that are high in lignocellulosic biomass, they have a propensity to generate high DM digestate. This would be advantageous to farmers for such digestate could be managed easily without the need to undergo solid-liquid separation, reducing associated costs on financially constrained SH farmers.

Based on the moisture content (MC), digestate can be categorised into three groups: whole, liquid or solid digestate (Plana and Noche 2016). Whole digestate is the digested material obtained at the end of AD in the form of solid-liquid suspension and is characterised by a high MC with less than 15% DM. Due to its high volume, transportation costs become a major obstacle for the application of whole digestate for agricultural purposes, especially when farms are situated far from AD plants (Plana and Noche 2016). In an effort to reduce water content and concentrate the nutrients of digestate to ease production economy, whole digestate is subjected to solid-liquid phase separation (Fuchs and Drosg 2013; Plana and Noche 2016). After separation, the liquid fraction contains most of the soluble N and K while the solid fraction retains most of the digestate P and less than 20% DM (Logan and Visvanathan 2019; Sigurnjak et al. 2017).

On the other hand, low DM content can be beneficial, making digestate easier to pump and apply as an organic fertilizer or irrigation water, with a reduced need for stirring, compared to raw animal manure (Seadi et al. 2008). This is of particular importance to SH farmers where digesters are situated on farms and the resulting digestate is intended for on-farm use, alleviating the costs associated with transportation of large volumes of liquid digestate. Moreover, crop burns are avoided during such application since digestate flows more easily off the plants' vegetable parts

Table 19.2 Overview of limitations and strengths of digestate application based on its physico-chemical and biological properties

Parameters/ properties of digestate	Advantages/strengths	Disadvantages/limitations
Soil nutrients	*Fertilizer value* • Improves fertilizer quality of animal manure • Provides important plant nutrients resulting in improved crop yield. Increased N-availability for crop growth • Mitigates negative impacts of mineral fertilizer and enhances environmental sustainability • Farmers can also benefit from the sale of excess digestate as an organic fertilizer *Soil amendment properties* • Improves soil quality by increasing bulk density, humus balance and overall soil structure	*Leaching potential* • Given digestate's high nutrient content, contamination of surface and groundwater through leaching is a serious concern (Sigurnjak et al. 2017) • High NH_4^+-N may lead to NH_3 volatilization and phytotoxicity in plants
Heavy metals	*Minimal heavy metals in digestate from smallholder waste streams* • Residues from household and agricultural wastes are of little concern regarding heavy metal contamination (Zirkler et al. 2014)	*Possible persistence of heavy metals* • Increased risks of soil contamination with toxic materials including heavy metals as well as organic pollutants, especially in digestate obtained from sewage sludge and biowaste (Tampio et al. 2016)
pH	*Soil acidity control due to alkaline pH of digestate* • Contributes to soil acidity control and can reduce overall running costs through replacement of expensive liming materials (Różyło et al. 2015; Ogwang et al. 2021)	*N losses associated with elevated digestate pH* • Elevated NH_3 volatilization during digestate spreading due to alkaline pH of the digestate, particularly for digestates with pH > 8 (Nicholson et al. 2017)
Biological property	*Pathogen removal under thermophilic conditions* • Under thermophilic conditions, the AD process contributes to efficient pathogen removal reducing the risk of human infections and environmental contamination (Nakamya et al. 2020) *Positive effects on soil microbes* • Stimulates soil microbial activity associated with plant growth (Głowacka et al. 2020) *Reduction in antibiotic resistance genes (ARGs)* • Contains a lower level of ARGs in comparison to undigested raw manure (Sun et al. 2020; Lukehurst et al. 2010).	*Incomplete pathogen removal under mesophilic and psychrophilic conditions* • The use of mesophilic or psychrophilic conditions during AD does not guarantee pathogen-free digestate

(continued)

Table 19.2 (continued)

Parameters/ properties of digestate	Advantages/strengths	Disadvantages/limitations
	Odour and crop burn reduction • Reduction of odour emissions and prevention of crop burns (Insam et al. 2015; Seadi et al. 2008)	*Odours emitted if system is not well maintained* • Neglected anaerobic digesters may result in the emission of odours.
	Weed seed destruction under thermophilic conditions • The AD process eliminates weed seeds resulting in digestate with minimal risk of weed spread (Lukehurst et al. 2010)	*Elevated HRT for weed seed destruction under mesophilic and psychrophilic conditions* • Elevated HRT may be required for the destruction of weed seeds under mesophilic and psychrophilic AD conditions (Lukehurst et al. 2010) • Seeds with a tough cuticle may not be inactivated during AD

compared to raw manure, which reduces the time of direct contact between digestate and the aerial parts of the plant, reducing the risk of leaf damage (Seadi et al. 2008).

19.2.2 Total Organic Matter in Digestate

Organic matter decreases during the AD process due to microbial hydrolysis of easily degradable (labile) matter in the feedstock; however, OM content in digestate is primarily related to feedstock composition (Tambone et al. 2009). Digestates from feedstock with a high degradability are characterized by low OM while agricultural biomass, that are rich in fibrous materials, lead to a high OM digestate (Teglia et al. 2011). As a result, OM content of digestate resulting from the decomposition of highly degradable feedstock such as food waste can drop to as little as 6% (Tampio et al. 2016) whereas digestate from agricultural residues and cattle slurry, such as the digestate mostly evident on SH farms, are richer with greater than 60% OM content, and can, therefore, be utilized to improve soil OM (Nõlvak et al. 2016). However, the ability of digestate to contribute to soil OM is not only dependent on the level of OM contained, but also influenced by the composition of its recalcitrant fractions (Möller 2015). Anaerobic digestion process modifies digestate OM via conversion of readily available OM into biogas and preservation of recalcitrant components such as lignin and complex lipids, thus contributing to the production of digestate rich in recalcitrant OM (Tambone et al. 2009). A biomass characterized by high-recalcitrant OM is considered to be biologically stable and could be utilized to maintain soil humus balance making it a suitable organic amendment material (Mukhuba et al. 2018). In recent years, intensive agriculture has promoted soil degradation, loss of soil fertility and OM, hence recycling of digestate rich in recalcitrant OM has an important role of resource conservation and soil quality maintenance in agricultural systems, particularly in SSA (Mukhuba et al. 2018; Peng and Pivato 2019; Głowacka et al. 2020; Ogwang et al. 2021).

19.2.3 Carbon-to-Nitrogen Ratio of Digestate

In comparison to raw manure, digestate typically has a lower carbon to nitrogen (C/N) ratio due to degradation of total organic carbon (TOC) and elevated N concentration (Tambone et al. 2009). A decrease in C/N ratio from 13.43 to 3.43 has been reported during AD process of mixtures of energy crops, cow slurry, agro-industrial waste and municipal solid waste (Tambone et al. 2009). As major components of OM, the concentration and proportion of C-to-N is essential as an unbalanced ratio can have negative effects on soil microbes by influencing N turnover in agriculture (Johansen et al. 2013). The C/N ratio is often used to describe the balance between these elements and is an important indicator of digestate stability, nitrogen availability, nutrient balance and agronomic value (Nkoa 2014). Organic matrix with high C/N ratios (greater than 30) utilizes soil nitrogen to aid decomposition, limiting its crop availability (Alburquerque et al. 2012a, b), and therefore contributes to N-immobilization if applied to soil. On the contrary, those with low C/N ratios (less than 20) present higher amounts of total N with possible elevated levels of mineralized, plant-available N (Głowacka et al. 2020). Generally, for agricultural residue digestate, a low C/N ratio of 11.3 to 17.1 has been described, suggesting their N-availability as well as their N-fertilization property (Głowacka et al. 2020). Application of low C/N digestate by SH farmers has the potential of enhancing soil N content and crop yield.

19.2.4 Total Nitrogen in Digestate

During the AD process, organic nitrogenous compounds such as proteins are broken down into mineralised ammonium-nitrogen (NH_4-N), which is easily available to plants (Alburquerque et al. 2012a, b; Mukhuba et al. 2018). In comparison to mineral fertilizers, cow dung and pig slurry, digestate has been shown to contain a higher amount of mineralized N and, therefore, produces better crop yield (Risberg et al. 2017; Mukhuba et al. 2018). High N content in digestate is advantageous for agriculture considering that N is an essential plant nutrient, and due to its increased bioavailability post-AD, digestate integration in the fertilization programme by SH farmers is promoted.

Considering that digestate has higher amount of mineralized nutrients, particularly NH_4-N, than raw manure, potential contamination of surface and groundwater through leaching following land application is a serious concern (Sigurnjak et al. 2017). However, nutrient leaching potential of digestate is influenced by many variables such as soil texture, topography, time of application, fertilization strategies and precipitation. Thus, the utilization of good agricultural practices, general measures for quality control as well as safe handling, storage and application can limit the risk associated with digestate valorisation (Alburquerque et al. 2012a, b; Logan and Visvanathan 2019). Moreover, it has been shown that digestate has low leaching potential relative to inorganic fertilizers, making them a better alternative (Tshikalange et al. 2020).

19.2.5 pH of Digestate

Most digestates are usually alkaline having pH values in the range of 7.6 to 8.5 as a result of volatile fatty acid (VFA) degradation and NH_3 production during the AD process (Table 19.1) (Teglia et al. 2011). The pH value influences the effect of digestate on soil quality and plant growth. Low pH is a major constraint for crop production in SSA and is considered the most important plant growth-limiting factor in certain parts of South Africa where 85% of arable land is affected by acidic soil (Helberg 2019). Low pH affects the activity of beneficial soil microbes with a resulting negative effect on the degradation of OM, nutrient mineralization and immobilization, uptake and utilization of nutrients by plants and subsequently on crop growth and yield. Biogas digestate offers a sustainable and cost-effective solution that could be adopted to overcome the constraints arising from soil acidity and offset expensive liming materials for acidic soil (Różyło et al. 2015; Mukhuba et al. 2018; Głowacka et al. 2020; Mukuna et al. 2021; Ogwang et al. 2021).

19.2.6 Phosphorus and Potassium in Digestate

During AD, the concentrations of P and K are not significantly affected, and their level in digestate is majorly influenced by the concentration of these elements in the feedstock (Drosg et al. 2015; Insam et al. 2015). Generally, digestate contains 1% P and 1.4% K (Tampio et al. 2016). Digestate showed similar fertilizing potential to high-soluble mineral P fertilizer such as Triple Super P (TSP) and undigested slurry due to its high content of plant-available P and K as well as other macronutrients, and therefore represents a valuable source of these essential elements (Bachmann et al. 2016).

19.2.7 Biological Properties of Digestate

Interest in the biological composition of digestate has been heightened by concerns that many pathogenic microbes may enter the environment through digestate when applied on agricultural land. While digestate is not free of microbes, studies have indicated the efficacy of AD process in reducing potentially pathogenic bacteria (Avery et al. 2014; Nakamya et al. 2020) as well as deactivating pathogenic fungi (Bandte et al. 2013). In addition to enteric pathogen reduction, the presence of plant growth-promoting bacteria (PGPB) in digestate, which contributes to improved plant nutrient uptake, accentuates its fertilizer potential (Mukhuba et al. 2018). Furthermore, the effects of digestate on microbial activities were shown to be similar to those of cattle slurry, as the addition of digestate to the soil did not negatively affect soil microbes, suggesting their usage as fertilizer will not upset microbial activity in the soil (Risberg et al. 2017). Rather, numerous studies have described the enhancement of soil microbial diversity and activity related to plant growth through improved soil enzymatic activity in response to application of digestate in comparison to other mineral fertilizers (Głowacka et al. 2020; Möller 2015). Moreover, the AD process has been shown to contribute significantly to a reduced level of antibiotic resistance genes (ARGs) in comparison to raw manure; thus, application of digestate as fertilizer probably poses a limited risk of spreading ARGs in the environment (Sun et al. 2020). In summary, the AD process does not only increase the agronomic value of feedstock through their transformation into nutrient-rich digestate but also improves other important properties of digestate suggesting them as good candidates for an array of applications by SH farmers.

19.3 Applications of Digestate

Digestate is used in several applications such as soil amendment and fertilization, disease and pest control, seed pre-treatment, aquaculture, microalgal cultivation, hydroponics, energy production, nutrient recovery, livestock management, bioadsorbent production, building material production, irrigation, soil remediation and as substrates in bioprocesses (Zhao et al. 2014; Nagarajan et al. 2019). In fact, a paradigm shift in the focus of AD has been suggested from biogas optimization to 'integrated biogas–digestate optimization'. The need to valorise digestate is now more attractive than ever; it is deemed necessary in order to enhance food security and overall to achieve a circular economy and holistic farming, which is particularly important in resource-poor SH farming systems (Logan and Visvanathan 2019).

In developing African countries, SH farmers represent a vast population of rural dwellers whose rate of adoption of biogas technology is relatively slow, in comparison to other countries such as India and China, as they are restricted by political, financial and sociocultural factors (Roopnarain and Adeleke 2017). This also applies to the utilization of digestate for the purpose of sustenance of agriculture in developing African countries. Sub-Saharan Africa is plagued with the crisis of food insecurity, which is often a result of limited soil N content for the production of crops in several regions (Ndambi et al. 2019). In the few SSA regions where utilization of digestate for agronomic purposes has been adopted, it has contributed to enhanced soil fertility as well as improved crop production for SH farmers. Batchelor et al. (2017) reported on the improved income generation and increased production rate of staple foods such as potato, maize and tomato in some African countries resulting from the application of digestate as a substitute to synthetic fertilizers. Many European countries have set regulations on the handling, pre-treatment, processing, transportation and storage of digestates (Aso 2020). There are no set regulations for digestate handling, storage and application in most SSA countries yet; however, South Africa has a set regulation for the utilization of digestate as a soil ameliorant (DAFF 2018). In place of regulations for digestate management, some SSA countries have policies and regulations for manure handling and application by SH farmers (Ndambi et al. 2019). Nevertheless, some studies have pointed out the indiscriminate disposal of livestock manure in Africa as opposed to productive applications; this poses a threat to public health and the environment at large (Lederer et al. 2015). Productive applications of livestock manure include AD to generate digestate and biogas for different uses. Selected digestate applications relevant to SH farming systems are elaborated on below.

19.3.1 Digestate as Soil Amendment or Organic Fertilizer

Digestate is rich in both macro and micronutrients as well as OM. Nutrients in feedstock are conserved during AD and converted to a more mineralized form, which are better accessible to plants (Logan and Visvanathan 2019). Digestate has, therefore, been applied globally in a variety of soils and crops to amend soil and enhance soil nutrients (Islam et al. 2010; Yu et al. 2010; Alburquerque et al. 2012a, b; Al Seadi et al. 2013). Application of digestate on farmland is typically done by surface spreading, injection, trailing hose or by incorporation through trailing shoe (Nkoa 2014). Since many SH farmers have anaerobic digesters on their farms, digestate, therefore, becomes an inexpensive source of soil nutrients, reducing the use of synthetic chemical fertilizers while minimizing the huge cost thereof and associated carbon footprint as well as energy requirement for manufacture of synthetic fertilizers (Alburquerque et al. 2012a, b; Barzee et al. 2019; Barłóg et al. 2020). It also prevents downstream effects of such chemical fertilizers, which include deterioration of soil structure and eutrophication due to runoff of chemicals into water bodies (Baştabak and Koçar 2020). Digestate application on farmlands recycles nutrients, improves soil OM (Pezzolla et al. 2012) and increases both macro and micronutrients in soils and plants (Głowacka et al. 2020; Mukhuba et al. 2020). When digestate is used to amend soil for vegetable crops, it is found suitable even at low soil temperatures, which is often the case for crops that have to be planted in cold seasons as early cultivations and that have high N requirements (Möller and Müller 2012). Incorporating fertilization with digestate by SH farmers would go a long way in enhancing their food security, enabling them to maintain a circular economy and holistic farming on their farms and empowering them to contribute to ensuring national food security.

Reclamation or harvesting of nutrients and compounds from digestate is another possible option as some feedstock used for the metabolic process of AD are rich in macronutrients and compounds which usually persist in the digestates (Aso 2020). Reclamation of nutrients from digestate through ammonia stripping (ammonia recovery) and formation of struvite (precipitation and crystallization of phosphorus) is of agronomic benefit as these reclaimed nutrients are essential plant nutrients and potential fertilizers (Vaneeckhaute et al. 2017). However, the cost implication of the process of reclamation of nutrients from digestate poses a challenge to SH farmers (Shi et al. 2018). Nevertheless, SH farmers could improvise by concentrating the digestate using affordable technologies like filtration, sedimentation and decantation. The liquid portion of the digestate could be sprayed or injected into the soil for enhanced fertilization. Surplus biomethane from the biogas plant could also be combusted and the generated heat used for evaporation of the liquid portions of digestate in cases where the solid fraction is desired (Drosg et al. 2015).

19.3.2 Digestate for Seed Priming

Digestate has found application in seed priming due to its elevated nutrient composition. Conventionally, seeds are pre-treated or soaked prior to planting in order to overcome the challenge of field emergence in certain seeds possessing thick seed coats (Harris et al. 2005; Paparella et al. 2015; Farooq et al. 2019). Pre-treating seeds before germination also offers the advantage of separating dead seeds as well as low-vigour seeds from viable ones prior to planting. Pre-soaking seeds in such nutrient-rich slurry as digestate would offer the added advantage of incorporating nutrients onto the seeds. This was found to enhance seed germination and seedling growth (Feng et al. 2011; Zhao et al. 2014). Soluble nutrients in the digestate are absorbed by the seeds via osmosis, and this effectively activates the enzyme source in seed embryos and endosperm in addition to accelerating nutrient transformation, promotion of metabolism and protection against pathogens (Feng et al. 2011).

19.3.3 Digestate as Fungicide

Chemical fungicides have been used as a common method of protecting plants against fungal phytopathogens among SH farmers. Long-term use of these chemical agents may result in several challenges due to their hazardous effects, which include residence time in the environment and acquisition of resistance by pathogens (Mukherjee et al. 2016). Moreover, the adverse effect of chemical fungicides on biodiversity due to surface water runoff and leaching propels the need to identify different types of fungicides that are efficient and environmentally friendly. The application of digestate for the control of phytopathogens is a viable approach to the management of pathogens on farmlands as digestate has been observed as a biocontrol agent that inhibits the proliferation of phytopathogenic fungi (Feng et al. 2011; Baştabak and Koçar 2020). A report by Pan et al. (2018) presented the antagonistic effects of digestate on phytopathogenic fungi, *Alternaria solani* which causes the potato blight disease (*Phytophthora infestans*). Further laboratory investigations have ascertained the inhibition of several phytopathogenic fungi, *Rhizoctonia cerealis*, *Fusarium oxysporum*, *Rhizoctonia solani*, *Bipolaris sorokinianum*, and *Sclerotinia sclerotiorum*, by the utilization of digestate (Tao et al. 2014). Application of liquid portion of digestate significantly inhibited the growth of the above-mentioned phytopathogenic fungi. Biocontrol of parasitic nematodes affecting tomato plants is another benefit of digestate as bionematicides (Jothi et al. 2003).

19.3.4 Digestate as Soil Remediation Agent

Africa is rich in mineral resources, hence the predominance of different exploration, mining, utilization and transportation of these minerals and their finished products (Busia and Akong 2017). These processes have resulted in the introduction of pollutants to the environment leading to contamination of potential agricultural lands (Salam et al. 2018). These pollutants range from mine tailings to hydrocarbons, and the need for remediation is imperative as it will alleviate public health risks and improve agricultural as well as socioeconomic activities (Ngole-Jeme and Fantke 2017). Residency of these pollutants in the environment have resulted in decreased fertility of African soils by reducing the soil pH, which has contributed to more than 33% of SSA soils being acidic (Pauw 1994). Valorisation of digestate for the remediation of metal-polluted soil is essential since digestate has been correlated with the immobilization of metals in the soil, elevation of soil pH and promotion of soil microbial activities, thereby enhancing remediation and agricultural processes (Garcia-Sánchez et al. 2015; Peng and Pivato 2019).

Thermal pyrolysis of digestates rich in lignocellulosic materials results in the production of biochar (Mohammadi et al. 2019). Besides utilization of biochar as a soil amendment to enhance plant growth, biochar has been associated with additional applications, which includes filtration of drinking water due to its ability to remove heavy metals from aqueous solutions (Aso 2020). It also expedites the remediation of soil polluted by pesticides and organic contaminants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) via stabilization of the organic contaminant and improvement of the decomposition of the contaminants by indigenous soil microbiota (Guo et al. 2020). Production of biochar is similarly of environmental benefit as it is a potential carbon sink (carbon sequestration) which aids in reducing our carbon footprint (McHenry 2009).

19.3.5 Digestate in Livestock Management

Utilization of densified digestate as a substitute for sawdust and wood chips for litter and bedding for poultry and cattle, respectively, is of economic benefit (Feng et al.

2011; Quintern and Morley 2017). Similarly, incorporation of bulking agents of lignocellulosic origin during composting of digestate makes the final product a suitable source of nutrition for livestock (Stoknes et al. 2013; Stoknes et al. 2016). Production of vermicast via vermicomposting of digestate for agronomic purposes is a feasible application of digestate. Besides agronomy, vermicomposting of digestate is an appropriate technique for the production of earthworms for livestock feed (Jjagwe et al. 2019). Pyrolyzed and gasified pellets of dehydrated digestate are a potential feed additive for farm animals (Wu et al. 2017; Hagemann et al. 2018). Conversion of the excess or agricultural-unsuitable digestate into pellets forms a source of carbon and energy (Al Seadi et al. 2013; Nagy et al. 2018).

Due to its elevated nutrient content, liquid digestate is also used in microalgal cultivation (Massa et al. 2017; Ayre et al. 2017; Nagarajan et al. 2019). Application of digestate as a growth medium or culture booster for the cultivation of microalgae is of immense benefit to different industries as separated microalgal biomass can also serve as animal feed (Monlau et al. 2015; Quintern and Morley 2017; Kaur et al. 2020). Algae is extensively utilized in various applications such as production of livestock feed, biodegradable packaging as well as chemical and cosmetics production, which contributes to a circular economy (Aso 2020). Despite the fact that application of digestates enhances the cultivation of microalgae, digestate with elevated NH_3 content and turbidity could limit the proliferation of algae by impeding photosynthesis (Xia and Murphy 2016). This also supports the concept of characterization of digestate prior to utilization to inform selection of the application route that will result in maximal benefits to the user.

19.3.6 Digestate in Bioprocesses

Recirculation of digestate as a feedstock for generation of additional biomethane is an effort to valorise digestates and mitigate the challenge of methane emission from undigested materials in the digestate (Monlau et al. 2015). Although, this is practiced on a large scale, SH farmers may borrow a leaf from this and recirculate digestate. In addition to mitigating the challenge of GHG emissions, recirculation of digestate as a feedstock could also serve as a means of conserving water, which is a limited resource to some SH farmers in Africa. Furthermore, production of commercially and industrially beneficial bioproducts such as bioethanol, biodiesel, hydrolytic enzymes (cellulases, proteases) and biosurfactants through solid-state fermentation of digestates is a viable option for the application of these digestates (Fuldauer et al. 2018; Cerda et al. 2019). Utilization of digestate for the production of bioproducts are economically and environmentally beneficial to SH farmers (Cheteni 2017). It has potential to alleviate poverty via creation of employment opportunities for the community. The products can also serve as eco-friendly, renewable substitutes for petroleum fuel. Fermentation of liquid digestate for the production of bioethanol is an economical and sustainable substitute for utilization of freshwater and nutrients during production of bioethanol (Gao and Li 2011; Logan and Visvanathan 2019).

Bioethanol is an extensively used biofuel globally and its effective production is attained via various metabolic processes of hydrolysis, fermentation, distillation and dehydration of digestate biomass (Cerda et al. 2019). Incorporation of digestate as a substrate for bioethanol production also limits the pre-treatment time for substrates as well as reduces the concentration of rate-limiting pentose whose accumulation obstructs the fermentation phase of bioethanol production (Teater et al. 2011; Cesaro and Belgiorno 2015).

Another bioproduct proposed is a starch-based biofilm. This biofilm incorporates valorised digestate, and it serves as a sustainable alternative to farmers to replace plastic biofilms that are conventionally used for mulching on farmlands. Solid digestate was treated by an ultrasonic thermoalkaline treatment to remove the non-functional compositions and subsequently incorporated in plasticized starch paste, which was then used to prepare mulching biofilms. The produced composite biofilm exhibited a higher tensile strength and degradation temperature as well as elastic modulus compared to pure starch-based film (Zhao et al. 2021). Production of these bioproducts may be cost-intensive to SH farmers; however, SH farmers could generate income by marketing the digestate as a resource to bioprocessing industries where it is subjected to different post treatments to enhance its applicability and environmental friendliness.

19.4 Post-Treatment of Digestate Prior to Downstream Applications

Digestate, generally used for several applications highlighted in Sect. 19.3, needs to meet hygienic, safety and quality requirements to avoid environmental and health risks as well as to improve digestate quality for storage purposes and later use (Peng and Pivato 2019; Aso 2020). Heavy metals and disease-causing microorganisms as well as impurities like plastics and glass can leach into the environment if digestate is applied without treatment (Logan and Visvanathan 2019). Additionally, unfavourable greenhouse gases (GHGs) such as carbon dioxide, nitrous oxide and methane are emitted from digestate when used untreated (Rehl and Müller 2011; Askri et al. 2016; Peng and Pivato 2019). Over-application can also lead to N and P leaching thus contaminating water bodies (Maurer and Müller 2019). The AD process partially sanitizes the digestate, especially if a thermophilic AD plant or extended HRT is used (Manyi-Loh et al. 2019). However, when stored for a long period, digestates emit GHGs and can accumulate pathogenic microbes; therefore, post-treatment is required to pasteurize and improve the quality of the digestate as well as to reduce environmental impact (Askri et al. 2016). Several digestate post-treatment methods that are applicable to SH farming systems are highlighted in the subsequent sections and summarized in Fig. 19.3.

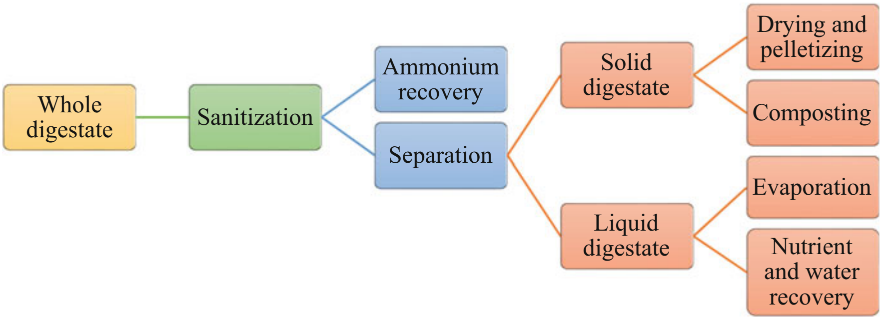

Fig. 19.3 Flow diagram for digestate post-treatment steps for smallholder farmers

19.4.1 Separation of Solid and Liquid Digestate

Whole digestate can be separated into solid and liquid fractions unless the digestate is produced from a dry AD system that contains 30–40% solids or is thickened to solid fraction using wood chips or other bulking agents (Logan and Visvanathan 2019). Generally, whole digestate that is produced from a wet digester contains less than 6% total solid content (Baştabak and Koçar 2020). Through separation, less storage space is required to store solid digestate compared to whole digestate (Lukehurst and Bywater 2015). Separation of liquid and solid digestate can be achieved through dewatering processes, for example screw-press separators that consume less energy compared to decanter centrifuges and belt presses (Møller et al. 2000; Wiśniewski et al. 2017). Alternatively, if the digester design includes a storage/overflow tank (Fig. 19.4), it is possible to collect the liquid overflow as liquid digestate and the sediment that remains as solid digestate. Designing digesters to include the overflow tank will aid in simplifying the separation process by SH farmers.

19.4.2 Sanitization of Digestate

Whole digestate should be treated for 1 hour at 70 °C in a mixing tank after removal from the digester for sanitation purposes as recommended by the European Union sanitation standard (Baştabak and Koçar 2020). A suggestion for SH farmers is to harness the heat produced by composting or by combusting a small portion of the biogas produced by the digester to sanitize the digestate through heating. If biogas is used as a source of heat, it is essential to perform a cost-benefit analysis to weigh out the benefits of using a portion of it for sanitation while producing quality digestate products for commercialization as well as to replace expensive chemical fertilizers for crop production. The evaporated water from sanitation and/or post-treatment processes can be recycled into the digester or used for irrigation purposes to reduce

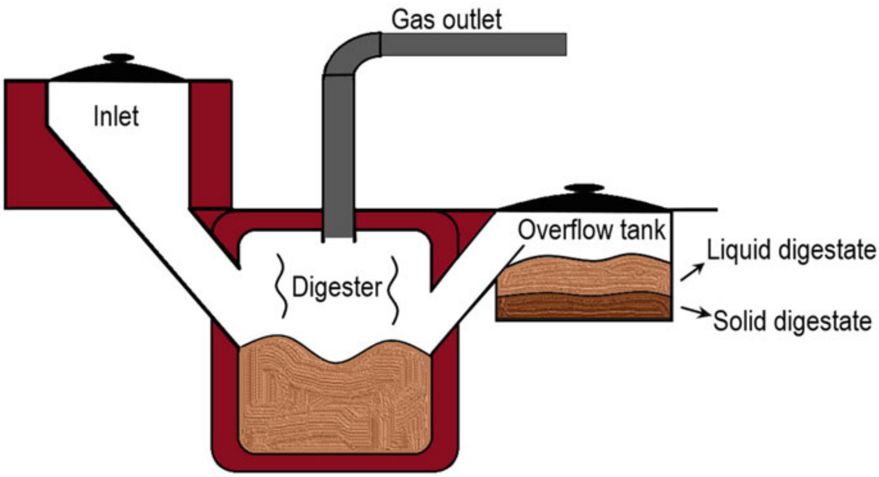

Fig. 19.4 Fixed dome digester design that includes an overflow tank (Adapted with modifications from Saleh 2012)

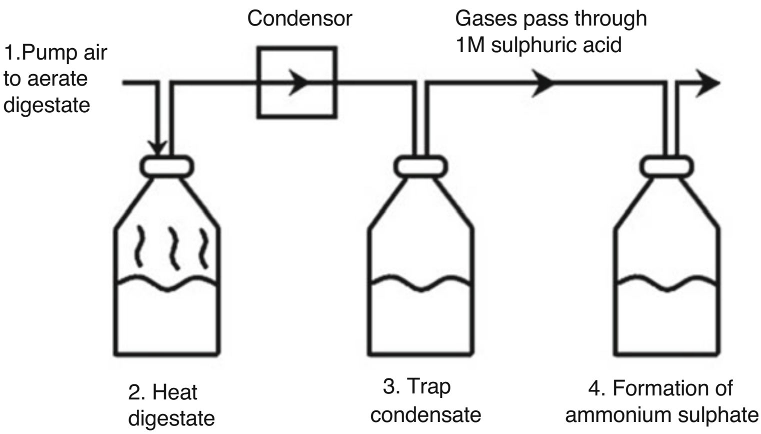

Fig. 19.5 Digestate sanitation and ammonia recovery approach (Adapted with modifications from Törnwall et al. 2017)

water requirements. A drawback to heating digestate is the loss of ammonia and mineral nitrogen in the form of nitrous oxide (a GHG) (Baştabak and Koçar 2020). As demonstrated in Fig. 19.5, high amounts of ammonia can be recovered from heated digestate by trapping the condensate for reuse and allowing the gases to pass through sulphuric acid solution to form ammonium sulphate (Törnwall et al. 2017). The ammonium sulphate can be added to dried/solid digestate, which generally contains less nitrogen content than liquid digestate (Logan and Visvanathan 2019; Manyi-Loh et al. 2019).

19.4.3 Solid Digestate Post-Treatment

Following separation, solid digestate must undergo post-treatment to improve its quality for downstream purposes. Some solid digestate post-treatments discussed in the following subsections include drying, pelletizing and composting.

19.4.3.1 Drying and Pelletizing Digestate

Although various methods for drying digestate exist, such as thermal, thermochemical, hydrothermal, physical and mechanical (drum-drying or belt drying) methods (Manyi-Loh et al. 2019), the biogas generated from the AD plant is an available form of energy that can be harnessed to dry solid digestate for handling and storage purposes (Maurer and Müller 2019). Solar drying is another feasible approach for SH farmers to remove moisture from unseparated or solid digestate. Solar drying involves drying out digestate in a ventilated greenhouse or open hall with turning to ensure good quality digestate is produced. Exposure to the renewable thermal energy provided by the sun enables evaporation to occur (Frischmann 2012). As previously mentioned, using the ammonia recovery approach by Törnwall et al. (2017) on the evaporated contents could prevent nitrous oxide emissions into the atmosphere while the recovered ammonia can be added to the post-treated dried digestate to enhance its quality as a fertilizer.

Pelletizing dried digestate on a large scale involves the installation of heavy machinery that requires high-energy input. Due to cost implications of such large-scale machinery and associated energy, the process is prohibitive to SH farmers. It is, therefore, suggested that small manual pellet mills are used as a viable option for SH farmers to pelletize dried digestate. Petrova et al. (2021) recommended producing larger-sized pellets for application to reduce high levels of nitrous oxides from being emitted. The pellets may be commercialized as organic fertilizers and serve as an additional source of income for SH farmers.

19.4.3.2 Composting Digestate

Composting is the most practiced form of post-treatment of solid digestate. This self-heating process involves the decomposition of OM from digestate (if possible with bulking agents) under aerated conditions. The process forms stable, nutritive and safe humus from solid digestate that can improve the soil water-holding capacity and plant growth when applied (Zeng et al. 2016; Congilosi and Aga 2021). Apart from being a source of nutrients and OM, compost also provides an essential role in supporting soil biodiversity and controlling soil-borne phytopathogenic microorganisms (Vitti et al. 2021). Moreover, composting can lower metal mobility and pathogen levels (Congilosi and Aga 2021). Composting of manure was shown to reduce ARGs in several studies (Ho et al. 2013; Qian et al. 2018; Riaz et al. 2020).

Congilosi and Aga (2021) suggested implementing composting following AD to improve ARG removal from digestate. Vu et al. (2015) suggested that passively aerated composting with digestate, bulking agents such as wood chips or straw and biochar is an efficient post-treatment that produces low amounts of GHG emissions. Rehl and Müller (2011) reported that overall solar drying and composting were the most resource-efficient post-treatment methods to use with reduced environmental impact.

19.4.4 Liquid Digestate Post-Treatment

Membrane filtration followed by reverse osmosis, aerobic biological wastewater treatment or evaporation are expensive and/or energy intensive methods that are employed to purify liquid digestate by removing the water component and concentrating nutrients for use as a fertilizer. Other methods for treatment of liquid digestate include struvite precipitation, ammonia stripping, activated sludge treatment, UV irradiation, ozone treatment, chemical coagulation, electrocoagulation, flocculation and microalgal cultivation (Manyi-Loh et al. 2019). Similarly, to the treatment of solid digestate, it is suggested that liquid digestate is exposed to the heat derived by biogas combustion to evaporate the moisture and concentrate the nutrients. Smallholder farmers can commercialize the concentrated nutrients as a fertilizer product or intermittently apply diluted forms to their own farms for crop production. The recycled water can be mixed with cow dung and added to digester systems in place of freshwater or be used for irrigation purposes. This is of particular importance to SH farmers in areas where periodic water scarcity is experienced or excessive labour is required for water collection.

19.5 Recommendations

The utilization of digestate offers the possibility to recycle nutrients from organic waste materials back to the food chain. Thus, recommendations to SH farmers are as follows:

- In cases where SH farmers are faced with on-farm factors such as nutrient-deficient soils and pests, digestate can be used in their gardens as organic fertilizers and biopesticides, respectively.
- Digestate can also be used for seed priming to improve crop growth and quality.
- On SH farms that rear livestock, digestate can be used as animal bedding, for aquaculture and algae production.
- On occasions where SH farmers do not have sufficient water supply, the liquid digestate can be used for irrigation purposes.

- Finally, on SH farms that have sufficient income to invest in newer technologies, digestate can be utilized in several bioprocesses to generate high-value products such as biofuels. Alternatively, digestate can be sold to industries with the necessary facilities to produce such bioproducts.

Overall, the array of digestate applications that are available enable SH farmers to appropriately select the application that is relevant to their respective farms based on their needs and available facilities. Moreover, the variety of digestate applications available to farmers ensures that digestate management is simplified since farmers can explore several applications and in so doing create new digestate product markets with concomitant financial gain. Appropriate valorisation of all the resulting digestate from the AD process has the additional benefit of ensuring environmental sustainability of the AD process as it will prevent digestate disposal with associated negative environmental implications. That being said, the appropriate post-treatment of the digestate, which is closely linked to the choice of digestate application, is necessary to valorise digestate in an eco-friendly manner.

Digestate can be separated into two components (liquid and solid) that requires separate storage. Separation is normally done to reduce the volume requiring storage or for increasing income generation as solid and liquid digestate can be sold as separate products. For SH farmers, it is recommended that:

- Low-cost separation methods such as simple sedimentation/filtration be adopted.
- The solid digestate should be composted to reduce GHG emissions.
- The liquid digestate can be further concentrated to increase nutrient content by evaporating moisture through heat generated by biogas combustion.

Thereafter, both solid and liquid digestates can be commercialized for income generation or used for several applications.

19.6 Conclusion

The current chapter demonstrates the use of digestate as an organic fertilizer for improved agricultural production. In addition to digestate use as a fertilizer, digestate could be key to SH farmers widening their agricultural practices by expanding its use for pest control, aquaculture, livestock management, seed priming, soil remediation and renewable energy generation. This could aid in income generation, promoting holistic farming and moving from subsistence to commercial farming. The variability of digestate with respect to physical, chemical and biological properties (e.g. dry matter, C/N ratio, pH, nutrients and beneficial microbes) has been highlighted in this chapter. It is worth mentioning that the physico-chemical properties and efficacy of digestate depends on the nature of the feedstock utilized, storage method and handling as well as method of application.

For future research, studies should look into the association between feedstock type and the agronomic properties of digestate. Such awareness will permit informed selection of feedstock that can result in digestates with specific properties, which make it desirable for the intended downstream application. Identification of biological content such as beneficial and pathogenic microbes as indicators of digestate quality could also be useful for digestate product characterization. Overall, the digestate market in Africa is still undeveloped, coupled with its general knowledge for application. However, with increased AD adoption, digestate regulations could also grow, especially in countries such as South Africa, Uganda and Ethiopia, where AD studies have already been conducted for both digestate and renewable energy production. With the drive towards holistic farming and the shift in perspective of AD from 'biogas optimization' to 'integrated biogas–digestate optimization' it is anticipated that future research trends will be directed towards maximising benefits associated with digestate use. Maximising appropriate digestate use, particularly by SH farmers, based on scientific evidence and informed guidance would in turn qualify this valuable resource being termed 'liquid gold'.

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Chapter 20
Importance of Mushrooms for Food Security in Africa

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Abstract Humans require food for all essential activities of life. From ages, humanity is struggling with malnutrition and food scarcity because of poor and/or substandard agriculture production practices due to various factors. Growing population, climate change, urbanization, desertification as well as encroachment into production farmland by herders, especially in recent times, make this problem more difficult. Worse yet, the COVID-19 pandemic struck at a time when around 820 million people in the world are suffering from chronic hunger and more than 2 billion are malnourished. In view of these challenges, while effort should be made to address the aforementioned challenges, there is a need to explore other available food supplementary resources so the teeming African population may survive the present condition, meet their hidden hunger demands and protect Africans from food insecurity. One of the best natural resources available, which may be supplementary to other food crop, is mushrooms. Mushrooms are natural resources that could serve as functional food for nutrition and medicinal purposes. They are a good source of essential fatty acids which are polyunsaturated fatty acids vital for health and well-being. This chapter discusses the importance of indigenous mushrooms in food security in Africa and identified the essential fatty acids commonly found in some indigenous oyster mushroom, highlighting their biochemical and health-promoting relevance.

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Keywords Indigenous mushrooms · *Pleurotus ostreatus* · Essential fatty acids · Functional properties · Health values · Nutritional relevance

20.1 Introduction

Food provides the needed energy for all essential activities of life. From ages, humanity is struggling with malnutrition and food scarcity because of poor and/or sub-standard agriculture production practices due to various factors. Growing population, climate change, urbanization, desertification as well as encroachment into production farmland by herders,especially in recent times, make this problem more difficult. Worse yet, the COVID-19 pandemic struck at a time when around 820 million people in the world are suffering from chronic hunger and more than 2 billion are malnourished (HLPE 2020). According to FAO and ECA report (2018), Africa is not on track to meet the United Nations Sustainable Development Goal 2 (Zero hunger)—to end hunger. Youth employment is a fundamental challenge across the continent. Most youth work in the informal economy, and 67 percent of young workers live in poverty. Agriculture and the rural economy will play a key role in creating jobs to absorb the millions of youths joining the labour market each year. Climate change is a present and growing threat to food security and nutrition in Africa and is a particularly severe threat to countries relying heavily on agriculture. In general, reduced precipitation and higher temperatures are already impacting negatively on the yields of staple food crops, although there is some spatial diversity. By 2050, climate change will cause another 71 million people to be food-insecure in the world, over half of whom will be in sub-Saharan Africa (FAO and ECA 2018).

In view of these scenarios, while effort should be made to address the aforementioned challenges, in addition to the plant resources, there is a need to explore other available food supplementary resources so the teeming African population may survive the present condition, meet their hidden hunger demands and protect Africans from food insecurity. One of the best natural resources available, which may be supplementary to other food crop, is mushrooms. It is the most famous and documented edible forest product (Chamberlain et al. 1998) which is now being domesticated as a horticultural crop (Oei 2016; Adedokun et al. 2016; Adedokun and Okomadu 2017). Mushrooms are macro fungi with two broad divisions or phyla—Ascomycota (sac fungi) and Basidiomycota (filamentous fungi). Edible ones are not only of relished nutritional value, they are also replete with diverse medicinal properties, hence their being regarded as functional foods. Generally, mushrooms are saprophytes. Some of them in the family Pleurotaceae are in addition, nematophagous. Edible mushrooms are either collected from the wild growing on dead or decaying niche such as woods or cultivated in commercial farms. Of the edible mushroom species, those collectively and commonly referred to as the oyster mushrooms are among the widely sought for and mostly cultivated in Africa. They belong to the genus *Pleurotus.* Of this genus, *Pleurotus ostreatus* is one of the most widely sought for and commercially cultivated. Other species include: *Pleurotus* *tuber regium* (King tuber mushroom), *Pleurotus djamor* (Pink oyster mushroom), *Pleurotus eryngii* (King oyster mushroom). They are Agaricomycetes species belonging to the family of mushrooms known as Pleurotaceae.

Pleurotus ostreatus, commonly called oyster mushroom, has a broad fan-like (oyster shaped) cap 2–30 cm with the margin inrolled when young. The cap is smooth and often lobed or wavy. The flesh is white, firm and of varying thickness depending on the arrangement of the stipes. The stipe is not always present, but if present, it is short and thick. The gills are white to cream, descending to the stipe to cream. *Pleurotus species* are among the few nematophagous mushrooms (Marlin et al. 2019). Their mycelia release a calcium-dependent toxin that paralyses its prey (round worms) within minutes killing and digesting them to obtain nitrogen. Several health-promoting benefits have been attributed to extracts of *Pleurotus* species. These include: antitumour, antigenotoxic, anti-inflammatory, antihypertensive, antilipidemic, and antihyperglycaemic (Deepalakshmi and Mirunalini 2014). Besides its nutritional and functional benefits, it has also been used in soil bioremediation during crude oil pollution. In this chapter, we describe the importance of indigenous African mushrooms, essential fatty acids found in some species and hindrances to mushroom cultivation in Africa.

20.2 Some Indigenous African Mushrooms: Nutritional and Medicinal Content

The African territory is replete with varieties of mushrooms. These mushrooms play an invaluable role in nutrition and medicine and can be found in all nook and cranny (Odiketa et al. 2020). They are also a source of multiple nutrients, fibres, phytochemicals which provide various nutritional and health benefits (Cheung 2010; Afieroho et al. 2013, 2017, 2019). Mushrooms are popular valuable foods because they are low in calories, carbohydrates, fat, and sodium; they are cholesterol-free. Besides, mushrooms provide important nutrients, including selenium, potassium, riboflavin, niacin, vitamin D, proteins, and fibre and they are important for their healing capacities and properties in traditional medicine (Ishara et al. 2018). The nutrition and medicinal values of mushrooms can also be ideal for vulnerable groups in the society, such as children, breastfeeding mothers, the old and the sick, especially those suffering from diabetes, heart diseases and cancer. Mushrooms have also shown remarkable results in trials for HIV/AIDS patients in Africa (Chang 2006). In the past, edible mushrooms were only traditionally harvested and were difficult to domesticate and cultivate. In modern times, however, advances in research and biotechnology has made the domestication and cultivation of edible mushrooms possible in developing countries of Africa (Fanzo et al. 2012). This also enables horticulturalists and breeders to be able to increase species of domesticated mushrooms (Adedokun and Okomadu 2017). While cultivation of some species has had a long history, the shiitake (*Lentinula edodes*) could be one of the earliest species to be cultivated. The domestication and cultivation of oyster mushrooms and shiitake has grown rapidly in recent decades (Arora and Shepard 2008). However, the number of wild mushrooms has shrunk due to degradation of land and natural resources. Cultivated mushrooms would not only provide food security, but also sustainable and more nutritious diets (Vinceti et al. 2013; Adedokun and Okomadu 2017) (Table 20.1).

Table 20.1 Some edible and medicinal mushrooms in Nigeria analysed for toxins, secondary metabolites and nutritional contents

Mushroom	Nutritional content	Toxin	Secondary metabolites	References
Auricularia auricula-judae (bull.) Quél	+	–	–	Aletor (1995),
Calvatia cyathiformis (bosc.) Morg.	+	–	–	Aletor (1995)
Chlorophyllum molybditis (Mayer ex. Fr.) Massee	–	+	+	Fasidi and Kadiri (1995), Kadiri and Fasidi (1992)
Cortinarius melliolens Fr.	–	+	+	Kadiri and Fasidi (1992), Fasidi and Kadiri (1995)
Lentinus subnudus Berk.	+	+	–	Kadiri and Fasidi (1992), Aletor (1995), Fasidi and Kadiri (1995),
Lactarius trivialis Fr.	+	–	–	Adejumo and Awosanya (2005)
Pleurotus tuberregium (Fr.) singer	–	+	+	Kadiri and Fasidi (1992), Fasidi and Kadiri (1995), Adejumo and Awosanya (2005)
Psathyrella atroumbonata Pegler	+	–	–	Aletor (1995)
Schizophylum commune Fr.	+	–	–	Aletor (1995)
Termitomyces microcarpus (Berk. and Br.) Heim	+	–	–	Aletor (1995)
Termitomyces robustus (Beeli) Heim	+	+	+	Kadiri and Fasidi (1992), Aletor (1995), Fasidi and Kadiri (1995)
Tricholoma lobayense Heim	–	+	–	Kadiri and Fasidi (1992), Fasidi and Kadiri (1995)
Volvariella esculenta (mass) singer	–	+	+	Kadiri and Fasidi (1992), Fasidi and Kadiri (1995)

Key: +: Present, –: Absent
Adapted from Okhuoya et al. 2010

20.3 African Indigenous Mushroom and Components of Food Security

According to World Food Summit (1996), food security exists when all people at all times have physical and economic access to sufficient, safe and nutritious food that meets the dietary needs and food preference for an active and healthy life.

This leads to four dimensions of food security: availability, access, utilization and stability of food. Indigenous African mushrooms serve these four dimensions. There is a growing demand for mushroom products in sub-Saharan Africa. In Kenya, 38 out of 42 tribes are known to use mushrooms as food, though the key wild mushroom traders are found in Western and Coastal Kenya (Gateri 2013). Also, many immigrants and visitors from Asian, European and American origin utilize mushrooms as food for nutritional and medicinal purposes. This justifies the need to exploit every opportunity in promoting and increasing the capacities for mushroom production and consumption of both wild and cultivated. Although mushroom production was introduced into Kenya in 1969, Wambua (2004) describes mushroom industry in Kenya as still in its infancy and is growing slowly. To many people, its growth is still a myth because there is a lack of communication between the researchers in this field and the farmers, and the exchange of cultural knowledge is rather poor. The cultivation and utilization have been hampered by lack of information, extension, research and reluctance of those in possession of skills to share with interested parties (FAO 2007).

In Uganda, mushroom cultivation was introduced in 1990. Since then, there has been an increasing demand for cultivated mushrooms, especially among the elite. Hence, its introduction was expected to provide a great opportunity for the locals to raise their incomes. To meet the increasing demand, mushrooms are still being imported from South Africa and Britain to supplement the quantity produced by local farmers in Uganda. It was expected that mushroom growing in the country would reduce pressure on land, increase farmers' incomes and improve food security (Obaa and Nshemereirwe 2004).

It was garnered from findings of a research conducted by Obaa and Nshemereirwe (2004) to assess the potential of mushroom cultivation in improving household incomes of smallholder farmers in Uganda that the major income source for households was crop production, mainly sorghum, sweet potatoes and potatoes. Off-farm employment, petty trade, sweet potatoes and brickmaking were some of the supplementary sources of income mentioned. Now mushrooms have become an additional source of income, superseding some of the traditional income sources above. Market for mushrooms is available; it is the production that is still limited. Drying of mushrooms at small-scale level of production can be done without use of expensive equipment like solar dryers (Obaa and Nshemereirwe 2004). Less expensive solar dryer may also be fabricated. In Ghana, mushroom cultivation as an agribusiness has gained some modest success because many of her forest reserves that support rich wild growth of the mushrooms are depleting fast in rich biodiversity of indigenous mushroom species. It has now become necessary to adopt modern mushroom cultivation strategies to sustain supplies of edible mushrooms for human consumption in Ghana such as those obtained in the developed economies (Kortei et al. 2018). Obodai et al. (2003) attributed oyster mushrooms' emerging popularity among Ghanaians to its comparatively easy method of cultivation.

Intensive research into bioconversion of lignocellulosic wastes by mushrooms is making it possible to cultivate different species of mushrooms all year round with specific emphasis on Jun-Cao technology – the use of plastic bag and agro, industrial, forest lignocellulosic wastes. This practice is advantageous since it is more efficient and does not require so much space. Small-scale mushroom farms have emerged in Southern Ghana as a result of the introduction of the National Mushroom Development Project aimed at promoting the economic welfare of rural communities (Sawyerr 2000). Mushroom production is a demand-driven enterprise, and so requires the appropriate technologies to keep up with its supply. Consumers seem to prefer mushrooms on the basis of taste, appearance, texture or combination of these qualities. Although production of oyster mushroom is laborious, it is also very capital-intensive (Kortei et al. 2018).

In Cameroon, food supply in most rural areas is insufficient leading to reduced quality of health and increasing environmental deterioration. Many children and people in Cameroon are malnourished, and most families cannot afford meat in their daily meal; there is also high prevalence rate of HIV/AIDS, malaria, and tuberculosis, amongst others. Mushrooms can help to improve health and nutrition in Cameroon. Mushrooming in Cameroon rainforest zones is often possible only during the rainy season and is usually inefficient in terms of time spent to collect sufficient mushroom. Most edible species rot quickly, and the collector must be at the right time at the right place. Hence, there is a need for a cultivation centre for lasting availability of mushroom. People usually boiled or fried mushrooms as meat substitute in various types of sauces and dishes. However, some people are afraid to consume many mushrooms for fear of been poisoned. Mushrooms that cause itching if rubbed on the breast, nipple or elbow or spewed out if tasted are considered toxic. If insects, rodents and snakes do not feed on the mushroom, then it is assumed to be poisonous (Kinge et al. 2014).

Kinge et al. (2014) reported that mushrooms play important social, economic and ecological roles in Cameroon. About 70% of people live in rural areas and most of them on poor diets. Cameroonians are familiar with the saying: "rain follows the sun, and mushrooms follow the rain". So immediately after the rain, children and women go out early in the morning to gather mushrooms especially the *Termitomyces, Agaricus, Pleurotus, Flammulina* and *Auricularia*, amongst others. They normally gather this species in moist shady soils, dry or smoke their harvests and then keep them for several months. Alternatively, it is taken to the market to be sold.

In Nigeria, reports have it that the consumption of edible and medicinal mushrooms for various reasons cut across the different tribal groups, Yorubas, Ibos etc. with the Hausas being least in ranking in regard to information on edible and medicinal mushrooms. In times past, many mycophagists consumed mushrooms based on their organoleptic property (aroma, taste, flavour, texture etc.) not being aware of their nutritional values (Okhuoya et al. 2010); today, many individuals

Table 20.2 Summary of some edible and medicinal mushrooms and their distribution in Nigeria

Mushroom	Comments
Auricularia auricular Judae (Bull.) Quél	Edible
Calvatia cyathiformis (Bosc.) Morg	Edible
Chlorophyllum molybditis (Mayer ex. Fr.) Massee	Edible and medicinal
Coprinus picaceus (Bull. ex Fr.) S.F.Gray	Edible
Coprinus setulosus Berk. and Br	Edible
Coprinus tramentarius Ulje and Bas	Edible
Cortiarius melliolens Fries	Edible and medicinal
Daldinia concentrica (Bolt. ex Fr.) Ces. and DeNot	Medicinal
Lentinus subnudus Berk	Edible and medicinal
Pleurotus ostreatus Jacq.	Edible and medicinal
Pleurotus pulmonarius (Fr.) Quél	Edible and medicinal
Pleurotus squarrosulus (Mont.) singer	Edible and medicinal
Pleurotus tuberregium (Fr.) singer	Edible and medicinal
Psathrella atroumbonata Pegler	Edible
Schizophylum commune Fr.	Edible and medicinal
Termitomyces clypeatus Heim	Edible
Termitomyces globules Heim and Gooss	Edible
Termitomyces microcarpus (Berk. and Br.) Heim	Edible
Termitomyces robustus (Beeli) Heim	Edible
Volvariella esculenta (mass) singer	Edible
Volvariella volvacea (bull.) singer	Edible

Adapted from Okhuoya et al. 2010

intentionally seek mushrooms because of their functional values, medicinal and nutritional values. Okhuoya et al. (2010) further reported that in Nigeria edible mushrooms are eaten as food and/or used as food supplement; also the sporophores are used as a good substitute for meat protein in several suburban Nigerian soups by locals. Table 20.2 shows the different species of mushrooms found across the country and their possible usage.

In a study conducted by Adedokun and Okomadu (2017) to assess both the nutritional values and consumption of wild and cultivated mushrooms in Nigeria, it was reported that there was no significant difference in the nutritional values of wild and cultivated mushrooms, and also 33.3% of respondents obtained mushrooms from commercial farms; this reinforces the fact that mushroom farming is gradually growing (Adedokun et al. 2016). Consumption history revealed that, although a large proportion (71.1%) of respondents had knowledge about mushroom consumption, only a few (12.2%) consumed it year-round. Fig. 20.1 shows the consumption pattern for wild and domesticated mushrooms according to their report (Adedokun and Okomadu 2017).

Indigenous mushrooms in all the countries aforementioned fulfil the four dimensions of food security: availability, access, utilization and stability of food. These mushrooms are available either in the wild or domesticated, accessible and well-

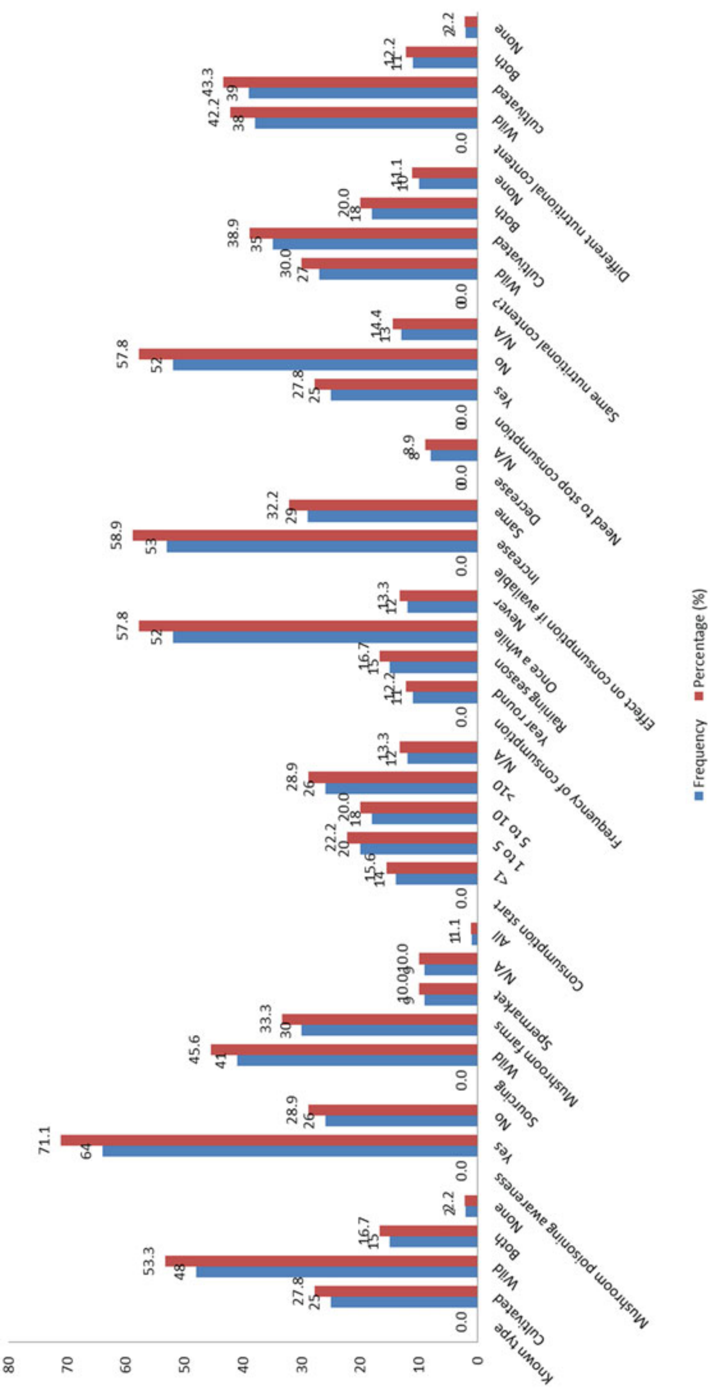

Fig. 20.1 Wild and domesticated mushroom consumption in Nigeria

utilized as functional food serving nutrition and medicinal purposes. The following section discusses specifically on one of the functional values of *Pleurotus ostreatus*, a very commonly cultivated mushroom in Africa as well as globally.

20.4 Essential Fatty Acids in the Oyster Mushroom *Pleurotus Ostreatus* (Jacq.ex.fr) P. Kumm (Pleurotaceae): The Content and Chemistry

Essential fatty acids are polyunsaturated fatty acids vital for health and well-being. They are not synthesized by the human body but obtained from dietary sources. They are needed for normal growth and development of foetus and infants, brain development and visual acuity. They are also beneficial for cardiovascular health and in the modulation of inflammation responses. Dietary sources are hence regarded as functional foods. *Pleurotus ostreatus*, commonly called Oyster mushroom, is a widely cultivated edible mushroom of high nutritional and health benefits. Though low in total fats, its fatty acid content has been found to be high in polyunsaturated fatty acids.

20.4.1 Fatty Acids Content of Oyster Mushrooms

Nutritionally, mushrooms are known to be low in fats. The reported crude fats content in different *Pleurotus species* are within the range of 0.2–8 g per 100 g dried fruit bodies (Hossain et al. 2007). These fat content values, though low, have a greater proportion of the fats being made of essential fatty acids (EFA) (Deepalakshmi and Mirunalini 2014). This is one of the justifications for their being considered as functional or health-promoting foods (Chang and Mshigeni 2001; Sadler 2003). Essential fatty acids are polyunsaturated fatty acids that humans and other animals must ingest because the body requires them for good health but cannot synthesize them. They are required for biological processes. Alpha linolenic and linoleic acids are the two main essential fatty acids although there are some other fatty acids such as docosahexanoic acid (DHA), eicosapentaenoic acid (EPA) and gamma-linolenic acid (GLA).

20.4.2 The Chemistry of Essential Fatty Acids

Two groups of essential fatty acids are known. These are the omega-3 (ω-3) and omega-6 (ω-6) families. The omega-3 and omega-6 fatty acids are polyunsaturated fatty acids (PUFAs) having more than one olefinic or double bond which is usually the *cis* geometric isomer. For the omega-3 fatty acids, the first double bond from the methyl end of the fatty acid is located between the third and fourth carbon atom, while for the omega-6 fatty acids the double bond is between the sixth and seventh carbon atom starting from the methyl end of the fatty acid. The standard abbreviation in fatty acid nomenclature is so indicated to depict the number of carbon atoms, number of double bonds and the position of the first double bond starting from the methyl end of the chain. For example, the standard abbreviation for α-linolenic acid (ALA) is 18:3n-3. The first part (18:3) indicates that ALA is an 18-carbon fatty acid with three double bonds, while the second part (n-3) indicates that first olefinic or double bond is at the third carbon atom starting from the methyl end of the chain.

20.4.3 Essential Fatty Acids Commonly Found in Oyster Mushrooms and Their Role in Health

20.4.3.1 Linoleic Acid

Linoleic acid (LA) is a polyunsaturated fatty acid belonging to the omega-6 family of PUFAs. It is an essential fatty acid and is the parent PUFA of the omega-6 family. In its pure form, this oily liquid is colourless or white oil, and just like all lipids, it is soluble in most organic solvents but insoluble in water. In nature, it exist mostly as esters as seen in triglyceride (ester of glycerine) and its linoleates. LA has been found to be the major PUFA in *Pleurotus species* with content ranging from 11.6–68.9% of total fat. (Kayode et al. 2015; Bamidele and Fasogbon 2020; Duru et al. 2019; Ergönül et al. 2013). The reported range for *Pleurotus ostreatus* which is commonly called oyster mushroom is between 20–68.9% of the total fat content (Bamidele and Fasogbon 2020; Duru et al. 2019; Ergönül et al. 2013). The variation could be as a result of substrate for cultivation or the dead wood on which it is growing on in the wild (Hoa et al. 2015). These values compete favourably with the LA content in other natural vegetable sources of dietary fats rich in LA like safflower seed oil, grape seed oil, sunflower seed oil, cotton seed oil, sesame seed oil and maize oil which are high in LA (FAO 2001). Linoleic acid is a precursor to arachidonic acid (AA). AA is the precursor to certain prostaglandins, leukotrienes, and thromboxane implicated in the mediation of inflammation. In the metabolism of LA to AA, it starts with the conversion of LA into gamma-Linolenic acid (GLA) by the enzyme Δ6-desaturase. GLA is then further converted to dihomo-gamma-linolenic acid which is the immediate precursor to AA (Fig. 20.2).

20.4.3.2 Alpha-Linolenic Acid

Alpha Linolenic Acid (ALA) (IUPAC name: 9Z,12Z,15Z)-octadeca-9,12,15-trienoic acid) is an essential fatty acid belonging to the omega-3 fatty acids group. It has been reported to inhibit the synthesis of prostaglandin resulting in reduced inflammation

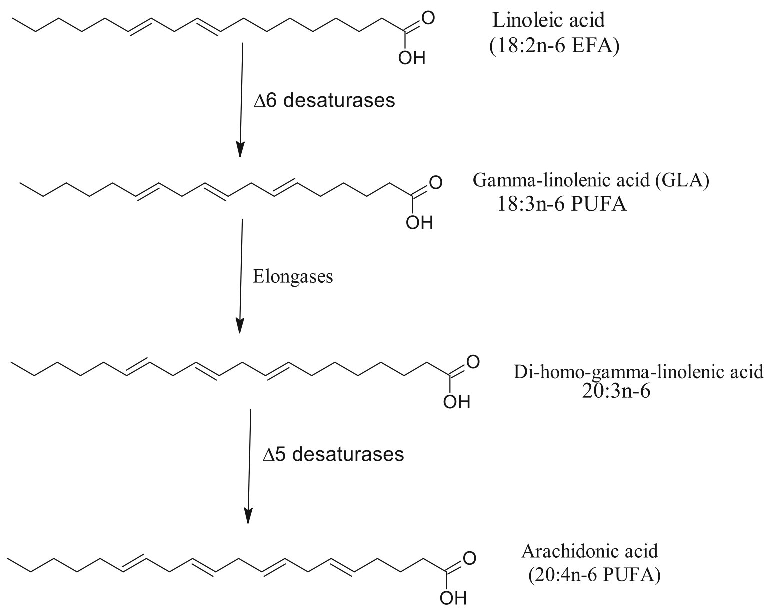

Fig. 20.2 Metabolic transformation of linoleic acid to arachidonic acid

and prevention of certain chronic diseases. Unlike LA, the reported proportion of ALA for *Pleurotus ostreatus*, the oyster mushroom, is between 0.03–20% of the total fat content (Bamidele and Fasogbon 2020; Duru et al. 2019; Ergönül et al. 2013). The variation could be as a result of substrate for cultivation or the dead wood on which it is growing on in the wild. ALA acts as the substrate for the synthesis of longer chain, more unsaturated n-3 fatty acids eicosapentaenoic acid (EPA) (20:5n-3) and docosahexaenoic acid (DHA) (22:6n-3) which are required for tissue function. EPA and DHA are also beneficial in clinical cases of cardiovascular and inflammation diseases (Calder 2004). DHA is known to also play vital role in optimal neuronal function and visual acuity (Fig. 20.3).

20.5 Hindrances to Mushroom Production in Africa

Despite the invaluable role mushroom plays in nutrition, medicine and food security as a whole, its production is met with several hindrances in Africa. These range from lack of infrastructure and technical supports from national and international agencies to scarcity of mushroom scientists, poor political and legislative support, poor knowledge of mushroom biodiversity due to dearth of mushroom taxonomists and bad press reports, amongst others (Labarère and Menini 2000). Literature from different parts of Africa shows that these hindrances are similar. For instance,

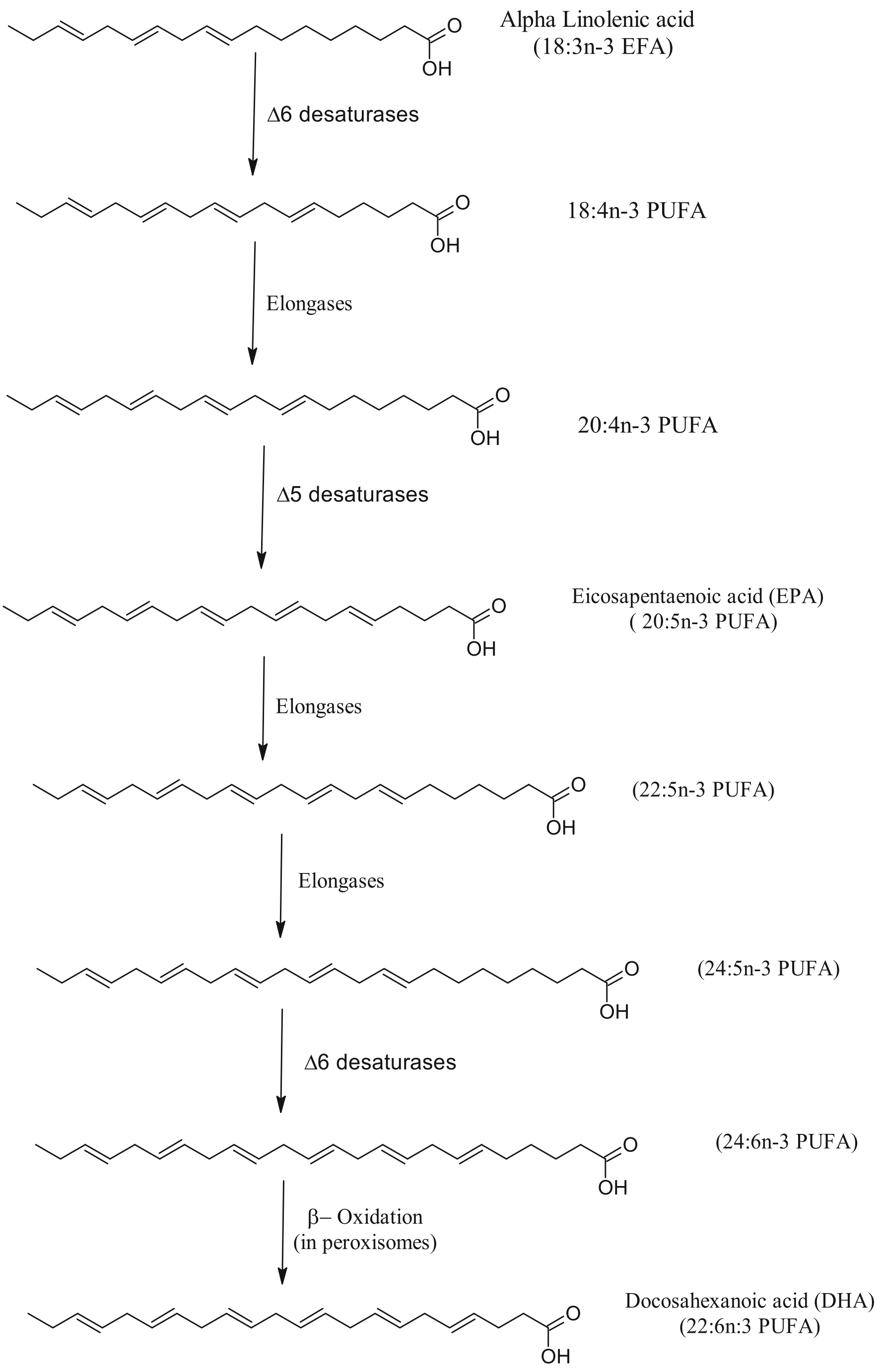

Fig. 20.3 Metabolic transformation of alpha linolenic acid to longer-chain omega-3 PUFAs

Azeez et al. (2019) summarized the general challenges associated with mushroom cultivation in Nigeria as:

1. *Difficulty in sourcing quality spawn*: The type of spawn used in mushroom cultivation determines the yield. Mushroom cultivators often find it difficult to get quality spawn as very few government departments and private producers are saddled with the responsibility of producing quality spawns.
2. *Pests attack:* Ants and termites are the common pests of mushrooms under cultivation. The two insect pests either target the substrate, spawn or the mushroom itself thus, reducing productivity and market value. Also, through prevention and control of these insect pests, cultivators often incur extra cost of production.
3. *Lack of low-cost mushroom farm design:* A scientifically designed mushroom farm requires heavy investment, and hence is out of reach of small and marginal mushroom cultivators.

In addition to the above, Mutema et al. (2019) elucidated further on other hindrances Zimbabwean farmers contend in mushroom production. These include:

20.5.1 Lack of Production Space

Farmers from high-density suburbs require more space for growing mushrooms and also for growing their substrates. Some rent space from nearby farms, which increases the operational costs.

20.5.2 Training Content, Cost and Certification

Government institutions provide formal training at higher costs than informal and private training organizations. Governmental institutions such as universities and research centres such as SIRDC train mushroom producers and issue certificates on completion of training, but other organizations do not issue certificates. There is need by the government to revise their training charges so as attract or increase trainees' enrolment. The training content should include marketing strategies, marketing information and maintenance of records. These items seemed to be lacking in most mushroom producers.

20.5.3 Lack of Financial Support

Ventures require capital for investments, operation and maintenance costs. Farmers are denied loans by banks because they do not have collateral required by the financial institutions. Literature revealed that, small scale farmers have poor economic background or they do not have enough finance to state a project, so they need assistance to start a viable project. According to Gebretsadkan (2015), financial support is needed at initial stages of production for buying inputs and labour, and for improving cultivation techniques and post harvest care.

The Reviving Urban Farming (RUAF) Foundation (2007) reports that there is no proper policy in Zimbabwe which supports mushroom farming. Mushroom production is sidelined financially from financial programmes which are given to other crops such as maize. The farmers do not have collateral, so they cannot access loans from banks and other financial institutions. The challenges on financial issues differ with countries; in China and Nepal the small-scale farmers have full support from both government and NGOs. A study in Nepal observed that small-scale farmers do not have a sound economic background but can access loans from banks at very small interest and can afford to pay back within few months (Poudel and Bajracharya 2011).

20.5.4 Markets

Most mushroom producers do not register their mushroom business, so it is very difficult for them to sell their products to the market. Some reported that, the supermarkets want to deal with wholesalers not individuals. Supermarkets managers need police and tax clearance and demand large volumes of mushrooms which cannot be supplied by individual farmers. For that reason, farmers resort selling harvested products to family, friends and neighbors.

20.5.5 Water Problems

Mutema et al. (2019) explained that mushroom producers in high-density suburbs such as Budiriro, Kuwadzana and in middle density suburbs such as Cold Comfort and Wesley faced water problems. As a result, some producers were planning to install boreholes at their homes. Water availability is one of the physical inputs that play significant roles in mushroom production (Marshall and Nair 2009). Research reveals that maturing mushrooms require high moisture level which is attained by watering the growing rooms (SIRDC 2017).These findings showed that water plays significant roles in mushroom production; hence, farmers should consider clean water availability on production land before engaging in mushroom production.

20.5.6 Perishability of Mushrooms

The importance of product storage can hardly be overemphasized. Farmers reported that sometimes their harvests got bad before being sold. Some producers dry the mushrooms and some look for markets before the harvest to avoid losses. They suggested that buying and installing air conditioners and refrigerators would keep the mushrooms fresh (Azeez et al. 2019).

20.6 Conclusion

From this chapter, mushrooms are invaluable in food and nutritional security. They may also be useful in tackling hidden hunger (lack of essential vitamins and minerals which are needed by the body for proper growth, development and functioning due to consumption of low-nutrient food compared to what the body requires). Mushrooms are sources of omega-6 and omega-3 fatty acids, which have critical roles in the membrane structure. They are also precursors of eicosanoids, which are potent and highly reactive compounds with varying and often opposing effects on smooth muscle cells, platelet aggregation, vascular parameters such as permeability and contractility, and on the inflammatory processes and the immune system. Mushroom production is scalable and appropriate for smallholder farmers as well as large-scale farmers. Mushrooms can be cultivated in the small space of a farmer's own house for small-scale production and generate income that aids in the family support. Mushroom cultivation is a most popular activity for development programmes targeting income generation among farmers in Africa. The product is highly nutritive, a good nutrient source for all gender classes, and because of its high economic value they can also earn some income from the production.

In many parts of Africa, farmers have grown mushrooms in a small scale and have benefited directly. They have managed to adopt the technology in a simpler way whereby they can afford to invest in a small scale. They are mainly utilizing the agricultural wastes as many as they may have access to. Thus, mushroom cultivation may reduce poverty, aid in attaining the SDG 1 and 2, attend to the issues of food and nutritional security, tackle hidden hunger as well as improve the lifestyle of many farmers in Africa. In order for African communities to attain food and nutritional security and tackle hidden hunger, there should be a renewed effort on campaign about the importance of mushroom cultivation and consumption. Government institutions, policymakers and all stake holders are enjoined to support mushroom farmers in order to promote availability of mushrooms through cultivation which will thereby encourage increase in consumption.

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Chapter 21
Mushroom Cultivation in Arid Namibia: Cultivation Status, Contribution to Human Health and Future Prospects

Martha Kasiku Hausiku

Abstract The population of Namibia has almost doubled since independence, and this has resulted in increased demand for food supply. Access to affordable, nutritious food by all human beings is a fundamental human right enshrined in various declarations and developmental goals, such as the Global Declaration of Human Rights, the Sustainable Development Goals, Namibia's Fifth National Development Plan (NDP5) and the Harambe Prosperity Plan. Mushrooms, having a long history of being consumed as food, play a significant role in human lives by contributing to food security. This chapter attempts to dissect the relevance of mushrooms, both indigenous and exotic species to Namibia, and their role as food and medicine. Indigenous mushrooms of economic value are scrutinized and their role in the human diet and the economy of the country are discussed. The status of mushroom consumption in Namibia and the role played by mushrooms in preventing health issues associated with nutrient deficiencies are also discussed. Mushrooms have always been consumed for their palatable taste and their flavour-enhancing property. Besides their palatability and flavour enhancement, they are a highly nutritious food, comprising high-quality protein. Mushrooms also consist of a spectrum of minerals and vitamins that can supplement the dietary requirements of the population and contributes to addressing food insecurity. This chapter, therefore, highlights the status of mushrooms consumption in Namibia, their cultivation and their contribution to human health. The chapter further summarizes the future prospect of mushroom cultivation in Namibia and assesses the strengths, weaknesses, opportunities, and threats analysis of the country's mushroom industry. Value addition to mushroom spent substrate and its utilization in agriculture and in animal feed industry as well as its application in biotechnology and environmental management is also discussed.

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21.1 Introduction

Namibia gained independence in 1990; at that time, the country's total population was only 1.4 million (Republic of Namibia 2015). Ever since 1990, the country's population has increased to 2,588,193 as of July 2021 (Worldometer 2021). This increase in the population size has been associated with a demand on food supply in terms of quantity and quality, as each additional person has nutritional needs and causing the total food demand to increase. Food is a fundamental human right, as enshrined in article 25 of the Global Declaration of Human Rights of the United Nations (United Nations 1948). As a country, Namibia has committed itself to the principles and goals of the Global Declaration of Human Rights since independence. Following this commitment, a policy on Food and Nutrition for Namibia was developed to serve as a framework and provide guidelines for addressing the challenges of food insecurity and malnutrition in the country over medium to long term (Republic of Namibia 1995). Similarly, the United Nations' second goal of Sustainable Development Goals (SDGs) emphasizes elimination of hunger and ensure access to safe, nutritious and sufficient food by all people including the poor and the vulnerable by 2030, which is in line with the human rights' declaration (United Nations 2017). In efforts to implement the international goals and principles on food security and nutrition, Namibia initiated the Fifth National Development Plan (NDP5) (2017/2018–2021/2022) proposing various strategies to increase horticulture and livestock output. Among the proposed strategies is the development of the agro-processing industries, increasing communal smallholder farmers' productivity, and promoting drought-resistant crops (Republic of Namibia 2017). In order to effect the NDP5, an initiative, Harambe Prosperity Plan (HPP) was designed by the Namibian government. One of the proposed action areas under the social progression pillar of the HPP is "zero deaths in Namibia due to a lack of food" (Republic of Namibia 2016).

As if Namibia being the driest country in sub-Saharan Africa is not bad enough, the country is prone to floods and drought spell, affecting the productivity of the agriculture sector upon which the country's economy is anchored. Majority of the Namibian population (about 65%) lives in communal areas and depends on the agriculture sector directly or indirectly. These people engage in rain-fed crop production, livestock farming, and artisanal fisheries for their livelihood. Household surveys reveal high levels of inaccessibility to food, limited options in terms of food choices, heavy dependence on starchy, sugary and foods made from oils, and inadequate consumption of healthier foodstuffs such as fruits and vegetables (Crush et al. 2021). These challenges are indicators of food insecurity in the country and needs to be addressed. Food insecurity is defined as the state of being whereby people lack reliable access to affordable, nutritious food in sufficient quantity to maintain a healthy and active lifestyle (Sage 2014). Besides general poor health, food insecurity contributes to mental health problems (e.g. depression and anxiety), chronic diseases (e.g. cardiovascular disease, obstructive pulmonary disease, cancers, asthma, autoimmune disease and depression), poor child growth and birth defects. A combination of poor nutrition and stress can make even treatable diseases challenging to manage.

Good nutrition is not only a function of the quantity but also the quality of food consumed. In the present diet-conscious era, mushrooms are increasingly considered as a future vegetable, owing to their nutritional and medicinal properties as well as consumer demand. Mushrooms are nutritious foods, excelling in macronutrients such as high-quality protein and micronutrients such as minerals and vitamins that are necessary for good overall health. Due to their nutritional properties, mushrooms have potential in preventing health problems resulting from nutrient deficiencies such as anaemia, goitre, kwashiorkor and birth defects. Mushrooms also have therapeutic values such as wound-healing, immunity-enhancement, antiviral and anti-tumour properties. The mushroom cultivation industry has economic significance as income is generated from trading of mushrooms and mushroom by-products. Mushrooms are mostly cultivated on recycled lignocellulose material that are otherwise burnt. Lignocellulose biomass burning contributes to carbon emission, exacerbating the current global warming (IPCC 2014); thus, mushroom cultivation is a sustainable farming practice which contributes to waste management.

21.2 Mushroom Consumption in Namibia

Mushrooms have always been part of human diet since time immemorial. Different edible fungi occur naturally in Namibia, and they form fruit bodies at various times of the year. Termite hill-mushroom (*Termitomyces* species), for instance, is one of the popular indigenous mushrooms that is harvested from the wild during the rainy season. This mushroom is mostly foraged by local people for personal consumption, and surplus collection is sold at a small cost in the informal market. Farm workers are usually seen selling their surplus mushroom harvests along the road in parts of the country where this mushroom grow. In the informal market, the price of this mushroom is not fixed but open for negotiations. The usual price ranges between N$5 and N$10 (*1USD = approx. N$ 14*) per fruit body depending on the actual size of the fruit bodies and the amount of harvest available. The price is minimal relative to the demand as those who sell some off their harvest, especially in rural areas up north do not consider it as a money-making opportunity but rather as a way of sharing, as they believe that mushrooms are God's given gift to people (Mshigeni 2001).

Kalahari truffles (*Kalaharituber pfeilii*) is another indigenous mushroom harvested in Namibia at the end of summer and the beginning of winter. Truffles are the most sought after and the most expensive mushrooms in Namibia. Just like *Termitomyces*, they are usually harvested for personal consumption, and excess harvest is sold in the informal market for about N$30 per kg. Again, this precious mushroom is underpriced in the informal market; as the author has noted, the same mushroom is being sold for N$180 per kg in a local supermarket. These mushrooms and other less popular ones play a crucial role in complementing the diet of local people, especially during rainy season when food is rather scarce. Despite the socio-economic significance of indigenous edible mushrooms, they are underutilized. This could be a result of limited knowledge regarding identification of edible mushrooms as such knowledge is not documented but rather passed on orally within families and communities. The dearth in this crucial knowledge coupled with isolated incidents of mushroom poisoning has made many people to become reluctant about foraging for mushrooms in the wild and prefer to purchase them instead. The mushroom poisoning incidents magnified by media have hindered the introduction of most indigenous edible mushrooms in the formal food market chain, affecting their economic potential as a result (Hyde et al. 2019). Consequently, only a small proportion of the population with grounded knowledge on differentiating edible from non-edible mushrooms benefit from this precious natural resource.

21.3 Status of Mushroom Cultivation in Namibia

Vegetable gardening plays a significant role in the livelihood of many households, both in the rural and urban areas in Namibia. Many households grow vegetables mostly for personal consumption, and surplus is sold mostly in informal markets. Poor yields due to infertile soil and shortage of water for irrigation are common challenges faced by these smallholder farmers. These challenges in turn force individuals, especially the youth, to abandon agriculture and resort to job searching instead.

Mushroom cultivation offers an alternative means addressing the challenges of unproductive soil and water shortages faced by smallholder farmers. Mushrooms are referred to as "vegetable meat" in some parts of the world because they can provide a fair substitute for meat, with a comparable nutritional value to many vegetables (Pandey et al. 2018). The cultivation of mushrooms is a reliable and effective way for households struggling with infertile soil and even those without land to grow nutritious food in a short space of time (Sharma et al. 2017). Rather than using soil, mushroom cultivation technology is based on recycling of agricultural residues, that are available in huge quantities, especially in the northern, northern central and north-eastern parts of Namibia, where cereal crop production is one of the most agricultural activity being carried out by inhabitants. For mushrooms to be successfully cultivated, lignocellulose material (organic material with cellulose, hemicellulose and lignin as the main components) such as cereal straw, coffee grounds, saw dust and wood shavings amongst others are required as substrates. These substrates are easily obtained even in urban areas as they are generally regarded as waste, making the input cost of mushroom cultivation relatively affordable compared to that of other crops. Mushroom cultivation is indeed an ideal horticultural alternative for both the rural and peri-urban households with massive potential in addressing food insecurity (Pandey et al. 2018). Actually, the development of technical knowledge for commercial cultivation of mushrooms was an effort to extend the period of edible mushrooms' availability and reduce the inherent risk of mushroom foraging, being poisoning, thus addressing their growing demands for culinary purposes (Kortei et al. 2018). Mushroom production cycle takes about 6–12 weeks, making them fast yielding compared to many other crops. What is more, different mushrooms species can be grown during different seasons making them ideal for production throughout the year.

In spite of the availability of suitable material that can be used for the cultivation of different mushrooms species coupled with standardized cultivation technologies of many exotic species, Namibia is not yet a major producer of mushrooms. Efforts have been made by the University of Namibia, with the support from various stakeholders, to promote mushroom cultivation in the country with no tangible results. Oyster mushrooms species that have been identified worldwide as easy to grow and thus mostly recommended for beginners have been promoted extensively and capacity-building workshops on their cultivation have been conducted countrywide; Namibian mushroom farmers continue to face challenges in terms of yield (Shivute 2020). According to the author's observations, small quantities of mushrooms are usually found in some supermarkets especially in the urban areas and even this is dominated by one type, the button mushrooms, implying that oyster mushroom production is indeed minimal. Even with button mushrooms, there is only one producer in the entire country at the moment and the production cannot meet the demand; consequently, a huge proportion of the mushroom consumed in Namibia is imported. A few oysters mushroom species are spotted in a few supermarkets but their stock level is almost negligible, pointing to the low production. Recently, there has been a growing interest in mushroom cultivation to supplement, or replace wild harvest. The growing interest in mushroom cultivation amongst Namibians is mostly attributed to the increased awareness of their nutritional and medicinal value as well as the realization of their income-generating potential through trade. The cultivation of mushrooms and their consumption thereof has immense potential to make a valuable contribution not only to food security but also to the country's gross domestic product (GDP).

21.4 Contribution of Mushrooms to Human Health

The use of mushrooms by humans is fascinating; they are consumed both as food and medicine. In fact, mushrooms have all the three functionalities of food: appealing taste, nutrition and physiological properties. Many mycophilic individuals consume mushrooms for their sensory attributes, including palatable taste, unique texture and distinctive aroma. Their unique taste is attributed to several water-soluble substances including free amino acids (e.g. glutamic and aspartic amino acids and 5′-nucleotides) and soluble carbohydrates ((Du et al. 2021). These

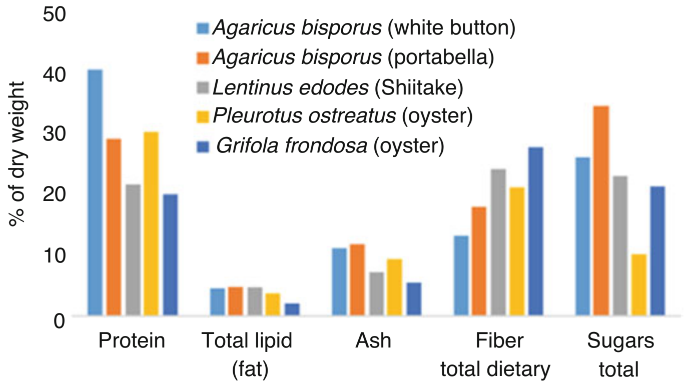

Fig. 21.1 Nutritional composition of common commercial edible mushrooms (source, Friedman 2016)

substances also give mushrooms a savoury, meat-like taste, called *umami*, a Japanese word meaning essence of deliciousness. Dry, cooked and roasted mushrooms have more *umami* compared to fresh and uncooked ones. Some edible mushrooms have characteristic mouthfulness, complexity, and continuity flavour called *kokumi*, a Japanese word meaning rich taste. *Kokumi* tasting substances have slight taste or even no taste by themselves, but they can enhance the flavour of the basic tastes, such as sweet, salty, and *umami* (Ueda et al. 1997). The *umami* and *kokumi* properties of mushrooms can influence the sensory quality of bland food, making them versatile and a preferable ingredient in many food formulations.

Mushrooms are nutritious food low in fat and calories, free from cholesterol, substantial amount of soluble carbohydrates, modest in dietary fibre and high in proteins as depicted in Fig. 21.1. The presence of these nutrients in mushrooms make them a superfood, with a potential of addressing malnutrition.

Malnutrition is a public health problem because it is a precursor to many preventable illnesses. It is associated with micronutrient deficiencies, and this deficiency may lead to serious health problems such as goitre (iodine deficiency), anaemia (iron deficiency), pellagra (niacin deficiency) and xerophthalmia (vitamin A deficiency), among others (Republic of Namibia 1995). Mushrooms are a good source of various beneficial minerals (e.g. potassium, phosphorus, calcium, magnesium, iron and copper) and multivitamins (e.g. B, C and D, including niacin, riboflavin, thiamine and folate) that can prevent these diseases. Furthermore, edible mushrooms contain essential amino acids (e.g. histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine) (Hausiku and Mupambwa 2018); thus, their regular consumption contributes to balanced diet and prevent many health issues (Mattila et al. 2001).

Besides their palatable taste and nutritional benefits, mushrooms have also been appreciated for their medicinal properties. Regular mushroom consumption plays a significant role in human well-being as they contain unique health-promoting and therapeutic properties. Their bioactive compounds such as polysaccharides, carbohydrate-binding protein, peptides, proteins, enzymes, polyphenols, triterpenes, and triterpenoids have antimicrobial properties (Seo and Choi 2021). Their medicinal values include wound-healing, immunity-enhancement, antiviral and tumour-retarding properties. Mushrooms are also valuable and are commonly used to prevent, treat and cure ailments such as heart disease, hypertension, cerebral stroke and cancer (Rizzo et al. 2021). Mushroom polysaccharides have prebiotic properties with anti-obesity and anti-diabetic effects aiding with regulation of energy homeostasis and plasma glucose levels. Their medicinal properties are summarized in Fig. 21.2.

The awareness of mushroom medicinal properties has resulted in spectacular growth in commercial activity associated with formulations of dietary supplements (e.g. tea, tinctures, health tonics and soups), functional foods and other herbal formulas observed on the market recently (Das et al. 2021). The formulation of these dietary supplements presents a window for value addition to the highly perishable mushrooms while generating income and creating job at the same time.

21.5 Future Prospects of the Mushroom Cultivation Industry in Namibia

Mushroom cultivation has become a profitable commercial agribusiness in developing and developed countries alike, and Namibia is no exception. Given the rapid decline in the diversity of indigenous edible mushrooms species in the natural environment due to loss of natural habitat resulting from climate change, cultivation of mushrooms is more relevant now than before. For optimum production to be achieved, it is imperative to adopt and improve modern mushroom cultivation strategies to sustain the supply of mushrooms for human consumption both locally and internationally. Just like any other industries, the mushroom cultivation industry has its own strength, weaknesses, opportunities and threats, as summarized in Table 21.1. Capitalizing on the opportunities, however, will boost the mushroom industry and propel it to greater heights while addressing the food and nutrition challenges in the country and the world at large.

In the present diet-conscious era, mushrooms are increasingly considered as a future vegetable owing to its medicinal and nutritional properties and consumer demand. With a domestic population of more than 2.5 million (Worldometer 2021), Namibia alone presents a large market opportunity for the mushroom industry. What is more, there is presently supply and demand gap in the world trade of mushrooms due to a reduction in the production in western countries resulting from high labour costs (Sharma et al. 2017). This is an opportunity for Namibian mushroom producers, as they can secure better market prices for their produce.

Having been rated as one of the countries with the best road infrastructure on the African continent thus far (World Economic Forum 2019), Namibia provides more opportunity for marketing of highly perishable products such as mushrooms in order

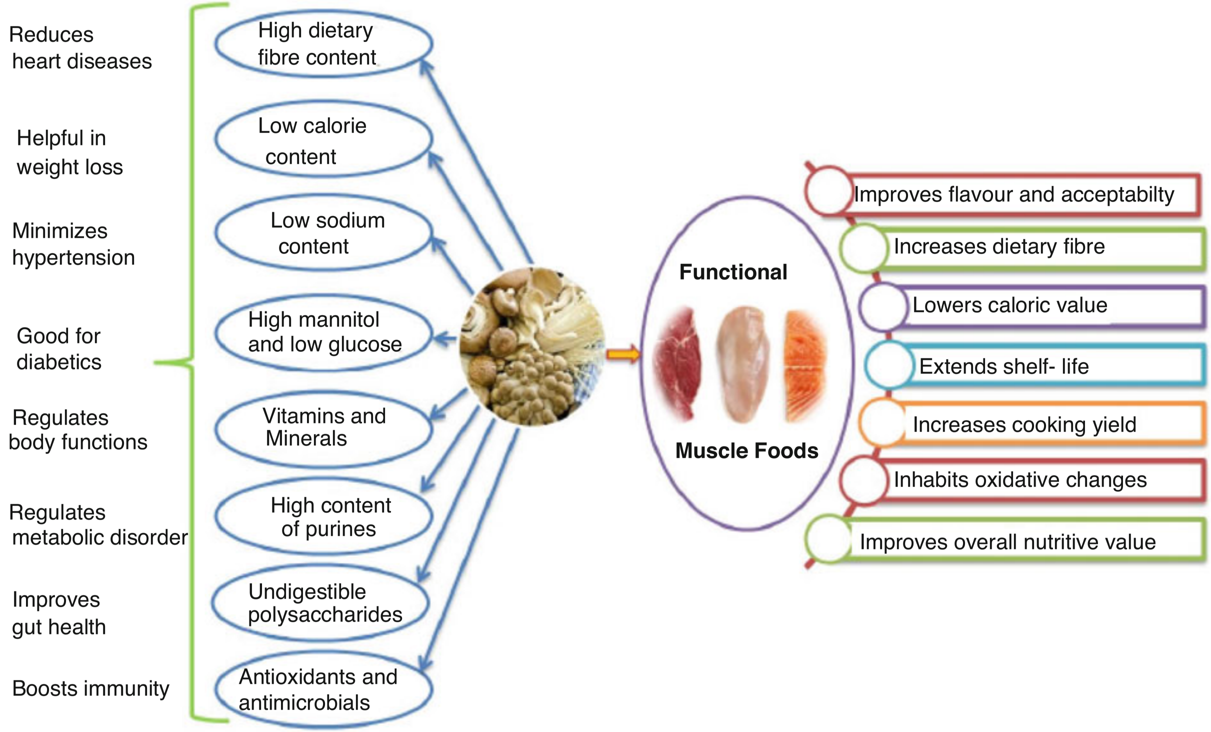

Fig. 21.2 Schematic diagram depicting health-promoting and medicinal properties of mushrooms (source, Das et al. 2021)

Table 21.1 SWOT analysis of the mushroom cultivation industry in Namibia

Strengths	Weaknesses
• Recycling of crop residues such as wheat straw, rice straw, maize Stover, wood shavings and other materials are easily accessible and cheaply available as mushroom substrates • Mushroom provides high added-value products opportunities possible for industry-use chain • Mushroom industry has high potential for both local and global markets widely • Spent substrate can be recycled and processed into value-added products	• Lack of advice on establishing new mushroom enterprises • Lack of facilities to produce quality spawn and to process products • Lack of new production technology and farm management practices • Unstable farm-gate prices and profit margins • Short shelf life of fresh mushrooms affecting long distance markets • Lack of enterprising spirit amongst entrepreneurs • Lack of financial resources for establishment of small and medium mushroom enterprise. • Unorganized production and sale particularly by seasonal farmers while demand in the markets increases
Opportunities	**Threats**
• Increasing awareness about nutritional and medicinal values of creating better domestic and global market demand • Improved future sales by enhancing public awareness in environmentally friendly farming by using crop waste and spent mushroom substrate as a value-added product • Growing mushrooms require limited land, making it ideal for both rural areas and peri-urban dwellers • Creating self-employment for female empowerment and older persons • Reducing dependence on mushrooms imports into Namibia	• Diseases and pests' invasion effects on product quality and supply • Limited supply of organic pest control products • Competition from neighbouring countries • Increasing production costs

to meet domestic consumer demands. Further development of more infrastructure facilities and a well-organized distribution network will potentially increase mushroom trade with other countries, attracting foreign currencies that will grow the country's GDP. To be successful in both domestic and export market, it is essential to produce quality fresh mushrooms and mushroom-fortified value-added products at competitive rates without any agro-chemical residues. There are ongoing research activities focusing on enhancing the health benefit and nutritional properties of cultivated mushrooms in the country (Hausiku and Mupambwa 2018; Kaaya et al. 2012), and this type of research needs to be intensified and findings disseminated for the benefit of the general public. Since mushroom cultivation does not require a lot of land, it can thus be done as a part-time enterprise while engaging in other farming activities. Certain aspects of mushroom cultivation such as filling substrate into plastic bags and harvesting is a labour-intensive exercise and can be done by women, which provides them financial independence and also self-respect (Zhang et al. 2014). Spent mushrooms substrate (material left after cultivation of mushrooms) is also a valuable by-product. It can be blended into fresh substrate and reused to grow mushrooms. Unprocessed spent substrate can be used as growing media for seedlings development. Spent substrate contains nitrogen, phosphorous and potassium (NPK) that are important components of organic fertilizer (Mz et al. 2016). Spent substrate is rich in crude protein, minerals such as magnesium, calcium, iron, vitamins and polysaccharides from the residual mycelium. This makes it a valuable additive to feed formulation for chicken and livestock. Spent substrate is also rich in the lignocellulose enzymes such as laccase, xylanase, lignin peroxidase, cellulase and hemicellulase, which can be extracted for biotechnological and environmental applications. Spent substrate can also be processed into vermicompost, briquettes, etc.

21.6 Conclusion

Population growth is a driver of food demand, affecting the quantity and quality of food available. The population of Namibia has been increasing steadily since independence, and this has led to food insecurity. The food insecurity in the country is not only a result of population increase but also that of the declining productivity of land since Namibian people depend heavily on traditional crop production and livestock for their livelihoods, both depend on land being productive. The country's present situation in terms of food production reveals that neither crop production nor livestock rearing is showing dominance to significantly affect food security outcomes for the country as both these agricultural activities depend on not only productive land but also good rainfall to thrive. With the ever-increasing population, depleting agricultural land, changes in the environment and water shortage, there is a greater need to diversify the country's produce to supplement the livelihoods of the people and address their food insecurity. There is a need to opt for alternative crops with a shorter production cycle in order to narrow the existing nutritional gap for households. In order to achieve food security, intensifying the production of quality food crops with shorter production cycle such as mushrooms is crucial.

Mushrooms being a superfood due to their essential macro and micronutrients that are required by individuals should be promoted. Since their nutritional constituent bridges between that of vegetables and meat, earning them a reputation as vegetable meat, they are a healthy choice food, even for vegetarians. Since the medicinal properties of mushrooms do not only enhance the health of individuals but prevent chronic illnesses associated with poor nutrition, their consumption should be encouraged. What is more, since mushroom production technology does not require much land or rainfall as mushrooms are grown indoors, it is an attractive venture for the people who are limited in terms of space and even those living at the coast where the supply of freshwater is rather limited. The surging interest among many farmers to adopt the mushroom cultivation technology is a good indication and paves the way for adoption and mass production of mushrooms in the country. Although at a rather slower pace, the mushroom industry is gradually taking root in

Namibia, especially among smallholder farmers, and given time, it will eventually make significant contribution to the agriculture sector in the country. Namibia has indeed incredible potential in mushroom cultivation; with the assistance of technological advancement, marketing and related education on technology, the production can easily be done on a large scale.

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Part V
Socio-agro Economy

Chapter 22
'Can Women Own Land'? Land Inheritances Convolutions: Evidence from the Zimbabwean Resettlement Areas

Kwashirai Zvokuomba and Kezia Batisai

Abstract The chapter examines women's land ownership experiences within the context of land reform in the Zimbabwean resettled spaces, focusing on how land previously owned by women in Masvingo district is passed from the principal owners to the next generations. Using African Feminist 'lenses', the chapter unravels the sociocultural and political factors affecting the transfer of land. As the chapter grapples with the question of and feasibility of land transference from women to women in a patriarchal ideological system, it adopts the feminist approach that best explains feminist experiences. The chapter reflects on the evidence-based findings by deploying the narrative inquiry as an epistemological locus for unearthing and capturing nuances about women's land inheritance matrix, bringing to the fore new trends and developments in resettlement areas. Central to this chapter is the argument that although on the surface it appears acceptable that women can own land, evidence-based data illuminates how patriarchal hegemony asserts itself and subtly reverts land back to males. It is against this backdrop that the chapter recommends continuous review and contextualised understanding of the patriarchal gender policies in order to drive transformative social change in the African agricultural sector aimed at enhancing productivity and improving women farmers' food security on the continent.

Keywords Widowhood · Land reform · Inheritance · Resettlement · Feminism

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22.1 Introduction: Contextualising the Gender Realities of Land Inheritance

Global wide land and agrarian reform literature is replete with contested evidence of women's partial and complete ownership of land (Deere and Leone 2003; Lastarria-Cornhiel 1997; Rurangwa 2013; Bryceson 2019; Batisai 2020; Zvokuomba and Batisai 2020). Despite showing less regard to women's land ownership rights, longitudinal studies in many South American countries, Asia and other parts of the Muslim world reveal a softened stance towards that gendered development (Deere and Leone 2003). African scholars acknowledge the positive impact of land reform on women land ownership over the years. A synthesis of literature reveals the rise in the percentage of Zimbabwean women who owned land prior to 1980 through to the early years of independence and in the post-2000 era—'from below 5% to about 18%' (Zvokuomba 2018, p. 173). However, these African scholars simultaneously expose the longstanding gendered ownership, particularly among widows who constitute a very small minority of beneficiaries in Zimbabwe (Chipuriro 2021); Rwanda (Rurangwa 2013); and Kenya (Karanja 1991). The African experiences are summed up in former President of Tanzania Julius Nyerere's remarks about how 'Women in Africa toil all their lives on land that they do not own, to produce what they do not control and at the end of the marriage, through divorce or death, they can be sent away empty handed' (Geisler 2004, p. 89).

Echoing Nyerere's remarks, Wanyeki (2003) documented women's experiences in Cameroon, Ethiopia, Rwanda, Kenya and Tanzania where land ownership and inheritance by women is constricted due to gender-based discrimination. Women in most parts of Africa have gendered access to usufruct rights on their fathers' or spouses' land (Wanyeki 2003). While the usufruct rights enhance women's productivity, scholars point at the precariousness of these rights as they can be lost in the event of life-changing moments such as divorce and widowhood (Wanyeki 2003; Msiyazviriyo 2016; Batisai 2020; Chipuriro 2021). An analysis of both colonial and postcolonial experiences in Southern Africa reveals that the complexities of women's ownership of land arise from cultural practices and the legal system which is yet to be reformed. The practices and system must be modified to suit and prioritise the needs and interests of women (Chingarande 2012; Batisai 2019) and ensure that their livelihoods in land reform processes are not compromised in order to break the cycle of poverty (Chipuriro 2021).

While most African societies fit into Nyerere's characterisation of the gender relations in an African agrarian setting, Gaidzanwa's (1995) observation that women generally outlive men brought an interesting dimension in relation to the surviving spouse passing on land to the second generation. The concept of inheritance (*nhaka*) in Zimbabwe and within the wider African context refers to '. . .the transfer of property from an heir or after the property owner is deceased' (Hoebel 1966, p. 424). In agrarian settings, the transfer of land from one person to another becomes a means for individual or family empowerment or exclusion from the accumulated physical capital. The chapter examines women's land ownership experiences within the context of land reform in the Zimbabwean resettled spaces, focusing on how land previously owned by women is passed from the principal owners to the next. Drawing on evidence-based data from Masvingo district, the chapter specifically interrogates the issue of property transfer from one generation to the other, regarded as the intergenerational transmission of resources (Bird and Pratt 2004).

The chapter adopts Ploeg's (2008) conceptualisation of smallholder farmers as those engaged in peasantry production, whose sustainable way of production is attuned to ecological capital. While some smallholder farmers may use other sources to fund production and hire labour, family resources are at the centre of production. The chapter adopts Moyo et al. (2008, p. 3) definition of land reform which has three components, '...namely, land distribution, land restitution and land tenure changes...' whereas agrarian reform on the other hand deals with the broader political economy in the countryside. Therefore, land reform in its narrow sense depicts a state of legal and policy changes with respect to rights affecting access and control over land. The ultimate aim would be to transform the land ownership patterns. Putzel (1992, p. 3) broadened this definition and included changes in both legal and customary rights to land, '...which define the rights of those who own or use agricultural land.' Thus, ownership in this context is conceived as a bundle of rights representing varying degrees of control of land, including the right to possess, use, manage, transfer, sell and earn an income from that land (Chiweshe et al. 2014). Contextualising this argument, land reform in Masvingo district refers to both the outright redistribution of the entire bundle of rights over land to those who cultivate the soil, as well as single adjustment of the conditions under which a tenant or other cultivators gain access to land. Using African Feminist 'lenses', the chapter unravels the sociocultural and political factors affecting the transfer of land. The chapter grapples with the question of and feasibility of land transference from women to women in a patriarchal ideological system; and through the narrative inquiry, it reflects its epistemological locus and captures nuances about women's land inheritance matrix.

22.2 Epistemological and Theoretical Framing

Guided by the African feminist theory, the study in Masvingo district grounded the research in feminist epistemologies to ensure that women's voices are heard, and their experiences of the land reform are deeply understood. Furthermore, utilising the African feminist model meant the deployment of Afrocentric 'lenses' (Asante 2000) in a way that challenges traditional positivist epistemologies that contribute to women's marginalisation (Tamale 2011). The study adopted Karam's (1998, p. 5) definition of feminism as '...an individual or collective awareness that women have been and continue to be oppressed in diverse ways for diverse reasons, and attempts towards liberation from this oppression...' The chapter acknowledges the existence of various feminist brands of which some are not best positioned to explain African issues due to their Eurocentric orientation. It is against this backdrop that the chapter adopts African feminism, which is about viewing the 'sociocultural and political' scene from the vantage position of African women.

The research site is Masvingo district in which the City of Masvingo is located. The resettlement sites are found on the north, south, east, and west of the city and Masvingo district is generally a land for the Karanga ethnic group of the Shona people known for strong beliefs in patriarchal ideology. The practicalities of data collection were influenced by several scholars who strongly believe in Afrocentric feminist research epistemologies that acknowledge the centrality of women in knowledge production (Oyeronke 1997; Asante 2000; McFadden 2000; Bakare-Yusuf 2011; Tamale 2011; Chisaka 2013). The rationale for adopting the qualitative feminist research methods was to capture power and unpack relational issues in land ownership since gender issues are fluid and require the flexibility in qualitative research. Qualitative feminist research allows considerable space for the actual 'voice' of participants to be part of the knowledge creation process, which is central in the grounded theory where reality from the ground filters up and becomes part of the building blocks of new theory (David and Sutton 2011). In this study, the approach allowed the investigation processes to have a deep engagement with participants and produce authentic accounts as they constructed their social reality, complemented by the authors' interpretation of their stories. Hence, the authors' views and feelings, including the critical self-reflections, became part of the research data.

The study used purposive sampling and identified 10 women landowners and explored their 'lived realities' and how the transference of land to the second generation occurred. This reflexive sampling technique allowed for data generation from a 'naturalistic stance' emphasising on seeing things from the perspective of those studied, similar to classic qualitative ethnographic work by Malinowski, Radcliffe-Brown, and Mead. Thus, the researcher 'excavated women's voice' from below the patriarchal covering in resettled spaces. The methodological framework of 'excavating women's voice' (Zvokuomba 2018) borrows from Foucault's (1972) work on 'The Archaeology of Knowledge' which does not necessarily mean the geological excavation but the extracting of voices. In the context of the research in Masvingo, it is the women's voice that was brought out from underground to inform the creation of social reality and knowledge that enhances land ownership, productivity, and food security. Although ten women landowners were interviewed, the chapter selectively directs its lenses at four specific cases deemed rich enough to unravel the sociocultural and political dynamics of land transfer.

22.3 Reflections from Women Smallholder Farmers in Masvingo District

The sections below thematically analyse women’s land ownership complexities in the Zimbabwean resettlement areas, which is an attempt at answering conceptual and empirical questions around gendered land transference. As the chapter grapples with the issue of women land ownership, it directs its lenses at specific cases, the first one representing the nexus of widowhood, witchcraft, and land ownership. The second case analyses how women land ownership became an outcome of the deployment of the idiom of ‘honorary husband’, the third and fourth cases represent seemingly simple cases of women becoming landowners but simultaneously become part of the preparations for male takeover in intergenerational land transfer, as further debated below.

22.4 Rural Food Security-Witchcraft Nexus

The evidence-based data from resettlement areas in Masvingo district showed the connections and linkages of women land ownership in household food security and witchcraft. The case of two widows (mother-in-law and daughter-in-law) brought debatable dimensions of women land ownership and food security. The mother-in-law had lost her husband some decades ago while they were already in the resettlement scheme. They had been gifted with only one child, a son who in turn married and continued to reside with her mother and wife on the same land. However, the son died in South Africa leaving a young wife and two male children. Relatives had initially accused the grandmother (mother-in-law) of having bewitched her husband so that she could inherit the land, accusations which she contested. Despite the contestation, the relatives of the deceased did not want her to inherit the property because they strongly believed that the widow was a witch. Her only son, based on Shona customs, became the automatic heir to the estate. However, his untimely death in a road accident in South Africa resulted in double widowhood in one household and further witchcraft accusations.

By the time of our field visit, *divisi* was communally framed and believed as the direct cause of death of the mother-in-law’s husband and son. *Divisi* is a Shona term which refers to farming witchcraft or the use of magic or *muti* (medicine) to enhance crop production and/or increase the number of livestock, especially in rural communities (Humbe 2018). Further conceptualisations acknowledge that *divisi* in most cases encompasses *mubobobo*, a form of mysterious sexual conduct on unsuspecting victims to enhance productivity (Humbe 2018). Sibanda (2013) refers to it as experiencing sex via ‘blue tooth’ due to the mysterious sexual contact. Chireshe et al. (2012) posit that the term *divisi* could have been derived from the Shona word *kutiva*, literary meaning dipping, whose connotations are about having sexual intercourse in a metaphoric usually abnormal manner such as incest, bestiality and/or homosexuality or having unprotected sex with a woman who is on her monthly period. Thus, *kutiva* depicts the wickedness of the nature of the sexual encounter and is powered by the desire to accumulate more resources than others. Therefore, based on their high-level productivity in the fields which was outstandingly better than other farmers, the widows were accused of using the *divisi* form of witchcraft to boost their production. The community held the belief that the mother-in-law was having a mysterious sexual contact with her son, which magically contributed to producing a bigger harvest than others. Hence, it was believed that the *divisi* magic caused the death of the victims, first her husband and eventually her son. Narratives of some research participants further pointed to the fact that the magic would allow the witch to wake others up during the night without their knowledge and have them work on the witch's field such that they would be tired to work on their land the following day, which explained their low productivity.

According to Chavunduka (1997), Zimbabwean societies believed in farming witchcraft since time immemorial. The Morris Carter Land Commission of 1925 referred to a case of witchcraft in which Elizabeth Musodzi and her family were believed to be using *divisi* for better farming. Giving evidence to the Commission, Father Burbridge, a Jesuit Priest in Harare, reported how successful Elizabeth did her farming and even supplying a factory with grain for oil production in the early 1900 (Yoshikuni 2008, p. 7). 'All the other put her success down to the magic and ask her to supply them with seed which they believed assumed must have been doctored with *divisi muti* to produce such good results' (Yoshikuni ibid). This chapter echoes Chireshe et al. (2012) observation that witchcraft accusations in Zimbabwe are grounded in gendered power struggles given that women who challenge male power are believed to be witches. The two widows' success in agriculture challenged patriarchy and male hegemony, and for that reason, their success was projected as evidence of engagement in *divisi* farming.

Although Izumi (2007) argues that witchcraft may be used to cause death or inflict pain on competitors in the inheritance issues, positive witchcraft was allegedly used in the context of this study to protect women's land and enhance their production levels. However, magic and witchcraft did not have any bearing on the gender of the next generation to which land would be transferred. It was almost pointing to the sons of the daughter-in-law who were still young and the only children in the household such that transference of land was towards the male generation, which would mean that land ownership by a woman in this case would have only been experienced for one generation.

22.5 Women’s Land Ownership Through the Idiom of Honorary Husband

Mrs. Chuma’s widowhood after the death of Mr. Chuma left her to fend for six children on her own in the resettlement areas. Since Mrs. Chuma was relatively young, in her late 30s, the family of her deceased husband proposed that she reverts to her natal home as it was not culturally good for a young woman to live in an unfamiliar territory. The reasoning behind this idea from the deceased’s relatives was to allow one of his brothers to take over the land as a way of preserving family heritage. Upon realising that the widow was not giving in to subtle ways of dispossessing her of the land, they did not support her in the change of ownership processes at the Ministry of Lands’ registers as they argued that it was ‘too early’ to do so since the death was still ‘fresh’. However, Mrs. Chuma, fully alert to the family members’ inheritance interests, hatched a plan with the late husband’s sisters traditionally known as lineage daughters (Amadiume 1987).

Amongst the Igbo and Yoruba in Nigeria, like in many African families, the lineage daughters are known for their power and influence as they either protect or worsen fellow women’s situations (Oyeronke 2003; Amadiume 1987). In this study, the powerful aunts were in favour of their sister-in-law, Mrs. Chuma, and they appointed her eldest son aged 15 to be the ‘honorary husband’. The term honorary, in ordinary daily usage, is a title or membership given to someone without the necessary qualifications or prerequisites, but consideration is given to their public achievements. In the context of widowhood and land security, either a widow’s biological young male child could be appointed to be the honorary husband, or an aunt could be a ‘female husband’ to her late brother’s widow and act ceremonially as the father figure in the family, constituting another form of honorary husband (Zvokuomba and Batisai 2020). Honorary husbands in Africa are a contradiction of Western female-to-female relations, which in some instances become romantic and sexual; hence, the argument that Afrocentric feminism is best attuned to explain the lived realities in Africa because Western feminism has different conceptual meanings to African settings (Zvokuomba and Batisai 2020). Drew et al. (1996) made similar observations in Nyanga district, Zimbabwe.

Honorary husbands in the form of aunts in Uganda, like in the Zimbabwean context, serve the same protective purpose despite other aunts in the family being perpetrators of women marginalisation (Izumi 2007). This echoes Amadiume’s (1987) seminal observation that lineage daughters could worsen fellow women’s situations, put across by the Women and Law in Southern Africa Zambia (1989) as ‘today’s grabber is tomorrow’s victim’. Arguing from an Afrocentric feminist perspective, the chapter concurs with Oyeronke (2003) that women’s land ownership in Africa depends on how they navigate and negotiate the cultural landscape. The case of Mrs. Chuma depicts the relevance of an Afrocentric feminist standpoint to our understanding of how she subtly deployed an acceptable cultural practice as a strategy to protect her land and safeguard her livelihoods. On visiting this homestead during fieldwork, the researcher established that the son, despite his age, was regarded as the ‘father figure’ and was being prepared to enrol with an agricultural college soon after completing ‘O’ level to become a competent and professional agriculturalist. This dimension of a ‘father’ figure is enough evidence that women’s land is on its way into the hegemonic power of patriarchy. Thus, the chapter grapples with the question whether women can own land and pass it on to the next generation of females? Evidence-based data from the resettled spaces suggests that intergenerational land inheritance is a complex cultural process that continues to be influenced by patriarchal ideology. Consequently, patriarchy reasserts itself in agrarian settings despite concerted efforts to promote women’s land ownership.

22.6 Women Land Ownership: Woman Heir in the Rural Enclave

Ester was disowned by her late husband’s family and had to return to her natal family where she eventually became an heir and landowner. After Ester’s father had passed on in the late 1990s, her mother became the principal landowner in the Masvingo resettlement area based on the Shona tradition of *nhaka,* which means inheritance. The traditional practice depicts a broad spectrum of issues given that it may mean inheriting the property left by the deceased and/or including his surviving spouse and children. However, by the time of the field visit, Ester’s mother had passed on leaving her at the centre of the inheritance matrix. While the rest of her siblings were living with their families of marriage, Ester had become a ‘returnee’, which refers to women who go back to their natal home and live under *samusha*, a hereditary leader of a family or clan (Zvokuomba 2018; Zvokuomba and Batisai 2020). With two of her male children, she managed to take care of and utilise the land to full capacity as production levels remained high. A conversation with Ester about land ownership by women revealed that she was not sure if land would continue to be transferred to females in future.

The patriarchal system, unlike a matrimonial kinship ideology that dictates that land is strictly transferred to women, does the opposite, or at least remains gender-neutral without guaranteeing the upholding of a feminist land ownership philosophy. Outstanding gendered aspects about land ownership in Ester’s case were that it originally belonged to the man but was transferred to a woman upon the death of the original owner, and in that case, the widow only became a landowner because of her marriage to a male figure. However, upon the death of all her parents, Ester took the stewardship of the land, and eventually became another female in the line of family inheritance. Could this case be enough proof and be generalised that ‘women can own land’ and facilitate intergenerational land transfer to other women?

Even though a percentage of women now own land in their right from the point of land redistribution (Mutopo 2014; Zvokuomba 2018; Zvokuomba and Batisai 2020), many continue to only have usufruct rights under the control of males. Contrary to Mutopo (2014), Chipuriro (2021) argues that encroachment into women’s land by male relatives undermines the security that they should enjoy after benefiting from land redistribution. In addition to usufruct rights, another percentage of women owns land through inheritance which operates as a double-edged sword facilitating that those women either become landowners or lose it because of the complexities of inheritance. Upon the death of the husband, these complexities compel women to deploy traditional practices such as the 'honorary husband' phenomenon (Zvokuomba 2018). The honorary husband, as alluded to earlier, serves as a 'father figure' whose role is to protect the family and its resources, including protecting the land, from being plundered by other extended family members.

While these cases represent a shift in society towards accepting the practice of women owning land, there is no guarantee that the same land could remain in women's control and ownership. The chapter, therefore, argues that patriarchy gently waits for an opportunity to revert the same land to the males in intergenerational land transfer politics. The ambiguity around the intergenerational land needs of the resettled households compelled elderly women farmers in Chipuriro's (2021) study in Mashonaland Central, Zimbabwe, to resolve the policy gap on their own and ensure that the agrarian needs of their growing households are catered for and guarantee future productivity and food security.

22.7 Single Women, Land Ownership and Livelihoods

This section of the chapter focuses its analytical gaze on the case of a single woman, Mai Suzana (Suzana's mother), whose four daughters were allocated land in her own right during the 2000 Fast Track Land Reform. Mai Suzana left her natal home in search of land during the land redistribution phase because she did not have a place of her own. She struggled in the early years as the 'journey' was not easy for a woman during the *jambanja*, the chaos and violence that characterised land redistributions (Matondi 2012; Chipuriro and Batisai 2018). She narrated her ordeal of having to stay in a makeshift hut for a long time, which did not protect her from the rain; and the challenges of taking care of her school-going last-born child. Mai Suzana also gave a general overview of the contestations around sexual abuse in the new settlements. The overview resonates with Andrew Meldrum's report in the *Guardian Newspaper* of 18 March 2003, which described how women were sexually abused in new farms.

Although Mai Suzana was not forthcoming to discuss about transactional sex from a personal point of view, her vivid recollection of the early days of *jambanja* point to scenarios in which some widows and single women engaged in sexual encounters to protect their land and livelihoods in the farms. The generic interpretive meaning of her narrative, 'todii tisina varume' (what can we do as women when we are not married) could be that engaging in sexual encounters is a normal activity for unmarried women. However, in the context of land and livelihoods, it is a survival strategy—a means of protecting their land and existence in the farms. The argument resonates with the preceding observation that some women get into marriage as a form of protection and securing livelihoods although it exposes them to HIV infection (Calves 1999) and sexual violence (Chipuriro and Batisai 2018). When gazed at from another angle, Mai Suzana's case reveals common underlying gendered issues about women subjugation, particularly the dispossession of widows' property in communities as unique aspects of societies trying to assert some cultural identity, riding on abuse of the same culture to satisfy personal interests bordering around greed and jealousy (Young 2006).

22.8 Synthesis: Yes, Women Can Own Land But...

This chapter trekked the deployment of traditional cultural practices and other mechanisms as strategies for women land ownership in Zimbabwean resettled areas. Women have understood the art of being part of the political movements at local, regional, and national levels which strategically protect them from the vulnerability associated with being women in a patriarchal system. Literature ascertains that at the disposal of women has been the new culture in which they use civic organisations, policies, and the law to own land and protect their interests (Matondi 2012; Scoones et al. 2010; Zvokuomba and Batisai 2020). Combined, the foregoing realities of women who fight for their land and eventually benefit from it and migrate to middle-class farmers or successful farmers represent and confirm the fact that women can own land, and this has become an acceptable reality in rural communities. However, amidst the progressive reality about women owning land has been the proof that the same women may only have total control over land for a shortened period.

There is evidence of a societal system that does not have a mechanism to sustain the same gendered land ownership patterns through generational land transfer, neither is there a law or policy to that effect. Consequently, the chapter argues that land may 'slide' back into the hegemonic control of patriarchy through family and lineage land management arrangements, especially after the death of the principal woman owner. There is need to adopt a women-friendly inheritance system in Zimbabwe as an alternative land ownership arrangement to keep the land in the hands of women when the principal woman owner has died. This recommendation resonates with the policy alternatives raised by (Chipuriro 2019) among other African Feminist scholars at the 2019 Agrarian Studies Summer School in Harare, Zimbabwe. It is envisaged that the women-friendly inheritance system, as previously observed by other African Feminists (Kameri-Mbote 2009; Tsikata and Amanor-Wilks 2009), will promote gender equity in land inheritance and help resolve the current gendered patriarchal dilemmas and complexities that women face. For instance, in all the four cases that constituted the debate about women land ownership in this chapter was the preparedness and readiness of patriarchy to take back land in subtle ways and means. The same traditional cultural practices turn their energies towards the allocation of the same pieces of land to males, especially in intergenerational land transfer. The analysis of the four cases in this chapter illuminated that even women themselves prepare their male children or grandchildren for the eventual takeover of land when they pass on, a practice they do with disregard of female children.

An in-depth analysis of the gendered intergenerational land transfer phenomenon paves way for responding to the central question in this chapter: can women own land and pass it on to the next generation of females? The response to the conceptual and empirical question above is deeply rooted in the gendered patriarchal socialisation of children and its subsequent effects on the transference of land. In particular, the gendered dynamics of land transference are driven by the culture that natal families do not prepare women for land inheritance because they will be expected to leave their families upon marriage and start a new life with their spouses away from home. The gendered realities of land transference echo how families traditionally trivialised and 'mapped a girl's educational path to parallel her becoming a woman' (Batisai 2013, p. 88). This was heavily influenced by the *mupfumbidzakumwe* phenomenon – the cultural belief that 'girls make other families rich upon marriage, whereas boys look after the family [i.e.] boys are capable of establishing and sustaining families' (Batisai ibid). In the context of intergenerational land transfer, the gendered patriarchal ideological position is also based on the cultural societal view that giving the female child land, like educating her, means giving away family property to another family, which she marries into at some point. Consequently, female children, based on this gendered ideology, are not considered as benefactors in the land inheritance matrix. The foregoing analysis reveals the power of cultural socialisation in nurturing women as non-benefactors such that the gendered preparation of their male children and grandchildren to become the next generation's owners of land emerges as normative.

22.9 Conclusions

Women's land ownership in many patriarchal systems has been and remains a contestable aspect of human life. However, legislative reform and the pervasive modernity wave caused an alteration of certain die-hard traditions such that women are now accommodated in the land ownership systems of agrarian societies. This chapter has demonstrated, through the documentation and analysis of women's lived experiences and realities, that women can become principal landowners be it through inheritance cultural practices such as the honorary husband phenomenon or other mechanisms. The four cases illuminated how communities have shifted towards a progressive gendered approach that accommodates women who were traditionally deprived of the chance to own land. Irrespective of the magnitude, the acceptability of women as owners of land in their own right points to the positive societal transformation that drives and brings about social change in the African agricultural sector aimed at enhancing productivity and improving women farmers' food security on the continent.

However, the same case studies analysed in this chapter demonstrated pervasive and subtle cultural hegemonic power of patriarchy as an institution. While women may be legally and culturally allowed to own land, patriarchy makes sure the same land reverts to its original owners, the males in a particular society. The chapter demonstrated that even women, as products of patriarchal socialization, tend to nurture their male children for the takeover of the family land and other properties. Thus, in terms of intergenerational land ownership, land always finds its treks into men's world, hence, the conclusion that women's land ownership is restricted to certain periods in life while total control over the same land remains a patriarchal privilege and dividend. On the surface, it appears acceptable that women own land but evidence-based data illuminates how patriarchy asserts itself and transfers land back to males even in subtle ways. While there is no doubt that ownership of land by women is a reality of the times that is central to gendered livelihoods debates, the chapter concludes that there is no guarantee that the same land may remain in the custody of women. Therefore, we argue that there is need to maintain the momentum of legally prioritising women in land ownership discourses and inheritance policies that contribute to the deconstruction of cultural practices; and reform the legal system that undermines women's land ownership. Compromising women's livelihoods in land reform discourses and processes entraps them in the circle of poverty as agricultural productivity and food security are simultaneously undermined and remain a distant reality in Zimbabwe and other African contexts.

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Part VI
Agricultural Policy

Chapter 23
The Governance of Aquaculture in Namibia as a Vehicle for Food Security and Economic Growth

Johannes Angala Iitembu, Ndakalimwe Naftal Gabriel, Martin Tjipute, Hiskia Asino, and Johannes Hamukwaya

Abstract The Namibian aquaculture sector is still very small, but it has the potential to act as a vehicle for both food security and economic growth for the country. The governance structure in place regulates matters such as public health, environmental protection, animal health and disease. The aquaculture license includes the classical bundles of property rights such as transferability, renewability, specified duration and cancellation based only on failure to perform. However, aquaculture land ownership/leasing is not sufficiently regulated to encourage long-term investment into aquaculture. Freshwater aquaculture has the potential to contribute to food security, but the absence of differentiation between community-based and commercial farming creates regulatory burdens which cannot be easily be met by prospective small-scale fish farmers. The strict regulatory requirements for importing new species limit the opportunity for growth that can be achieved with fast-growing non-native species. Mariculture can significantly contribute to economic growth, but a significant part of the value chain needs to be localized. Aquaculture investors, just like those of its sister sector (agriculture), require a regulatory framework that gives sufficient tenure security and ascertainable property rights, an important requirement that appears to only partially be met by the Namibia aquaculture governance structure.

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23.1 Introduction

Fish and aquatic products are considered the most valuable traded food commodities internationally (Davies et al. 2019). Internationally, aquaculture is also regarded as the fastest-growing fishery sector and has now surpassed that of capture fisheries (FAO 2020). Aquaculture in Namibia started in the 1980s by introducing carp and several other exotic species for stocking of cattle dams and state water dams (Iitembu 2005). An increase in aquaculture began in the 2000s onwards because the private sector became more involved in commercial farming, especially marine species (Iitembu 2005) (Fig. 23.1). After Namibia's independence in 1990, the government identified aquaculture as a priority development through development plans such as Namibia's VISION 2030 and National Development Plan (NDP). In May 2004, the Ministry of Fishery and Marine Resources produced the first Aquaculture Strategic Plan, built on the existing Aquaculture policy, the Aquaculture Act and its regulations.

Although progress has been made in marine and freshwater aquaculture in Namibia, its production levels are still not comparable to capture fisheries, which averages 450,000 metric tons per year (FAO 2019). While the aquaculture sector is still relatively small in Namibia, it has a huge potential given the changing fish-eating habits of the population (Erasmus et al. 2021; York and Gossard 2004), whose demand need to be met. It is well known that much of the cost of aquaculture is

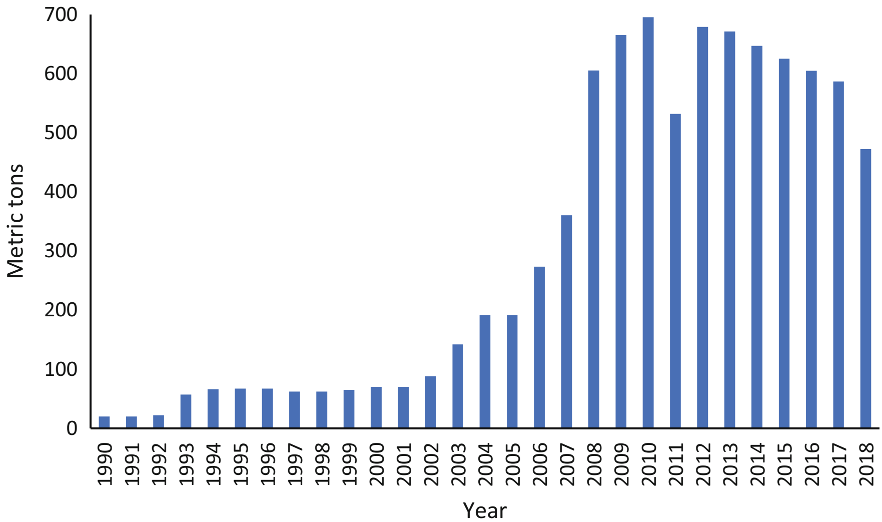

Fig. 23.1 Aquaculture production from Namibia (1990–2018) (Data source: World Bank)

incurred to meet the feed requirements. Namibia here also potentially enjoys a competitive advantage because of its established capture fishery and the nutrient-rich Benguela ecosystem (Hutchings et al. 2009), which can act as a source of cost-effective fish feeds.

However, for aquaculture to grow, its governance frameworks must be pro-growth and must ensure aquaculture's continued contribution to food security in Namibia is promoted. The absence of effective governance has, for example, led to the boom and bust experienced in shrimp aquaculture in the 1990s (Arquitt et al. 2005). Significant environmental degradation experienced from aquaculture in countries like India has also been attributed to a lack of adequate regulatory frameworks (Belton et al. 2017). The regulatory frameworks for aquaculture must be explicit to support the sustainability and legal certainty of the aquaculture growth path. In this chapter, the status of marine and freshwater aquaculture in Namibia is presented. Their regulatory frameworks are also presented in consideration of aquaculture as a vehicle for food security and economic growth in Namibia. Recommendations for future directions in aquaculture in Namibia are also made.

23.2 Aquaculture in Namibia

23.2.1 Marine Aquaculture

The Namibia marine aquaculture industry is found within the waters of the Benguela marine ecosystem. One of the Benguela Current's main characteristics is the wind-driven coastal upwelling which brings nutrient-rich deep water to the surface (Carr and Kearns 2003). While upwelling is a dominant oceanographic process in the Benguela Current area, other features include the leakage of warm Angola Current water from the north (Gammelsrod et al. 1998), hydrogen sulphide eruption and red tides (Weeks et al. 2004). The Benguela Current ecosystem is one of the most biologically productive regions of the world's oceans, supporting large commercial fisheries due to its high primary productivity (Hutchings et al. 2009. The marine waters off Namibia, though productive, are subject to several human activities, including offshore mining, oil and gas extraction, and fishing (Finke et al. 2020). There are few aquaculture sites for aquacultures along the Namibian coastline, which include the only two sheltered embayments in the country (Lüderitz and Walvis Bay), and shore-based aquaculture restricted to Lüderitz, Oranjemund, Walvis Bay and Swakopmund (Britz et al. 2019) (Table 23.1).

The Namibian commercial marine aquaculture is relatively small, with a total production that has been constant at around 600 tons/y since 2008 (Britz et al. 2019). The main farmed species are oyster (*Crassostrea gigas*), mussel (*Mytilus galloprovincialis* and *Perna perna*) and abalone (*Haliotis midae*).

Marine farming experienced a boom in the 2000s because of government incentives to invest in aquaculture and establishing the Aquaculture Park as per Aquaculture Act 2002 (Act No.18 of 2002). However, sulphur eruptions in 2008 and 2010 in Walvis Bay (Ohde and Dadou 2018) led to mass mortalities resulting in many operations going out of business.

Table 23.1 The farmed species and locality of marine aquaculture operations (December 2017) (Information source: Britz et al. 2019)

Species	Locality
Abalone *Haliotis midae*	Lüderitz
Oysters *Crassostrea gigas*	Lüderitz, Radford Bay
Oysters *Crassostrea gigas*	Walvis Bay Aquaculture Park
Mussels *Mytilus galloprovincialis* and *Perna perna*	Walvis Bay Aquaculture Park
Oysters *Crassostrea gigas*	Swakopmund salt works
Oysters *Crassostrea gigas*	Oranjemund

23.2.2 Freshwater Aquaculture

Freshwater aquaculture can trace its roots to the late 1800s by introducing carps, bass, and tilapia in private and state dams (Iitembu 2005). The freshwater aquaculture sector took off in mid-1990 when the government established community-based intensive freshwater aquaculture facilities in Omusati, Okavango and Caprivi region, producing tilapia and catfish for local distribution. Although still at an infant stage, this sector has been envisaged as the most significant production source by the year 2030 (Failler and Tall 2012). The freshwater aquaculture sector is primarily community-based, emphasizing promoting food security, creating employment, and generating income for the community members (MFMR 2004). Namibia has no small-scale or subsistence freshwater aquaculture tradition, so all activities in this sub-sector have been government- or donor-driven. Under the Directorate of Aquaculture, the Ministry of Fisheries and Marine Resources manages several fish farms, most of which are located near catchment areas as there are few privately owned fish farms.

Namibia's natural water bodies have several species that might have great potential for aquaculture. Species selection for aquaculture is based on certain criteria, including the growth rate, length at maturity, feeding, stocking density, and market price. Species being cultured include the three-spotted bream/tilapia (*Oreochromis andersonii*), red-breasted bream/tilapia (*Coptodon rendalli*), the African catfish (*Clarias gariepinus* and *C. ngamensis*), all of which are endemic. The exotic species cultured in Namibia are the Nile tilapia (*O. niloticus*) and Mozambican tilapia (*O. mossambicus*), and common carp (*Cyprinus carpio*). These exotic species have excellent traits that make them attractive for aquaculture, such as exceptional growth potential, hardy and ability to thrive in high stocking densities. They also have a high market demand.

Data on Namibian freshwater aquaculture is scarce, and the annual production reports are few and far between. Hamukwaya (2021) report indicated production of 36.9 tonnes for the year 2011, mainly from government-managed fish farms, with the combined production output (government and private fish farms) at more than 50 tonnes per annum. Most of the production yield comes from the Tilapia species.

In Namibia, freshwater aquaculture uses various production systems such as ponds, cages, and recirculation aquaculture systems (RAS) using tanks. The pond systems, being the oldest production method (Brune et al. 2003), are widely used and provide natural productivity. The RAS is mainly deployed at hatcheries managed by the MFMR. RAS is becoming the key technology (Ebeling and Timmons 2012) and one of the fastest-growing fish rearing systems (Martins et al. 2010), especially to produce larvae and juveniles of diverse species. The sites that are suitable for a cage culture system include the national dams and disused mine pits (e.g. Uis tin mine pit), which are filled with water sipping from underground aquifers.

23.3 Governance of Aquaculture in Namibia

23.3.1 Governance Institutions

Regulatory frameworks are essential for the aquaculture industry to operate under the circumstances, giving predictable and stable working conditions (Davies et al. 2019). In Namibia, aquaculture is regulated under the Aquaculture Act (No.18 of 2002) ("Aquaculture Act" hereinafter), which designates the Namibian Ministry of Fisheries and Marine resources as the competent authority. Other institutions involved in aquaculture governance include the Ministry of Environment, Forestry and Tourism (MEFT), as aquaculture is listed as one of the activities that may not be undertaken without an environmental clearance certificate in terms of the Environmental Management Act (No 7 of 2007) and its Environmental Impact Assessment Regulations(Government Notice 30 of 2011). The above is vital as it can avoid environmental degradation experienced by aquaculture in countries like India (Belton et al. 2017). The Ministry of Agriculture, Water and Land Reform (MAWR) is responsible for veterinary services, and is also involved when a case of fish diseases or harmful aquatic organisms is reported in the specific aquaculture facility or area to advise on the steps that need to be taken to isolate, quarantine or treat the infected aquatic organism (Section 25 (2) of the Aquaculture Act). The Ministry of Health and Social Services, responsible for public health, also advises where harmful or detrimental effects to the aquatic environment or aquaculture from pollution or natural phenomena are reported (Section 26(2) of the Aquaculture Act). The Ministry of Health and Social Services may also advise whether the aquaculture products farmed are fit for human consumption; if they are not, the Ministry of Trade gets involved in preventing the sale or marketing of such aquaculture products. The Minister of Fishery must also consult the local authority (under Local Authorities Act, 1992 (Act No. 23 of 1992)), the regional council (under Regional Councils Act, 1992 (Act No. 22 of 1992)), or The Traditional Authority (under Traditional Authorities Act 2000 (Act No. 25 of 2000)), when determining or implementing aquaculture policies and regulations.

23.3.2 Licensing Requirements

The Minister of Fishery and Marine Resources, in consultation with the aquaculture advisory council, may declare any area of Namibia or Namibian water as an aquaculture development zone (ADZ) (Section 32 of the Aquaculture Act). A farming license is required for any location or area in Namibia, created for the primary purpose of aquaculture or to encourage aquaculture development. In terms of geographical scope, the license can be granted for any area within inland waters, the internal waters, and Namibia's territorial Sea (Territorial Sea and Exclusive Economic Zone of Namibia Act, 1990 (Act No. 3 of 1990)). The above also include areas from the seabed up to the high-water mark and private water as defined under section 1 of the Water Act, 1956 (Act No. 54 of 1956).

Aquaculture can only be conducted with a license (Section 11 of the Aquaculture Act), which must specify the organism to be farmed, including whether freshwater or marine. The prescribed application form further requires the applicant to specify the location, size, and description site, sources of the stock of the species, maximum annual production in quantity and weight per year, and the annual quantity effluent from the farm (Aquaculture (Licensing) Regulations, Government Notice 246 of 2003).

In deciding to grant the license, consideration is given to the technical and financial ability of the applicant; the proposed species to be farmed; the farming method and any other relevant matters applicable to the license applied (Section 12 (3) of the Aquaculture Act). The granting of the license can only be granted if the approval required land or water and environmental clearance and if the license will not create a significant risk of pollution or otherwise adversely affect the environment (Section 13 of the Aquaculture Act).

23.3.3 Property Rights in Aquaculture

One of the important aspects of aquaculture governance is the security of the farmers' interest (property rights) (Bankes et al. 2016). For the aquaculture right to function as a real property right, it must be transferable, duration and renewability must be specified, and its cancellation must only be based on failure to perform or meet the specified conditions (Saunders and Finn 2006).

The license issued in terms of the Aquaculture Act is only transferable with prior approval by the Minister (Section 23(1) of the Aquaculture Act), and the licensee is given the exclusive right to farm and harvest aquaculture products, the exclusive right to own the aquaculture products within the approved site; and the exclusive right to release and harvest aquaculture products within the specified site (Section 14 of the Aquaculture Act). The farmed organisms in farming sites and those that have escaped into the natural environment are the exclusive property of the licensee if they can positively be identified (Section 31 of the Aquaculture Act). The duration of the issue license is specified, and the Minister of Fisheries may make regulations concerning the duration of any licence and the renewal conditions (Section 43(2)(c) of the Aquaculture Act). An aquaculture licence is currently issued for 5, 10, 15, 20 or 25 years at the Minister's discretion.

In terms of the renewability of the licences, it can be refused if the licensee has not complied with the conditions of the license or has not remedied non-compliance within a reasonable period (Section 18(3) of the aquaculture Act). The renewal can also be refused, for the purposes of aquaculture management, to ensure the protection and conservation of the environment (Section 18(3) of the Aquaculture Act). In terms of revocability, for a license, this can be done on a similar basis as the renewal refusal. However, the basis for cancellation also includes failure to report the presence of any disease or harmful organism, failure to treat or destroy any aquatic organism or parasite-infested organisms (Section 19 of the Aquaculture Act).

Overall, the Namibian aquaculture property right regime has the general attributes of real properties rights, although issues related to leases of land for aquaculture are not clearly regulated, especially in communal areas where land is governed under a different property right regime (see Communal Land Reform Act 5 of 2002).

23.3.4 Aquaculture Management and Control Measures

Although aquaculture is one of the fastest-growing sectors globally, it has biosecurity risks and hazards it poses to the aquatic environment and society (FAO 2008). As aquaculture development increases, the possibility of a major disease also increases (Bondad-Reantaso et al. 2005). Aquaculture's possible environmental impacts may include direct pollution problems, waste from feed and faeces, medications, and pesticides (Read and Fernandes 2003). Some aquaculture species introduced because they offer more economic gain may threaten or damage the local ecosystems (Yan et al. 2001), including changes to the desired genetic diversity (Vanina et al. 2019). Therefore, the governance frameworks for aquaculture management and control measures mitigate or eliminate these risks.

In terms of the presence of any disease or harmful organism, a licensee or other person is required to report (Section 25 of Aquaculture Act) immediately; the failure to report such can be used as a basis to cancel the license (Section 19 (1)(e) of the Aquaculture Act). The farmers are also required to establish and maintain a water monitoring system that ensures timely detection of any event that may have a harmful or detrimental effect on the aquatic environment or any aquaculture product (Section 26 of the Aquaculture Act). The introduction of any species or any genetically modified aquatic organism and its transfer within Namibia requires written permission from the Ministry (Section 27 of the Aquaculture Act). The written permission is also required to import and export, remove, or transport live aquatic organisms (Section 29 of the Aquaculture Act). The contravention of any of the specified regulatory measures is an offence that attracts a fine ranging from 4000 to 8000 Namibian dollars or imprisonment ranging from 12 months to 2 years (or both) (Section 40 of the Aquaculture Act).

The management measures in place are wide-ranging and cover various areas of aquaculture that need to appropriately be controlled and monitored. Additionally, the Minister may make any regulations for any matters (section 43 of the Aquaculture Act), including emerging concerns.

23.4 Aquaculture as a Driver for Food Security in Namibia

Food insecurity is one of the most visible dimensions of poverty in most of the sub-Sahara African (SSA) countries, including Namibia (FAO et al. 2020). In Namibia, a meta-analysis of demographic and health survey (2006–2016) reported that about 23.8% of children were stunted (chronic malnutrition), 6.2% were wasted (acute malnutrition), and 13.4% were underweight (Akombi et al. 2017). Therefore, best strategies are required to transform or introduce food production systems that have the potential to ensure a sustainable food supply as part of the efforts to put an end to hunger and malnutrition in Namibia.

Today, fish are considered assets to fight food insecurity and livelihood upliftment worldwide (FAO 2016; USAID 2016). Fish provides 19% of animal protein and play a pivotal role in supplying essential micronutrients such as vitamins, minerals (i.e. iron, zinc, iodine), and essential fatty acid (i.e. polyunsaturated fatty acids and highly unsaturated fatty acids), which are required for maternal health and early childhood development (Kawarazuka and Béné 2011). The fish being enjoyed today are coming both from capture fisheries and aquaculture; however, the production growth rate of capture fisheries has been compromised over the years (FAO 2020). At the moment, aquaculture presents the opportunity to bridge the supply and demand gap of aquatic food in most parts of the world. In Africa, this sector is generally new; thus, it only contributes about 2% of the global aquaculture production (McClanahan et al. 2015).

In Namibia, this sector has considerable potential to contribute to food security and the alleviation of poverty, especially in rural areas. It can empower women to also play a role in rural socio-economic development and provide answers for resource governance since women fit well in the value chain of fish distribution. However, the aquaculture sector is faced with several challenges. For instance, the first investments were short-lived; thus, they could not deliver the expected outputs geared toward food security and poverty alleviation (Villasante et al. 2015). Furthermore, the lack of technical personnel, production and logistical facilities, limited access to funds, and the market hinder rural aquaculture development in Namibia. Therefore, aquaculture has not yet reached its full potential to significantly contribute to Namibia's food security and poverty alleviation.

23.5 Aquaculture as a Driver for Economic Growth of Namibia

In 2018, the global world aquaculture production had a value of USD 263.6 billion (FAO 2020). The human population and demand for fish protein are increasing globally (Godfray et al. 2010), and most of it is expected to be met by aquaculture production (Kobayashi et al. 2015). Therefore, aquaculture, like any economic sector, can be a driver of the economic growth of any country. The ability of the aquaculture sectors to contribute to economic growth depends on whether it is done for subsistence or commercial purposes. Subsistence aquaculture largely contributes to the social benefit, while small-scale farming enterprises, cooperative and state farms can be run for economic gains (Pillay 1997). As an economic sector, aquaculture also plays an important role in job creation, which stands globally at more than 23 million direct and indirect jobs (Ottinger et al. 2016). In Egypt, one of Africa's largest aquaculture products producers, it is estimated that the entire value chain of aquaculture generates about 19.56 full-time jobs per 100 tonnes of fish produced (Nasr-Allah et al. 2020). Aquaculture is also known to significantly contribute to the economic development of rural areas (Ottinger et al. 2016; Filipski and Belton 2018; Nasr-Allah et al. 2020).

In Namibia, aquaculture production is still very low (see Sects. 2.1 and 2.2 and Fig. 23.1), but it has an excellent potential to contribute to its economic growth. In 2020, the total employment in aquaculture was about 398 individuals (Hamukwaya 2021), which is significantly smaller than, for example, the 16,000 recorded in capture fishery (MFMR 2017). The production from marine aquaculture, which produces mostly shellfish, needs to be increased for its economic contribution to be visible. At the moment, the production is mainly of primary products from oysters, but if the entire value chain is localized to include, for example, the canning of oysters or mussels, it can have a significant impact on the Namibian economic growth. However, this will require massive investment from the private sector to set up large-scale farms that can benefit from the economies of scale. The potential for mariculture can benefit from the nutrient-rich Benguela Current, including the established seafood and distribution network. Other considerations can include the introduction of Integrated Multitrophic Aquaculture (IMTA) for wild-caught rock lobster seed and oysters, which has been suggested as a climate change adaptation option for Lüderitz lobster fishers (Iitembu et al. 2021, *in press*).

In terms of freshwater aquaculture, it can have a significant contribution economic growth of rural areas. The small- and large-scale enterprises need to be supported to produce more fish and establish a local fish market whose demand will continuously need to be met. The governance of freshwater aquaculture also needs to be improved, especially in tenure and land ownership security, which can encourage investment. Aquaculture investors, just like those of its sister sector (agriculture), require a regulatory framework that gives sufficient tenure security and secure property right in both land and infrastructure for long-term investment to be made.

23.6 Conclusion

The Namibian aquaculture sector is still very small, but it can grow to act as a vehicle for both food security and economic growth. Its governance structure is multipurpose and regulates matters such as water, public health, sanitation, animal health, and disease. Application processes for a licence resemble a one-stop-shop strategy, although additional permits like the environmental clearance are acquired separately. The aquaculture license includes the classical bundles of property rights, such as transferability, renewability, specified duration and cancellation, only based on failure to perform or meet the specified conditions. However, land ownership and tenure security need to be appropriately regulated to encourage long-term investment, especially for freshwater aquaculture.

In terms of food security, it is freshwater aquaculture that has the potential to have a significant impact on it. This is because freshwater aquaculture is mostly community-based or small scale (smallholder farms), which is driven to meet the local fish demand. However, the current regulatory framework does not differentiate small-scale/community-based aquaculture from large scale/commercial aquaculture. The results of the non-distinction are that the regulatory burdens (i.e. environment clearance requirements) cannot be easily be met by prospective small-scale fish farmers, which constrains its growth as a food security driver at a community level. The growth of freshwater aquaculture is also constrained because the species currently being farmed are mostly slow growing species. Although there are strict regulatory requirements for importing new species, which may help prevent the biosecurity risk to the environment from invasive species; flexibility should be given for well-studied freshwater fast-growing strains of species like Nile tilapia (*Oreochromis niloticus*). Importing some of the fast-growing species can contribute to the growth of aquaculture as both an economic and food security driver.

In terms of direct contribution to economic growth, marine or large-scale aquaculture can have a significant contribution. However, it will require that the whole value chain is localized or significant value additions (e.g. canning of oysters) to have a considerable contribution to, for example, job creation. Consideration of integrated multi-trophic aquaculture (IMTA) for wild-caught seeds of rock lobster and oysters must be seriously considered as it has the potential to contribute to economic growth if done at a large-scale level.

Therefore, the governance structure will need to be adaptive and appropriately regulate or deregulate areas that can promote aquaculture growth in Namibia. Practical-oriented policy guidance is also necessary for the development of this sector, especially that most Namibians do not have a fish farming tradition.

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Chapter 24
A Decade of Agronomic Research Impact on Commercializing Traditional Homestead Production of Amadumbe in Umbumbulu KwaZulu-Natal

Thembisile C. Mapumulo

Abstract Severe environmental problems result from unsustainable farming practices leading to natural resource degradation, particularly in rural areas. In response to South Africa's growing population, farming practices that increase productivity whilst compromising natural resources to ensure food security are rising amongst smallholder sectors. Hence, there is urgent need to establish methods and systems that support viable and attractive sustainable agriculture during the climate change *era*. This chapter reviews the impacts of research intervention post-funded project cycle of commercializing homestead agriculture in traditional production systems. The research project provided a platform for adapting traditional farming methods towards sustainable use of locally available resources to strengthen market involvement and sustain livelihoods. Only one of the five engaged villages demonstrated systemic integrity through displaying the wisdom of strong leadership, incremental technological integration and learning for sustainability. Overall research impact on natural resources was positively noted by the continued capacity of the soil to sustain productivity through high yields as well as maintain soil quality and health. Results also revealed that the lack of extension involvement in the project negatively impacts the sustainability of locally established institutional arrangements (socially and environmentally), thus highlighting the significance of extension engagement in sustaining research results achieved.

Keywords Amadumbe · Homestead produce · Participatory research · Traditional farming

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24.1 Introduction

The vehicle through which the goals of rural development and poverty reduction can be achieved is supporting and advancing smallholder agriculture. The South African government had committed itself to expanding the number of smallholder producers selling their produce from 200,000 to 250,000 by 2014 and 500,000 smallholders by 2020 and onwards (Aliber and Hall 2012). The increased yearly budgetary allocation clearly illustrates these attitudes towards supporting smallholders by the Department of Agriculture, Forestry and Fisheries (DAFF 2018). Ranking number two following the Eastern Cape, KwaZulu-Natal (KZN) is regarded as a rural province with households mainly involved in subsistence and smallholder farming. KwaZulu-Natal was reported to having the highest number of agricultural households, with 23% of the 2.3 million noted for South Africa (Stats 2016). Therefore, agricultural developmental efforts targeting rural communities should be implemented with high impact potential to succeed so that the winning formula can be repeated and distributed in other localities.

The South Africa Netherlands Partnership for Alternative Development (SANPAD) Participatory Project was the result of a long-term building of relationships between researchers at the University of KwaZulu-Natal (UKZN) and farmers who are members of the Ezemvelo Farmers' Organization (EFO). Table 24.1 includes first interventions (2001 to 2003) in Umbumbulu through the Public Understanding of Science and Technology (PUSET Project) focussed on transfer of technology initiated by Professor Rijkenberg and Professor Modi, both of the University of KwaZulu-Natal (UKZN). The strategy was to engage with society to increase awareness of the importance of science and technology in the environment in which we live. The second phase in the relationship initiated a farmer-researcher approach to investigate the organic production of traditional crops (Table 24.2). The third phase of this relationship, the SANPAD Participatory Project 05/32 (2006–2009), initiated a farmer-researcher partnership for research to support the growing involvement in commercial farming. The aim was to address commercialising challenges and understand how market relations changed the way farmers grow their crops and whether this transformation affected social relationships between and within homesteads and villages that constitute the EFO. This phase was a second SANPAD fund and viewed the transformation of homestead agriculture to commercial agriculture through social paradigm and agronomic dynamics.

The SANPAD Project of commercializing homestead[1] agriculture was the third phase of compound research by the UKZN students to develop a model for the successful marketing of traditional produce. As a compound study of social

[1] Homestead refers to a place where a person and/or family cultivates the land and tries to become self-sufficient. As a way of life, EFO farmers strive to live off the land by growing and raising what they eat (including livestock and poultry). Hence the agricultural production efforts around homesteads are usually a quarter or more of a hectare up to four hectares.

Table 24.1 University of KwaZulu-Natal Research engagements through individual research projects arising from the EFO needs and participatory research agenda

Researcher	Co-researchers	Year	Project data and learning
Modi		2001–2002	PUSET intervention project: Establishment of the EFO, February 2001, 31 farmers Constitution established for the EFO Supplied PnP (2001–2002) with traditional crops (sweet potato, landrace baby potatoes, *amadumbe*)
Modi		2003	What do subsistence farmers know about indigenous crops and organic farming?
Mokolobate	Haynes	2003	Evaluation of the comparative effects of organic amendments, lime and phosphate in alleviation of Al toxicity and P deficiency
Shange	Modi	2004	Amadumbe production by small-scale farmers under dryland and wetland conditions
Naramabuye	Modi	2004	The use of organic amendments to ameliorate soil acidity
Naramabuye	Haynes	2006	Short-term effects of three animal manures on soil pH and Al solubility
Phiri	Modi	2005	Performance of wild mustard under green beans intercropping system
Caister	Modi, Mapumulo, Ndlovu	2006	Participatory research agenda workshop
Naramabuye	Haynes, Modi	2007	Cattle manure and grass residues as liming materials
Mare	Modi	2006	Amadumbe planting dates experiment to extend harvest season—farmer field trials
Ndlovu	Caister, Mapumulo	2007	Role of community gardens with EFO villages, RRA
Caister	Mapumulo	2006–2008	Farm visits: interviews, observations, RRA
Mapumulo	Caister, Modi	2007	Intercropping questionnaire
Maragelo	Mapumulo, Caister	2007	Survey of indigenous farming knowledge
Thamaga-Chitja		2008	Determining the potential for smallholder organic Production through the Development of an empirical and participatory decision support tool
Mapumulo	Modi	2007–2009	Action learning crop trials on biological soil fertility amendments—farmer field trials
Caister	Mapumulo	2009	Grounded theory development of commercialisation process
Mare	Modi	2009	Amadumbe starch cropping trials—farmer field trials
Buthelezi	Mapumulo, Caister, Ndlovu	2010	Indigenous knowledge on soils—survey and focus group discussion

These are the individual projects that informed the current study in all aspects of the enquiry: choice of crops (amadumbe, wild mustard and cowpeas), farming system (intercropping), organic amendments (type of organic manures)

Table 24.2 Summary of outcomes of relationship between UKZN and the EFO

Phase of relationship	Outcomes
First SANPAD funded project Farmer-researcher relationship 2003–2005	By 2003, EFO membership increases to 54 farmers Organic certification of EFO subsistence farmers Woolworths' Food Market gains its first supply of organically certified traditional vegetables Identification of some vegetables suitable for cultivation and marketing (wild mustard, *amadumbe*, landrace potatoes) Increasingly respectful relationship between Prof Modi and the EFO Prof Modi elected as gatekeeper
Second SANPAD funded project participatory action research 2006–2009	Researchers were interested in both action and research. Researchers and community members participated in the change process and research took place when the researchers reflected on the change process that occurred. The change process itself was important to generating the new knowledge and places the research within a specific living context.

Adapted from (Caister 2012)

agronomy dynamics of commercializing homestead agriculture, the various aspects of commercializing *amadumbe*[2] were separated into individual research projects, leading to multidisciplinary[3] collaborations within the agricultural faculty over time. The research team leader was interested in designing effective economic models for appropriate small-scale commercial farming. The formal market (Woolworths) was interested in selling produce of high quality at the best price. The organic inspectors were interested in following the rules for certification.

Crop trials were focused on the reliability (potential) of soils and their relationship to the crops and yield improvement. Aspect of strengthening the household was about livelihoods, strategies and ways in which agriculture and people in households are related through the commercialization of homestead agriculture. Overall, the research team intentions were to research over a period of time to look at all the opportunities that farmers had at their disposal and find a new way of thinking and new strategies about how to use resources to make livelihoods sustainable. Our purpose was to one day convince all these different perspectives (people who had their different areas of interest) to compromise and agree to what was needed to

[2] *Amadumbe* is the isiZulu word for taro root or rhizome of *Colocasia esculenta,* a starchy staple eaten throughout rural KZN.

[3] When experts from different fields work together on a common subject, within the boundaries of their own discipline, they are said to adopt a multidisciplinary approach. However, if they stick to these boundaries, they may reach a point where the project cannot progress any further. They will then have to bring themselves to the fringes of their own fields to form new concepts and ideas and create a whole new, interdisciplinary field. A transdisciplinary team is an interdisciplinary team whose members have developed sufficient trust and mutual confidence to transcend disciplinary boundaries and adopt a more holistic approach.

sustain and encourage agricultural-based livelihoods within the Ezemvelo Farmers' Organization (EFO). In this context, we understood the need for diverse strategies by farmers to support agriculture-related livelihoods and were very interested in all their farming aspects. The research focus was imbedded on the way of life in this Umbumbulu community since the planting of *amadumbe* using traditional methods[4] mainly for subsistence was done by almost all households at various scales using only local production resources. In principle, traditional methods used in this area are similar to organic farming with tillage aspects oriented towards soil conservation. Considering the high rural unemployment levels, implementing a research project to commercialise locally available produce to generate an income and sustain livelihoods was appropriate. Umbumbulu is climatically suited to sustain crop production because of the varied higher rainfall of up to 1400 mm/annum (Camp 1999). This climatic advantage is of particular significance in rural agricultural systems that are mainly rain fed due to historical lack of agricultural infrastructure and investment. The success of prior projects phases in the area, especially concerning the environmental sustainability and conservation of natural resources, are therefore ascribed to this environmental advantage.

Historically, the primary mode of knowledge transfer had always been oral communication combined with modelled practice from generation to generation. Generally, most traditional phenomenon have been shaped by social, technical and ecological responses for ensuring food security and social cohesion within the socio-agronomic landscape. Traditional farming as a way of life has, however, been threatened by decades of a shift from the integrated social, political and economic focus of a focused agrarian economy to the multiple livelihood strategies designed to survive in a cash-based society as a result of economic and political power struggles. The loss of arable land and traditional strategies such as keeping livestock, the disruption caused by recent climate change, and especially, the lure of young people to higher, more reliable incomes also contributed to disturbing traditional farming livelihoods. Perceived job opportunities in the urban regions and decreasing food production in rural areas result in youth migration from rural areas searching for better livelihood (DALRRD 2019).

Rural development is almost always conducted in environments where resources are restricted, management is critical, and issues are often challenged. Scientific research generally delights this uncertainty as a new direction for knowledge production, whereas the rural dwellers live with consequences. Hence, research institutions gear their mandates and programmes towards socially robust development processes if outcomes are sustainably achieved. In the current market-driven economy, the opportunity was presented for social learning processes to link technology (including indigenous knowledge), service networks and markets in innovative

[4]Traditional farming methods in this paper refers to management-based factors of minimal soil disturbance mainly with handheld implements, no synthetic use of fertilizers, only limited quantities of kraal/livestock manure and manual weed control together with indigenous knowledge-based pest control. Continuous cropping of these systems leads to depleted soil resource with nutrient mining at every harvest that are not sufficiently replenished at planting.

ways. The outcomes of social learning lead to solutions that overcome typical agri-food-related constraints. Technological improvements and agricultural research are crucial for increasing agricultural productivity and safeguarding food security leading to poverty reduction and employment opportunities and ensuring sustainability within the development context. Gabre-Madhin and Johnston (2002) concurred that agricultural productivity growth had been driven by improved seeds, new farm technologies, and agronomic practices. Improved household income, creation of labour opportunities for the poor, reduced food prices, environmental sustainability are amongst the benefits of livelihood properties resulting from agricultural technological changes.

Factors that impact soil fertility challenges include the removal of input subsidy, high cost of moving fertilizers from source to the farm, inadequate supplies of organic and inorganic fertilizers, and untimely availability and low quality of fertilizers. Also, the poor cultural practices employed, deteriorating soil science capacity and weak agricultural extension services contribute to soil fertility challenges. Continuous cropping and inappropriate farming practices have had massive negative environmental outcomes characterized by declining soil fertility and erosion, degradation of vast expanses of arable land further causing low yields, food insecurity, and perennial starvation (Guto et al. 2011). In many rural areas where subsistence and smallholder farming is a way of life, these problems are particularly intense. Umbumbulu, like many other rural communities, consist of the majority of subsistence and smallholder farmers who still rely on simple traditional technologies and tools, mainly handheld hoes, minimal use of animal traction and limited tractor access. Recent land scarcity resulting from increasing pressure with residential land needs competing with arable land, poor agricultural management strategies and unsupportive agricultural policies exacerbate the problem. Despite the negative impacts on agricultural productivity, food security and environmental degradation, nutrient mining practices including food shortages and imminent threat of illnesses resulting from poor health lead to loss of social capital. To date, Ezemvelo Farmers' Organization community has been traditionally producing *amadumbe* with limited input sources for decades as a way of life and thus annually decreasing yields experienced are a true reflection of the extent of unintended nutrient mining done by the perpetual mono-cropping of these tubers with limited input supply. Therefore, it is for these reasons that this research was instituted to evaluate the long-term impact on the sustainability of this traditional production system.

Agricultural development interventions and research are known to improve the livelihoods of smallholder farmers. Hence, this study viewed sustainability as the primary objective within the context of overall agricultural production, thus implying that local agricultural success will depend on exploiting natural and man-made resources using human skills and labour. The outcome of this exploitation are products in the form of food for sustenance and their market production. Traditional, sustainable agriculture is based on optimising nutrient flows through the recycling of biomass, improving soil conditions and minimising resource losses (Altieri 2005). Accordingly, this system manages agricultural systems for improved and sustained productivity, increased food security while preserving and enhancing the resource base and the environment in general. Outcomes of sustainable agricultural practices are the precipitation of increases in food security, household income and general welfare, which are good and desirable livelihood outcomes, especially for the poor groups of smallholder farmers. Experiences with sustainable and conservation agriculture in South Africa have shown that the adoption of productivity-enhancing technologies often accelerate livelihood changes in economic and socio-institutional conditions of actors involved, as expected (Swanepoel et al. 2017).

Research engagement with the Umbumbulu community intended to adapt local traditional agricultural practices towards sustainable agriculture through soil fertility enhancement by using diverse crop species, alternative organic soil amendments and soil cover through non-removal of residues that protect the soil from erosion and suppress weeds with leftover residues during land preparation (adding to soil's physical resilience and gradual nutrient status build-up). Also, adapt farming system through crop rotation where the below-ground crop is followed by above ground helps weed control and boost soil fertility. The main advantage of adapting traditional agriculture for sustainability is the technology's ability to address a broad set of farming constraints particularly common among smallholder farmers in vulnerable communities. In this regard, the constraints in question include continuous hybrid seed requirement, depleted nutrient base, lack of sufficient access to equipment with varied implements for land preparation, sowing, weeding and harvesting. Answers to farming issues are the technologies to address expressed needs obtained through participatory methods using a facilitation model instead of technology transfer (Duvel 2001). Hence, this qualitative study looked at the impact of socio-agronomic intervention through integrated soil fertility management and farmers' use of best practices in the context of EFO values, opinions and behaviour towards sustainable growing *amadumbe* crop for a high-value market. EFO farmers were central from the beginning to the end, where their local farming system and knowledge of amadumbe production were recognized as assets honouring their existing livelihood strategy. As a result, the research project through this chapter seeks to:

- Investigate how the research technologies of adapting traditional agriculture for sustainable commercial purposes impacts change livelihood outcomes through changes in productivity, yields, household income, and food security.
- Understand the impact of the research interventions post the research project.
- Understand the effect of formal market loss on commercialization efforts, that is, understanding the determinants of continuity in commercializing homestead agriculture through informal markets.

The rest of the chapter is arranged as follows: Sect. 24.2 identifies the purpose for the return study, Sect. 24.3 discusses the underlying framework followed by the description of the study methods in Sect. 24.4. Section 24.5 presents the results and discussions; conclusions and recommendations are dealt with in Sect. 24.6.

24.2 Identification of the Purpose

24.2.1 A Decade Later (Return Study)

As part of the compound research study, the original study was meant to provide answers to low yields experienced by EFO farmers due to a lack of access to manure. This challenge was identified as a critical issue towards commercializing homestead produce in an organic traditional farming system. In keeping with local practices and farming norms, the study focused on investigating biological strategies towards *amadumbe* yield improvement. Funded by the SANPAD Project, the study took place between 2006 and 2009, and the funding cycle ended. Farmer engagement, however, continued to monitor progress on the use of adapted practices in field operations by farmers. In 2010, the SANPAD Project officially ended, and in 2011, EFO lost the formal Woolworths market. Gradually, many EFO members left the organization and stopped paying their membership fees. Formal monthly forum meetings became informal, with only a few held in a year with dwindling attendance. There were farmer engagements through informal visits to EFO homesteads, occasional attendance of the monthly forum meetings by the researcher to hear of the progress post-project exit. Over the years, through visits to the study site it was devastating to observe the EFO's disintegration of various institutional structures that were previously efficient in their functionality. The challenges of not having a formal market led many farmers to reduce the size of their production areas. Different EFO villages displayed different behaviours with four out of five villages showing signs of being unsustainable. Only, Ezigeni village showed consistent sustainability in its production, marketing and social cohesion patterns.

At the beginning of 2018, the researcher identified the need for the 'return study' to document understanding of what went wrong through a formal collection of qualitative data in assessing the impact of research interventions brought by the SANPAD Project more than a decade prior. In the quest to find answers to what was happening in the EFO community, the 'return study' became a systematic inquiry tool into a set of related events that aimed to explain the phenomenon of interest in social setting for the researcher to understand (Nieuwenhuis 2007). The challenge expressed by EFO farmers over many years post the departure of research team leader as facilitator and gatekeeper was that the organization cannot operate until he returns. In agreement, the EFO committee and members concluded that they cannot see anyone good enough to resurrect the organization (EFO) without the gate keeper. Prospects of ever getting a formal market, specifically Woolworths, have died until the return of the gate keeper, whom they believe will one day return in their lifetime to rebuild the organization. In spite of these challenges, Ezigeni village continued to use all the best practices recommended by the research interventions, whilst in other villages, a few pockets of the same behaviour was observed. The SANPAD Participatory Project (2006–2009) provided opportunities for participatory knowledge creation and actor learning in a movement towards commercialization of traditional agriculture. In this study, the commercialization of homestead agriculture, specifically *amadumbe* being the main EFO crop, was understood as having access to the Woolworths market. In over a decade, the question of the 'return' element of the study was to assess the impact of having a research intervention (through the SANPAD project) on the production systems of commercializing homestead agriculture.

24.2.2 An Emergent Research Topic

In 2006, a participatory research workshop facilitated by University of KwaZulu-Natal (UKZN) researchers with EFO farmers in Umbumbulu delivered the foundations for a shared (farmer-researcher) agenda for continued transformation and researchable problem-solving within the proposed SANPAD Participatory Project (Caister 2006). During the three months prior to the workshop held on 25 March 2006, farmers had recorded (written) questions about the problems they were experiencing in the conversion of traditional farming priorities from subsistence to commercial priorities. During the workshop, researchers explored with farmers the complete collection of questions raised, in order to ensure a mutual understanding of the nature and rationality behind the questions. Together, it was agreed who (amongst the research team) would be responsible for addressing these problems. Researchers took these insights away to reflect on and extract researchable problems within the natural learning process anticipated in the participatory agenda for transformation. Farmers have already made explicit their intentions for commercialisation in the constitution of the organization. In this document, they stated a deliberate intention to move beyond what they already knew and to transform traditional agriculture into a practice of market-oriented sustainable agriculture. Potential researchable problems were discussed by student supervisors, identifying individual research projects across a variety of disciplines that addressed farmers concerns. A further priority in these discussions was to ensure that current research activity would contribute to the accumulation of knowledge being produced through the collaborative accumulation of prior (2001–2005) and then current research (SANPAD Project 2006–2009). Through a comprehensive reflection on the farmer's agenda, research consultants and students designed multiple individual research projects for students that would contribute to the farmer's knowledge requirements. The commercialization topic became clear where all aspects were to be investigated by the various student research projects. The study uses the smallholder EFO farmer households with membership in Ogagwini (50%), Ezigeni (35%), Nungwana (10%) and kwaMahleka (5%) communities of Umbumbulu in the province of KwaZulu-Natal as the units of analysis. This chapter seeks to assess the impact of research engagements determinants post the research team's existence within the community thus termed 'the return study'.

24.2.3 An Emergent Research Question

This study presents research enquiries envisioned in the consultations between EFO and research supervisors as a way of understanding the agronomic dynamics of the 3-year (2006–2009) partnership. The research question emerging as the focus for this enquiry was: what are the biological strategies required towards sustainable *amadumbe* production in commercializing traditional agriculture? As decided by the EFO farmers, the role of this study was to contribute to exploring alternative organic soil amendments to ensure improved soil fertility status for sustainable yield in the production of *amadumbe*. In understanding the challenge of limited and no access to manure by farmers when no other form of soil fertility booster was available since the farming system for *amadumbe* in this area was primarily monocultural, the researcher needed to incorporate multiple strategies to providing improved soil fertility amendment for enhanced yield. Strategies involved the following components as sustainable practices to improve yield:

- System change from monoculture to polyculture and/or intercropping.
- Use of other edible legume intercrop instead of dry beans.
- Introduction of vermiculture for the use of vermicompost.
- Incorporation of mutual benefit crop (wild mustard) with residual nutrient gain to soil.

For this study, the underlying theme for investigation was: what kind of farming system would result in a successful and sustainable production for continued commercialization?

Sustainability measure of a farming system whether it is used for commercial or subsistence reasons depends on the productivity of the soil and is enhanced by the practices employed that takes into account the critical issue of timescale. *Amadumbe* have a nine-month crop cycle which suggests that 3 years of the SANPAD Project partnership with EFO was too short a time to determine any long-term indicators of sustainability in the production system. However, it is to be noted that yield improvement was observed in the third-year funded cycle of the project. Hence, there was a realization of the need for the 'return' study to evaluate signs (as perceived by farmers) of sustainability over a period of a decade that has gone since the research intervention. A 10-year lapse was unintentionally allowed to pass so that the initial study of adapting local traditional agriculture could be assessed and the return study of research impact could report on the impact post the intervention. In analyzing the research intervention impact and soil biological strategies gleaned through livelihood survey summarized in the section below, the study thus assumed the necessity to examine farmers' perception on the different technological adaptation for the promotion of sustainable production thus leading to better livelihoods.

24.2.4 Study Assumptions

- The study assumed that EFO farmers had access to unlimited organic manure sources to sustain the commercial endeavours of organically producing amadumbe as the main crop and other organically grown field crops (sweet potatoes, potatoes, pumpkins).
- Local crop rotation system (above ground followed by below ground fruiting types of crops) was adequate to ensure sufficient nutrient replenishment for the main crop of amadumbe without compromising the yield.
- Traditional farming system as a livelihood strategy had positive ecological benefits to the productive capacity of the soil.
- Advantage of research agenda being set by farmers would ensure better adoption/ adaptation levels of the best practices recommended for sustainable production (intercropping, use of legumes, use of vermicompost as an alternative).
- Over a decade of research interventions and enhanced capacity built amongst farmers will result in social cohesion, unity and strengthen internal institutional arrangements of EFO for sustainable united management in administration and productivity once the intervention period is completed and research team exits the area.

24.2.5 Study Limits

The study was presented with a variety of limits to its execution:

- The study inquiry was about the impact of biological soil fertility management practices on productive capacity of the soils in the production and yield improvement of amadumbe to sustain commercial aspect over time (10 years).
- The study relied on information provided by farmers directly and not any other sources, farmer perceptions on their lived reality following experiential learning and research team engagements after a decade (10 years).
- Study evaluated soil health status/soil quality (productivity) as a result of interventions based on farmer perception and impact on livelihoods over the years not the amount of money made in selling the produce.

24.3 Approach and Livelihood Framework

Agricultural research and technologies may not play a central role when we take into account the full picture of people's livelihoods. But understanding the full picture can help develop technologies that better fit in with the complex livelihood strategies, especially of the rural poor like Umbumbulu community. The livelihood framework thus provides a guide for research and intervention. In this chapter, the framework particularly serves the purpose of linking the previous research work (SANPAD Project phase 1 and 2) and capacities with what people are capable of doing, what they are looking for, and how they perceive their needs especially post the intervention (when the research project ends). Livelihood framework is a particular form of livelihoods analysis looking at more aspects of people's lives, analysing causes of poverty (low yields and reduced production/loss of formal markets), access to resources and their diverse livelihoods considering that amadumbe production was their primary livelihood strategy. The framework recognizes people, whether poor or not, as actors with assets and capabilities who act in pursuit of their own livelihood goals intended to be dynamic recognizing changes due to both external fluctuations and the results of people's own actions, activities and relationship between relevant factors at micro, intermediate, and macro levels (UNDP 2017).

The sustainable livelihoods framework (SLF) explain how livelihoods benefit from available resources through engaging in certain activities in an environment governed by some existing rules and institutions (EFO). People undertake livelihood strategies using assets owned to transform their lives. Assets owned are key in implementing livelihood strategies, such as crop production and livestock rearing, which are necessary for realization of desired livelihood outcomes. An indirect but positive relationship exist between the types of assets owned and envisaged livelihood outcomes (LaFlamme and Davies 2007). This chapter embraces the definition of a livelihood as comprising "capabilities, assets and activities required to make a living and to cope with and recover from shocks and stresses" (Krantz 2001). The framework describes how difficult issues of rural development could be approached and successfully addressed showing the importance of resources and transformation structures in realizing welfare goals (Start and Johnson 2004).

The sustainable livelihoods framework illustrated in Fig. 24.1, adapted from Chambers and Conway (1992), shows the relationship among the context of the farmers' assets (represented by different forms of capital), transformation structures, livelihood strategies, and livelihood outcomes. Specifically, the framework illustrates how, by availing households' opportunities/potential for livelihood strategies through promotion of agricultural technology, research interventions impact livelihood outcomes. The framework shows the indirect relationship between livelihood outcomes and households' assets and the role of transformation structures and livelihood strategies. The assets comprise natural (land and its resources), financial (savings, membership fees, own contributions and project funds), physical (infrastructure such as roads), social (EFO/social networks), and human forms of capital (skills and education levels). Assets form building blocks of sustainable livelihoods, impacting household capacity to withstand challenges of shocks encountered in improving livelihoods.

Given asset endowments, households make decisions regarding adaptation of technology perceived by farmers to generate positive social and economic outcomes. The livelihood context includes important broad political and economic structures and the existing policy environment. Arguably, these policies and economic structures influence livelihood assets holdings, strategies undertaken, activities of development agencies and ultimately resultant livelihood outcomes. Illustrated in

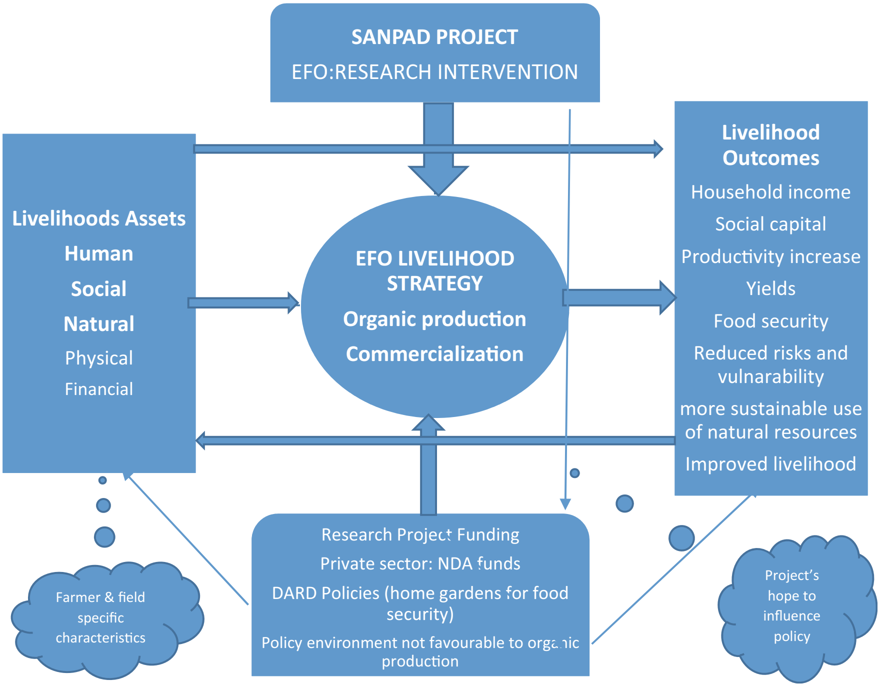

Fig. 24.1 Link between EFO commercialization and livelihood outcomes. Source: Author's own adaptation of Sustainable Livelihood Framework (UNDP 2017)

Fig. 24.1, the system is characterized by forward and backward linkages in response to changes in fields and farmer-specific variables captured through livelihood assets and observed livelihood outcomes. A specific "package" of field- and farmer-specific factors or livelihood assets is associated with each outcome although each factor may be linked to various other outcomes. Traditional organic production is an intervening mechanism through which farmers, given their socioeconomic characteristics and field characteristics, transform livelihoods. Farmers adapt their traditional organic production to enhance land productivity in order to ultimately improve livelihoods through commercialization of homestead produce. Therefore, socioeconomic and farm-specific characteristics and expected positive benefits from traditional organic production influence the farmers' decisions about technology adoption/adaptation. The actual and perceived impact of traditional organic production on livelihoods varies with the geographical location of the farm, biophysical and institutional constraints and socioeconomic factors that favour specific practices shown by the varied results in the five villages. Farmers are heterogeneous and face dynamic, local, political, and economic environments that determine adaptation trajectories taking care of ensuing constraints and opportunities for traditional organic production. As the perceptions' paradigm suggests, farmer behaviours are shaped by the perception that commercialization impacts directly and positively in improving livelihoods (Uaiene et al. 2009). These behaviours are driven by farmer-specific factors such as age, gender, household size, level of education, and marital status, all of which are indirectly linked to perceptions about livelihood outcomes and intervening technologies. In its approach, the project hopes to influence Department of Agriculture and Rural Development (DARD) policy environment towards supporting traditional organic production as part of rural development through their varied platforms addressing food security and poverty alleviation goals.

24.4 Methodology

24.4.1 Location and Characteristics of Study Area

The study area is defined by latitudes 29°58′30″ and 30°4′45″ south and longitudes 30°36′45″ and 30°43′15″ East; visually south and east from Pietermaritzburg and south and west from the city of Durban. The small town of Umbumbulu marks the closest urban economic hub and straddles the R603 (Sbu Mkhize Drive) between Camperdown (south and inland, west of Durban) and Isipingo (south of Durban), via the M30 (Fig. 24.2).

The area where farmers of the Ezemvelo Farmers' Organisation (EFO) live is commonly understood in South Africa as a former homeland area[5] of southern KwaZulu-Natal in Umbumbulu (Fig. 24.3) under Embo-Thimuni tribal authority. In understanding agricultural rural livelihoods, it is important to know local natural resources are available to support and sustain the lives of the people in the area. Also, the knowledge of structures and processes exerting the pressure in shaping the livelihoods is required. Study area is geographically located as well as described through livelihoods view of social and agricultural interaction with the environmental system context. Except for where otherwise indicated, the information in this chapter is a synthesis of the researcher's subjective observations, participatory experiences and discussions with informants from field notes recorded between 2006 and July 2019. During this time the researcher engaged with EFO farmers from all the villages. On first impression, Umbumbulu has visual boundaries on the rural landscape. One sees large-scale commercial agriculture (mostly vast, rolling

[5] The geographic location which thus emphasizes the extent of the production system's sustainability, considering that the land was initially marginalized. Geographically, homelands were strategically located in marginalized pockets of land for the settlement of black people according to the 1913 Native Land Act. Then, in 1936, the Native Trust and Land Act effectively formalized the separation of black and white land, causing decades of marginalization and hardship for rural black people. Noting that prior to the democratic dispensation in South Africa, homelands were perceived as a labour pool for the country's growing commercial activity. Hence, the agricultural work ethic embedded in homestead communities as a livelihood strategy or a way of life.

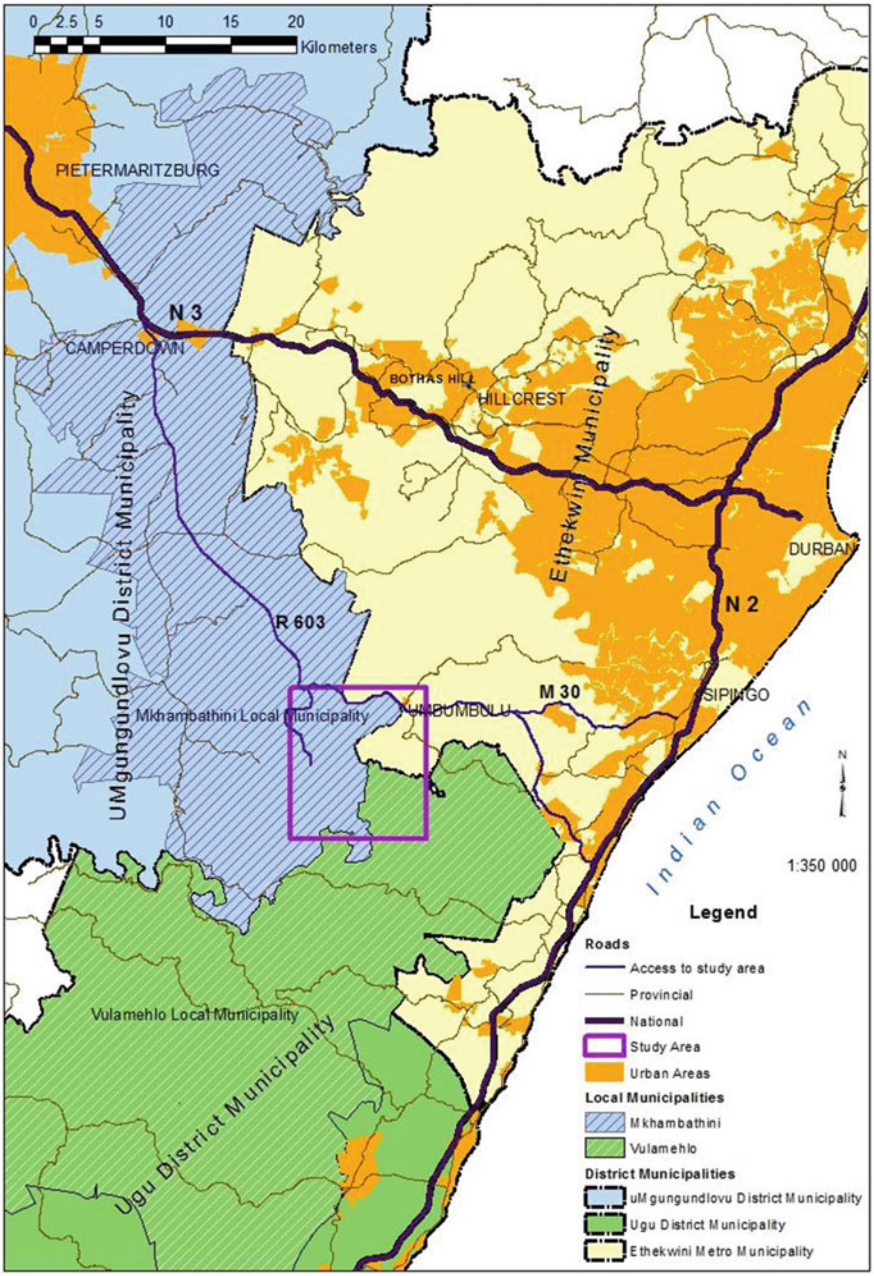

Fig. 24.2 Locality map of study area (Caister 2011)

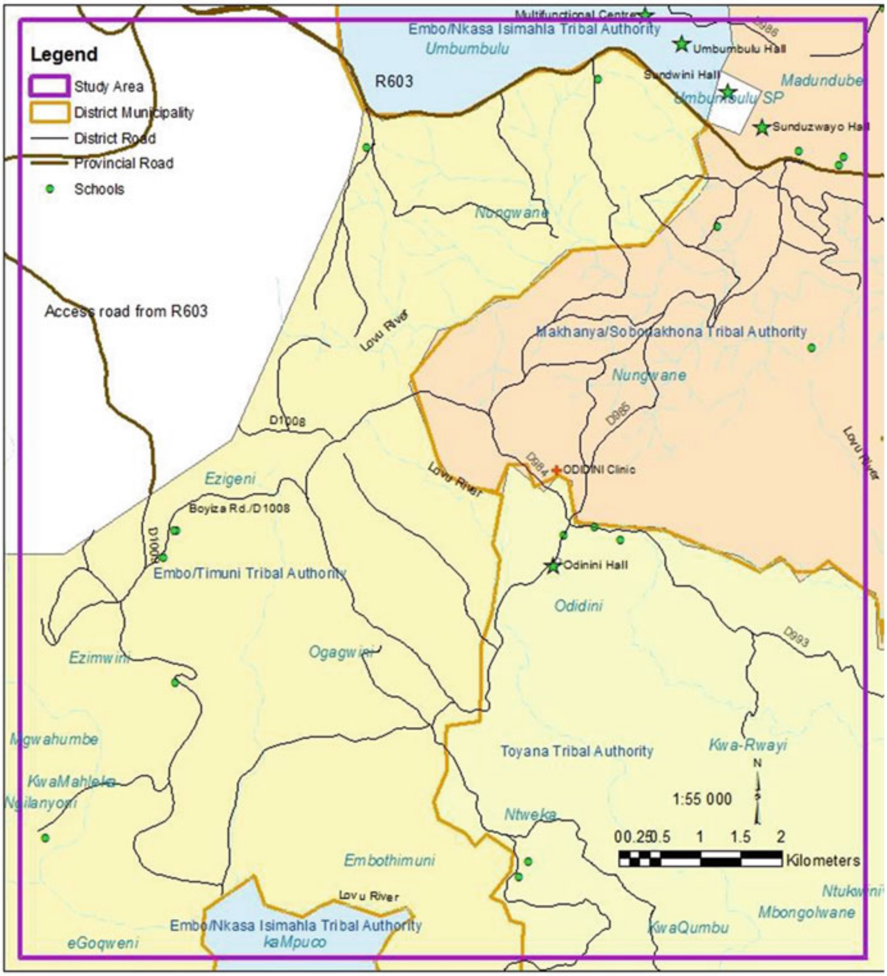

Fig. 24.3 Map of study area (Caister 2011)

fields of sugarcane) clearly separated from subsistence farming areas, where smaller contoured fields surrounding groups of circular-shaped traditional Zulu homesteads (*rondavels*) forms a patchwork effect.

As in many rural areas of South Africa, one notes that housing, a mixture of traditional and modern block or brick, clusters along the main access roads in an attempt to secure access to infrastructure and services. The study area is mainly agrarian and traditional homesteads with their associated cultivations, fallow fields and grazing lands remain dispersed over the rolling hills (Fig. 24.4a, b).

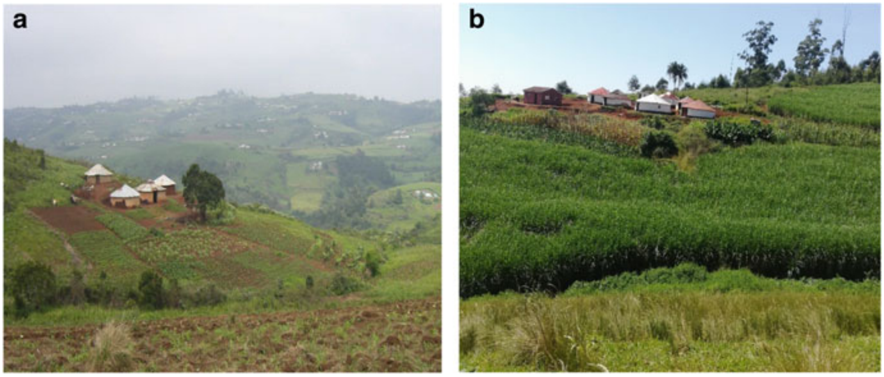

Fig. 24.4 (**a** and **b**) Umbumbulu, traditional farming homestead (12/12/2007 and 18/05/2018)

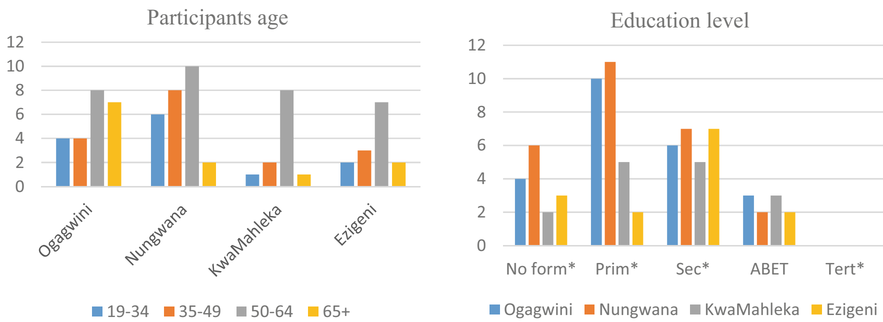

Fig. 24.5 EFO age and educational representation across villages

24.4.2 Sampling and Composition of Participants

From its establishment in 2001, EFO had membership growth of 54 in 2003 to about 280 in 2009 with farmers in the five villages (Ogagwini, Ezigeni, kwaMahleka, Nungwane and kwaRhwayi) of Embo in Umbumbulu. Recently, in 2018, membership dropped to <90 in four (excludes kwaRhwayi) of the five villages. For the four villages, a key informant in each section was the one who organised all the other farmers. As a result, a total of *78* farmers were available for engagement in the respective villages. All farmers who participated in the study were considered to give reliable information pertaining to the study since they have been EFO members since 2006. It was noted that composition of participants and EFO in general is dominated by adults (>35 years) in all villages (Fig. 24.5). As expected in many rural smallholder settings, women are in large numbers as they dominate farmer groups in this study and comprise 86% relative to the 14% of men representation. In their dominance, women are generally married, and there is no culture of divorce in this community as none were reported to have occurred (Fig. 24.6).

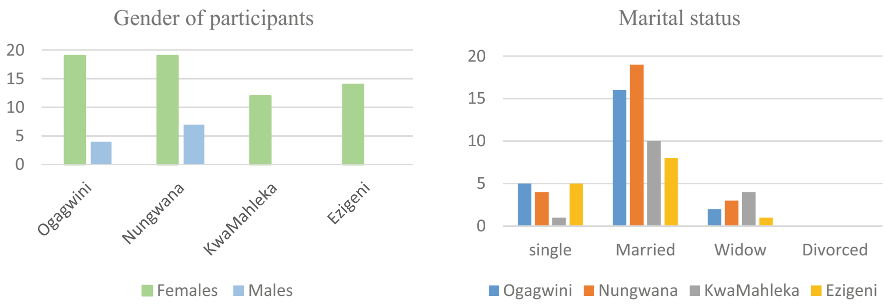

Fig. 24.6 EFO gender distribution and marital status within villages

24.4.3 Data Collection and Analysis

In the collection of data, several visits to all villages were made including a few formal group discussions per village. The data collected from all engagements with EFO farmers were both qualitative and quantitative in nature. Observations of objects was a quick and efficient method of gaining preliminary knowledge or making a preliminary assessment of field state or condition (Walliman 2011).

Semi-structured face-to-face in-depth interviews were used to obtain further clarity through probing open-ended type questions with key informants and typical EFO farmers (Fig. 24.7) in their own spaces at home in the field where amadumbe are planted.

All data collection strategies used are depicted in Fig. 24.8. Surveying is done through questionnaire with a focus group of EFO members to concentrate in detail on intercropping as a specific theme on their production system. This method was found to be flexible, cheap and quick to administer to larger groups (up to *16* famers) in different villages and lasted for up to 2 h for a group. In these focus group discussions, questionnaires were personally used by the researcher for better results (Van Niekerk 2002) as well as to ensure that farmers could be assisted to overcome difficulties with the questions, and could be persuaded and reminded in order to ensure a high-response rate. The open-endedness of the questions allowed farmers freedom to express their opinions as well as qualify their responses (Walliman 2011). Authenticity of the accounts were cross-checked with other farmers to achieve a higher degree of validity and reliability. De Vos (1998) explained this as triangulation where various methods are used to collect information on the same issue so that the strength of one method can overcome deficiencies of other method. The use of secondary data from various sources such as documents and statistics to support views or arguments (Scott 2006) constitutes documents research method. It should be noted that secondary sources of data and information can be published or unpublished and can be historical or contemporary (Laws et al. 2003). The triangulation of data and information can be achieved if secondary data is used in conjunction with other types of data.

Fig. 24.7 Key informants face-to-face interviews with open-ended type of questions

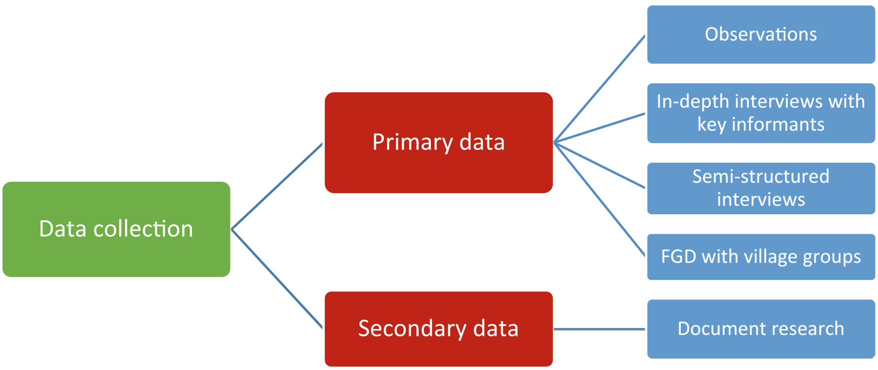

Fig. 24.8 Data collection strategy used during the return study

A total of three field trips per group were made between May and October 2018. Responses were categorised according to similarities; then, a theme was developed from all similar responses. From these themes, relationships and associations were identified to make sense of these relationships. In analysing content, a process of selecting categories of data was the starting point. Sentences (content) with similar meaning were grouped together to form a category that were accurate, exhaustive and mutually exclusive and clearly defined (de Vos 1998).

24.5 Results and Discussions

24.5.1 Overall Sustainability

Components of sustainable agriculture specific to EFO community are graphically depicted in (Fig. 24.9). These components framed the space in which farmers and UKZN research team operated on for EFO farmers to be successful at genuinely engaging in sustainable agriculture and ensuring that research interventions are successful in supporting them. The five pillars are:

- Maintaining and increasing biological (organic/traditional) productivity.
- Decreasing the level of risk to ensure larger security.
- Protecting the quality of natural resources (soils, water and veld).
- Ensuring agricultural production is economically viable (commercialization).
- Ensuring agricultural production is socially acceptable (strengthening social cohesion).

Ezigeni village presents a good opportunity to discuss these pillars where relevant principles for each pillar was demonstrated through examples of their practical application to illustrate the point. Relative to other villages, Ezigeni's unique circumstances based on their consistency in practicing sustainable farming will assist in developing appropriate responses to show sustainable practices in the continuous production of *amadumbe*. These pillars will be addressed in an integrated fashion not as individual aspect to be addressed in isolation. Environmentally, land scarcity is causing food scarcity for the ever-increasing population. In the context of EFO community where traditional agriculture is a way of life, it can be said that their

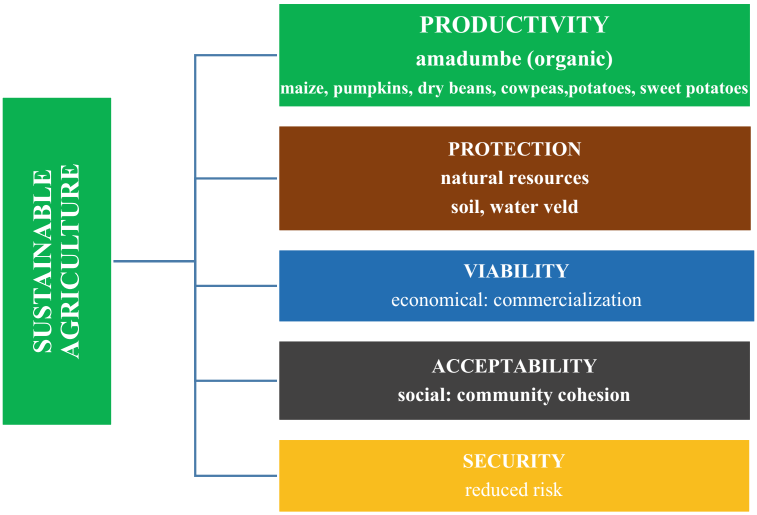

Fig. 24.9 Five pillars of sustainable agriculture (adapted from Khwidzhili 2012)

goals and understanding of long-term impact of their activities on the environment, and consequently, on other species trends toward sustainable agriculture (Francis 1990). Importantly, to be noted is that sustainability is a direction rather than destination. Therefore, it is assumed that EFO will continue to remain sustainable in their farming style. Farmers understood clearly what was being sustained, for who and for how long to afford future generation's agricultural livelihood opportunities. Sustainability was entrenched in the study's resulting technologies that reflected a combination of traditional and modern techniques. Central to sustainable agriculture is the necessity of taking a long-term view, in ensuring the supply of products to future generations, the necessity to maintain and enhance soil fertility, veld condition, water quality, supply and generic resource on which agriculture depend. Sustainable agriculture delivers on these critical elements through a variety of technology options as seen implemented by both phases of the SANPAD project at Ezigeni.

24.5.2 Biological Productivity: Improvements to Soil Health and Quality

The first pillar of sustainable agriculture is the requirement that the biological productivity of the soil is maintained and, if possible, increased. Biological productivity refers to the ability of soil to promote microbial activities. The continuous application of large quantities (Ezigeni) of cattle manure as part of traditional organic farming ensured that microbial populations are enhanced. Key to the biological productivity of soils at Ezigeni is the high organic matter content build-up as a result of these best practices including minimum soil disturbance that led to reduced mineralization. In this village, farmers understand that their soils' productivity forms the foundation that sustains consistent high yields to keep the commercial viability and maintain livelihoods. In the management of biological productivity, other pillars of sustainability are simultaneously considered like economic viability, social acceptance and reduced production risk. Protecting the quality of natural resources is directly linked to the biological productivity pillar toward attaining sustainable agriculture that works within the bounds of nature not against them. This means matching land uses to the constraints of local environment, planning for production not to exceed biological potentials with no use of synthetic fertilizers and pesticides. Traditional agricultural systems are in their nature a premise for sustainability (Miller and Wali 1995).

Soil is the fundamental capital asset as it is the most important part of any agricultural system. When in poor health, it cannot sustain a productive agriculture. In rural areas, many agricultural systems are under threat because soils have been damaged (due to bad management practices including over grazing), eroded or simply ignored during the process of agricultural intensification programs by government and various non-governmental stakeholders. Soil fertility is the primary factor affecting agricultural sustainability and known to be a function of current and previous management regimes. Amongst indicators used by farmers, crop production factors are considered most reliable indicators of differences in soil fertility. These crop factors include primarily crop yield and crop appearance during the establishment stage. Hence, it is reported that yield forms a benchmark for soil quality assessment in the indigenous approach (Gruver and Weil 2007). Even so, crop production indicators used by farmers (yield and crop appearance) may not always be a true reflection of soil quality since high yield can be a result of favourable weather and improved seed. In taking advantage of the climatic conditions and the results from the ARC cultivar trail outcomes (2013–2017) that identified the best local cultivar for use at Ezigeni and the good rainy seasons (2015/16 onwards) post the 2014/15 drought year, farmers maximized productivity and increased yield (FN020618: App IV). At Ezigeni, in particular, farmers treat soil fertility as a dynamic character of soil which they improve through maximizing crop diversity by using rotations and intercropping and large amounts of manures in boosting nutrient levels. Barrios and Trejo (2003) explained that soil colour provides a good measure of inherent soil fertility. Together, the dark soil colour and the presence of earthworms are recognized as indicators of soil quality beneficial to fertility. Farmers understand the positive linear relationship of manure addition and dark soil colour. Thus, the strong belief that continuous addition of large quantities of manure will enhance both these indicators for long-term productivity and maintenance of high yields. In turn, soil organic carbon reserves also get established in the build-up of the resilient soil system.

Annual agricultural ecosystems like the EFO *amadumbe* system often deplete soil carbon (C) and release more reactive nitrogen (N) into the water and atmosphere than unmanaged, perennial ecosystems. Yet, we rely on these ecosystems for food security, livelihoods, and they represent the largest stock of soil C we can directly manage to mitigate climate change (Kallenbach et al. 2019). How do we then resolve this dichotomy, in creating a win-win scenario whereby agroecosystems remain productive while contributing to climate change mitigation? To address this grand challenge, Wallenstein (2017) advised that agroecosystem soil biology should increasingly be managed to better regulate soil C and nutrient cycling. Many approaches like the soil biology strategies used in the EFO project focussed on soil C regeneration through increased residue returns and biomass production (legume intercropping) and decreasing C losses via reduced disturbance (minimum till).

In this traditional organic agricultural system, the net return of soil C and its storage was achieved through the adaptation of a wide variety of physical and biological soil conservation measures, use of legumes and intercropping, incorporation of phosphate-releasing plants into rotations, use of composts, cattle manures, vermicompost and maintenance of minimal soil disturbance during tillage. The use of vermicompost is known to enhance microbial life in the soil as the high populations (including earthworms) of microbes are active and continue with nutrient cycling within the vermicasts. The use of legume (cowpeas) that attract nitrogen-fixing bacteria naturally living in soils enhances the root zone with a community of microbial life. Project framework focused on linkages between best management practices and microbial traits allow us to better describe, predict, and manage the relationships among critical soil services, the microbes that drive them, and the environment under which they are manifested in the long run toward sustained soil health and quality. It is, therefore, suggested that the combination of various types of manure (cattle and vermicompost) to improve soil C sequestration effectively engineer rhizosphere microbiota and enhance nutrient efficiency needed to understand the long-term effects of fundamental soil microbial processes of the dominant microbes within the community created in this specific agroecosystem. Schimel et al. (2007) also found that a diversity of inputs represented a wide range of C and nutrient availability that may have facilitated a balance between individual and community-level C use efficiency optimization, thus indicating a productive system. Practices such as diversifying crop rotations or mixing legume crop biomass with *amadumbe* residues could provide resources that promote species with different life histories to coexist.

24.5.3 Impacts on Rural Livelihoods

24.5.3.1 Ezigeni Village Impact

With specific reference to Ezigeni village, results revealed sustainable agriculture improvements had positive effects on people's livelihoods with regard to social capital. Village membership increased and was demonstrated by collective management of natural resources and stronger social bonds, thus resulting in new norms. The perceived sustainability by non-members lured them into wanting to be united with the original members for better connectedness to external institutions bringing about the change at local (village) level. These improvements in human capital led to increased self-esteem in formerly marginalized group, increased the status of women with more local capacity to experiment and solve local problems. This situation gave an outcome of improved nutrition, especially from more food in dry seasons and reversed rural migration whilst creating additional local (village) employment opportunities.

Social learning is a vital part of the process of adjustment in sustainable agriculture projects. The conventional model of understanding technology adoption as a simple matter of diffusion, as if by osmosis, no longer holds. But the alternative is not simple either as it involves building the capacity of farmers and their communities to learn about the complex ecological and biophysical complexity in their fields and farms to then act in different ways (Caister 2012). When process of learning is socially embedded, it provokes changes in behaviour and can bring forth a new world to those engaged. The practical evidence seen at Ezigeni shows that social learning leads to greater innovation together with increased likelihood that social processes producing these technologies are likely to persist. This is noted in the history of EFO where a research relationship provided an excellent platform on which various kind of initiatives including new indigenous crops and conventional irrigation schemes (rainwater harvesting and supplementary irrigation) were slowly and carefully introduced. To date, these initiatives are still in use and beneficial. At Ezigeni village, farmers exhibited a reflection of the way values, attitudes and goals are shared within a group, thus showing fruition of building relationships in the development process including culture. As their way of life that has gradually progressed over a decade of continuous learning, Ezigeni farmers stayed true to their beliefs and expressions noted in their constitution as "we wish to cooperate with the Department of Agriculture at all levels and any other institution or persons in sustainable, productive, stable and equitable agriculture to commercialize our produce in a manner that improves our economic development without compromising our cultural integrity" (taken from the EFO Constitution 2001). In their understanding of the impact of research intervention as a driver for social change and material gains, Ezigeni farmers understood that momentum was generated to attract various funding possibilities. Acceptance of the ARC cultivar trial when primary EFO has rejected the request showed their progressive nature in aspects of environmental sustainability for economic development through their strength in social cohesion and maintained relationships. The villagers were aware that results from this cooperation will present them with new potential markets opportunities especially because their level of confidence of good quality product would be heightened by the trial outcomes of the best cultivar in their area. A lesson long learned during the UKZN SANPAD Project team was that all research results are built into action and used to sustain, advance and enhance the overall production system.

Farmers at Ezigeni made a conscious effort to elect lead farmers who facilitated the establishment of the human and social capital formation of the village with the understanding that yield improvements and production income do not translate to social capital formation. This was done through encouragement and facilitation of the formation of village-based farmer organisation. Ezigeni has strong and committed leadership and has been able to respond flexibly to the changing EFO set-up/break-up that happened (post 2010) and they managed to keep their village intact. There has been a move from original male-led leadership in the EFO generally to female-led leadership who are more skilled and patient in engaging the process of change and village independence. This move has seen more households being able to earn a good livelihood strategy to the point of sending their children to tertiary institution of learning with success. After leaving the employ of Farmwise Packhouse in 2010, Mr. Mkhize (First EFO chairperson 2001–2004) has been the support system for the village as the individual who played the key role in linking the village with external markets based on his history and experience (see Fig. 24.10). The relationship has been built on trust between the village representatives of lead individuals and new market at the Toyota Plant in Isiphingo. Flexible and responsive collaboration with a supportive market agent (at Toyota) and a wide range of opportunities within has seen a steady increase in sales momentum. Toyota plant is believed to have more than 500 employees per shift at the Isiphingo plant who prefers the system of having the produce delivered to their security gate. Twice a

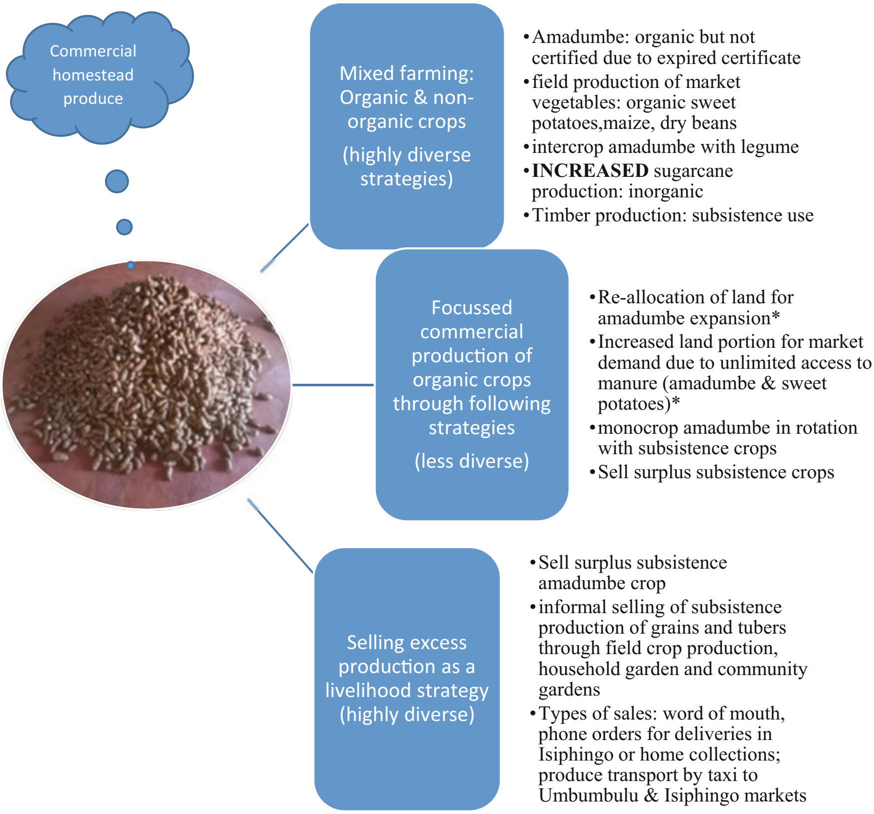

Fig. 24.10 System adaptation for commercial production compiled from observations and discussions 2011–2019 at Ezigeni village only

week produce delivery is expected as individual orders are placed with fortnightly (every 2 weeks) payments. This system is efficiently coordinated by Ezigeni lead individuals who then distribute the monies accordingly in the village every 2 weeks to all the respective homesteads who have supplied the produce. Farmers at Ezigeni do not have access to additional land outside their village to expand their area of production. Hence, to continue supplying their market consistently, they have to rely on the Mkhize clan relatives in other villages like Ogagwini to supplement their overall tonnage and extend the *amadumbe* market season (March to July) based on family relations and trust, a mutual financial benefit is thus accomplished.

Human capital appears in the framework for sustainable livelihoods as an asset which affects livelihoods. Aside from its intrinsic value, human capital is needed in order to leverage all other forms of capital. Because of this, whilst not sufficient as a stand-alone resource, it is vital for the achievement of positive results in any dimension regarding livelihoods. Since human capital is a multifaceted concept comprising a range of human attributes which are difficult to quantify, it could be

Table 24.3 Depiction of unity in women of Ezigeni in view of livelihood assets

	Research intervention		EFO institution		Commercialization	
Capital	Ezigeni	Others[a]	Ezigeni	Others[a]	Ezigeni	Others[a]
Human	3	**1**	3	1	3	**1**
Social	3	3	2	3	3	**1**
Natural	3	3	**1**	3	3	**1**
Physical	3	2	**1**	3	3	**1**
Financial	3	2	3	2	3	2

[a]Others: Primary EFO members with all villages together excluding Ezigeni
Bold denotes strong emphasis on the given value agreed upon by everyone (all) present

concluded that its stock value cannot be determined by existing knowledge and experience alone. It should also include an assessment of an individual's ability to learn new knowledge and skills according to their future development needs clearly demonstrated by the Ezigeni women over the years post the research intervention (Table 24.3).

24.5.3.2 Explaining the Score of 1

The livelihood framework is human-centred and involves a broader understanding of the process, including governance of natural resources and local practices, such as land access and distribution, veld management norms and similar. Hence, because the Ezigeni group is primarily women, they cannot access additional land despite their great need for increasing production as guided by the market trends. Similarly, with the physical capital women alone in a rural setting do not have much influence on development and enhancement of this capital.

The other groups (EFO villages) showed that research interventions did not enhance individual human capital development as many farmers have today gone against all the capacity and training done by the research intervention. This is observed as evidence in their decision of selling prime organic land for a small income brought in by the cane plantations that uses inorganic chemicals (FN130718: App IV). This may also be a result of the old age of many members thus causing them to easily backslide without much care for the future because of the lack of interest shown by their immediate young descendants in agricultural livelihoods. Without the market facilitator, many members believe that all four capitals (human, social, natural and physical) cannot be further developed to gain a livelihood. Their decision to disaggregate the organization by getting rid of the committee and destroying institutional arrangements of the organization are clear indicators that without commercialization not much can be achieved in the absence of their gate keeper. Despite the opportunity for financial gains brought by commercialization, many believe the effort (pursuing informal markets using public transport) is too much to do on their own for not much returns as they cannot get back the premium market they had during the days of having a market facilitator. Whilst at Ezigeni, all capital assets are viewed and treated as equals because of their understanding that these assets are interrelated. Located at Ogagwini village, EFO headquarters (packhouse) owned by a certain family caused many to view those premises as personal asset to that particular family as depicted by the score of 1 on both the natural and physical assets (Table 24.3). Internal conflicts resulting from collapse of institutional arrangements made the Ezigeni farmers feel unwelcomed at the packhouse, hence the establishment of secondary EFO at Ezigeni. In order to understand the importance which each stakeholder group attributes to each capital, they were asked to assign a value to each from 1–3 (the greater the value, the greater the importance).

24.5.4 Other Factors Impacting on Sustainability

24.5.4.1 Age and Level of Education

Figure 24.5 shows the distribution of the farmers by their level of education which was generally low across all villages. These results show numbers of participants that have no formal education are 4; 6; 2 and 3 for Ogagwini, Nungwane, kwaMahleka and Ezigeni, respectively. Also, none of the farmers had tertiary education. This places a large proportion of participant farmers within the primary and secondary school level as shown by 10; 11; 5 and 2 for primary and 6; 7; 5 and 7 for secondary schooling for Ogagwini, Nungwane, kwaMahleka and Ezigeni, respectively. These results clarify why most members of the EFO executive committee are from Ezigeni village because of the greater proportion of women with secondary school education. In agreement with small numbers representing the youth, dominating older folks did not have an opportunity to study further as a result of various factors in the South African political context as shown by the lower levels of formal education. This dominance has an influence on several decisions taken by the group in moving forward towards future engagements with other external stakeholders for sustainable development of their continued commercialization of traditional homestead organic production. The issue of age dominance was revealed by the responses on their opinion of the group (EFO) before and after the UKZN research team engagement (Table 24.4). Dominant older members felt that without the leadership of UKZN (gate keeper), the organization will suffer a slow death of internal differences due to conflicts. This was seen by the collapse of institutional arrangements where the first committee members had to resign because of difference of opinions with regard to leadership and development goals of the group without the leadership guidance of UKZN research team coordinator. The older members found it difficult to continue with the organization (EFO) when the SANPAD/UKZN research funds were exhausted and the engagements were reduced and eventually project ended after several years. The fear of the unknown was apparent in their view of a bleak future where sustainability of EFO was not expected especially by the older farmers. As a result of their dominance in numbers (bigger proportion), the

Table 24.4 Differences/changes in EFO over a period of a decade[a]

EFO characteristic	2006–2010	2011–2019
Institutional arrangement	United group: active committee strong social bonds within EFO community	Disaggregated: in-active committee, no direction, cannot read and understand records/books, extremely poor admin. Hidden records as anyone can learn important information about EFO
Gate keeper (research team)	Present and actively involved	Absent no activity
Organic certificate	Paid for and valid	Expired no funds to re-apply
Markets	Formal and active (all members)	Informal for all members
Field sizes (amadumbe)	1–2.5 ha and increasing	<1 ha and decreasing
Membership	>200 and increasing	<100 and decreasing
Future perception	Sustainable and growing	Hopeless and dying
Crop yields	Gradually increasing	Relatively very low[a]
Generation gap	Equal proportions of young and old	Older members dominate[b]
Executive committee	Representative of all group demographics	*Dominated by older members* with no leadership skills[c]
External stakeholder engagements	Open to a variety of engagements that brought development and growth to EFO	Opposed to any stakeholder opportunity which is detrimental to the growth. Obligation to seek EFO consent for participation from gate keeper "we belong to Prof only". Some stakeholders have been deterred by this attitude of the EFO
Beliefs	Gate keeper will always be with us and help us grow. Always listens and takes his advice. Only trustworthy person to work with into the future	Will await the return of the gate keeper and in the interim no-one is good enough to help us. Any arising opportunity is thus rejected. Without Prof anyone wants to 'rob' or cheat us of something or the other.
Monthly forums Management of EFO assets: tractor, bakkie, PC, camera, general admin and income generation	Constantly every first Monday of the month with formal agenda and meeting protocol observed with >70% attendance All assets properly managed with good record keeping. Income growth and transparent management of funds Efficient display of good institutional management	Random once every 3–-4 months with no agenda and no formal protocol observed with less than 30% attendance. Sometimes the forum is just about how much did the tractor make and how much will be spent on repairs, then meeting is adjourned. Currently there are sparse records of a few items, with tracker removal from the bakkie, unwarranted activities

(continued)

Table 24.4 (continued)

EFO characteristic	2006–2010	2011–2019
		observed by many but cannot be questioned as members are threatened by those holding the specific asset. Trust is completely lost within the organization
Fears	Generally no fears were noted except for the ability to satisfy the market needs (quantities)	EFO belongs to Ogagwini village and specifically to the family that owns the land where the packhouse/hall is situated. Any EFO asset enquiry by members upsets the committee and other Ogagwini members. They Live with perception that access to formal markets is lost for good or at least until the gate keeper returns to lead them. The absence of vision implies no progressive farming until he returns and resurrect the organization. Don't trust genuine efforts by any external stakeholders to bring development.

[a]Data presented excludes Ezigeni village which is detailed in the next table as the best village *i.t.o* sustainability
[b]Low yields: result of decreased planting areas (due to no formal markets) no soil's productivity (high fallow hactarage)
[c]EFO segregation did not attract new and younger members to join the organization for succession planning
[d]Current chairperson not a farmer but a reverend/pastor, entire committee have no leadership capacity training

whole EFO structure was compromised. Younger members were out voted and sidelined when, unfortunately, they had the capacity and skills to lead the group with better administrative and good institutional arrangement skills into a sustainable future. These differences because of age gap led to the break-up of EFO into primary and secondary cooperative entities. The relatively younger better educated members of EFO are more progressive, hopeful (even without the UKZN leadership) and better able to engage external stakeholders for their future betterment as they utilize the leadership capacity built in them by the UKZN research team.

Lower levels of literacy and lack of administrative competence led to farmers not using existing information for their development. However, secondary EFO cooperative made of primarily younger and better educated members based at Ezigeni village is more successful and has benefited from new external stakeholders and currently boasts a stable market and has increased its production areas (through new membership within the village) to meet its new market demand. At Ezigeni, a clear display of strengthened (age-related) group dynamics is seen in their combined use of local resources (land, labour, planting material) whilst preserving biodiversity. Ezigeni strength is seen through the unity of the village (added new pieces of land) planted with *amadumbe* and sweet potatoes, younger members are now part of the group also with their additional land dedicated to traditional organic planting of tubers. Planting material is shared amongst themselves (within the village) for quality assurance of the produce.

24.5.4.2 Impact on Production Practices

In honour of existing livelihood strategies and acknowledgement of the farming system, previous research (2006–2009) followed the use of traditional agriculture as part of local knowledge to improve management of locally available production resources in the journey of commoditising *amadumbe* and this allowed learning and new knowledge acquisition in dealing with organic market demands. Farmers learned through experiential work plant spacing and manure quantities that will achieve the market expected sizes of the produce. Over the years, the loss of organic certificate (expired validity) led to reduction of land area that was planted with *amadumbe* in fear of uncertain informal markets. With the exception of Ezigeni village, all other EFO villages have farmers (>50% Ogagwini) that have decreased the production areas over the years due to the lack of formal market. Considering that Ogagwini village is known as the base or centre of EFO, it is a great loss that half of the membership in this village have reduced their production land for amadumbe. Many farmers reported a land reduction of between 40–60% with the smallest areas at kwaMahleka village where members now grow *amadumbe* on 0.2–0.25 ha portions of land. Land use for sugarcane production has, however, increased which is rather unfortunate because cane production requirements are highly dependent on inorganic fertilizers. In keeping with organic principles and sharing of same values, attitudes and goals around agricultural productivity farmers reported that a 6 m contour is used as a border between cane fields and *amadumbe* land to manage the inevitable possibility of underground chemical seepage. This practice is accommodated by all new cane growers and those who are expanding their cane lands since access to land is now a constraint; thus large proportions of previously amadumbe/organic land is now lost.

24.5.4.3 Land Use and Cropping System

Mixed cropping that includes livestock has been gradually diminishing over the last decade as a result of changes in land use. Nungwana village, for example, is undergoing quick urbanization with residential land use increase. This trend is placing pressure on both arable and grazing land leaving farmers with limited production areas which leads to an intercropping adaptation practice increasing to mitigate land pressure using mixed cropping style. Loss of formal markets led to changing livelihood strategies and reshaping of cropping patterns. Results revealed that many home gardens (Nungwana village) are converted to create additional land for mixed cropping (*amadumbe*, legumes intercropping and maize, sweet potatoes rotations). All villages except Ezigeni have experienced decreasing number of livestock herds due to stock theft and lack of grazing land amongst other reasons. The loss of livestock consequently results in limited access to manure which impact yields negatively.

Pointed out by Ortmann and Machete (2003), historically, smallholder farmers have not had the opportunity to produce high-value crops due to limited input resources. This is especially critical for EFO farmers since access to manure is key to their traditional organic production and continuous commercialization goals.

Ezigeni village, on the other hand, has maintained their livestock with a slight increase in the number of herds as they expanded their production areas because of stable markets. Also, the element of unity in the village is indicated by the positive results of less to no stock theft relative to other villages where this challenge is increasing (Nungwana). In their adapting, Ezigeni farmers needed to attend to issues associated with intensified production, and recognise factors that shape market acceptability without any reliance on external resources (loans, organic fertilizers and planting material). This can be viewed as a clear advantage of incremental integration driven by market stability. As expected over a period of 10 years, many valuable lessons were learned through the process. However, due to the scope limitations of the study, only production-related impacts are reported including the adapted practice of legume (cowpeas and dry beans) incorporation in their standard *amadumbe* production routine. It is noted that in their understanding of sustainability within a development context, practices that require less effort on their part and are beneficial to their needs were easily incorporated and thus intergrated as part of best practices.

24.6 Conclusions

Ezemvelo Farmers Organization (EFO) conclusive leadership choice through the election of gate keeper (regarded as the interface with external institutions and processes) was key; in that there would be a particular personality influencing decision-making. This role also emphasised the importance of dialogue/inclusive discussion, representation of household, community, researcher's perspectives and external interests. Even the inclusion and acceptance of student researchers was also built on trust and confidence in the gate keeper. This relationship of trust with the gate keeper worked excellently over the years and mutually benefited farmers, students and other external stakeholders involved. The unintended consequence of this strong relationship was, however, seen years later when the gate keeper was no longer available to lead the organization. Standing on its own, the EFO executive committee revealed the inevitable cracks with issues of internal trust within that led to the collapse of leadership structure. Institutional arrangements within EFO gradually crumbled down as the old committee (active during the gate keeper's *era*) was expelled and the newly elected committee lacked administrative and leadership skills. Elected on the basis of their educational level, age and physical abilities, the old committee (gate keeper's *era*) was capacitated and geared to lead the organization in the succession terms of several decades ahead. The distinctive feature between the old and the new committee members was the age difference where the old members were in their midlife age range (45–60 years) and the new members were mostly elderly (65+ years). This age issue contributed immensely to EFO breakdown into primary and secondary factions and formation of new subgroup. The elderly members cannot easily change their beliefs and ways of doing things. Hence, in the absence of the gate keeper, many elderly members felt that, no one (even within EFO) was sufficiently trustworthy to lead the organization despite the good leadership shown by the old committee that reigned during the research team presence under the guidance of the gate keeper. From this observation, it is concluded that in rural settings where elderly folks still hold positions of power and influence, external actors with known and proven good conduct have a better chance of being trusted into local leadership roles compared to younger local people of the area. This is, however, an unfortunate situation of missed opportunities to groom and mentor younger local people into leadership roles towards agricultural development. Many (elderly folks) are still hoping that the gate keeper will return to assume his role and rebuild the fallen organization. It can also be seen that despite the strong foundations of people-centred engagements laid, achievement of sustainability which is a dynamic process can never be fully realized as people change together with their behaviour influenced by various factors over time. Four of the five villages have fallen into this unfortunate predicament of believing that without the gate keeper, EFO can never regain its good old days of enjoying success and agricultural prosperity. Ezigeni village, however, has thrived and demonstrated immeasurable growth utilizing the inherent local assets and the capacity built in them during the research intervention. The intended outcomes of research meeting society over uncertainties (markets, social cohesion and use of local assets and resources) for sustainable growth and improved livelihoods have been accomplished at Ezigeni. This conclusion suggest that in this village sustainable livelihoods not as an end point but as a dynamic process are realized considering that continuous successful production of *amadumbe* is the mainstay or primary livelihood strategy.

Research engagement in Umbumbulu built and tapped on the inherent assets within EFO to ensure that risk aversion or taking as informed by various constraints was a skill taught to realistically consider various alternatives. This was critical because farming is essentially risky, owing especially to unpredictable factors such as climate and economic change. Longer research engagement period (>10 years) was needed to understand the crucial EFO management decision for appropriate extension and development strategies to assist in reducing farmer risks, especially when considering adopting and/or scaling up traditional organic production. Today, many practical lessons learned with EFO community are practised and implemented in other areas where traditional farming is still a way of life. The low numbers of new membership in three of the five EFO villages draws to a conclusion that traditional organic farming system requires intense knowledge for successful implementation, hence the need for critical mass capacity building locally. It is thus concluded that if sustainable agriculture is to spread to larger number of farmers and communities, future attention needs to be paid to developing social capital within rural communities and between external agencies.

Project participants became confident to leave their narrow discipline traditions (or familiar farming strategies) and cocreated knowledge from multiple perspectives and experienced how people shape, and are shaped by agriculture as a 'way of life'. However, these changes were sustained over a short period of time post the end of research project in the four villages. In the long term (10 years), a divided organization and lack of social cohesion undermined the effectiveness of the sustainable interventions brought in by the research team. In many situations, uncertainty is perceived as a threat because it cannot be resolved and may possibly spin out of control. This situation was evident after the research team left the area and the majority of EFO members were left with uncertainty in many aspects of their practical operations that eventually led to the collapse of organization in 2012. These uncertainties were inevitable consequences left with individual farmers in their respective villages whereas with researchers/scientists these uncertainties were converted to new research agendas for future enquiries. Meanwhile, Ezigeni farmers were able to practically experience natural resource challenges being resolved in their participation on research trials. New informal markets were strengthened in their pursuit of traditional vegetable niché growth through direct contact with organic produce of high value made accessible to many. Contrary though, the participation for direct material gains of having access to formal market was shown by many when the research team left the area. Established and expected sustainability pillars were destroyed, and ensuing natural resource improvements were neglected/rejected after incentives[6] end.

It is unfortunate that the absence of extension officer (Eo) in the growth process of EFO is a historical challenge based on the fact that as a result of their formal training Eo's had limited expertise and competencies in organic farming, especially indigenous crops. In a more formal request through the chairperson of EFO (2001–2004), a reversal of roles was suggested that whereby EFO members provide exposure in traditional and organic farming to extension officers and departmental staff since it was known that farmers already knew a lot more about this system than the officials. This noble gesture was viewed like a subtle offence by the departmental staff which resulted in distance created between these two entities that lasted for more than two decades. This long-term situation yielded negative results as the role of extension

[6]Incentives in this regard refer to the ease of access to formal Woolworth's marker perceived to be the only high-value paying market for organic produce as well as not having the stress to search for own market that may pay way less than the formal market. Formal markets assure farmers of reliability of supply and payments until the produce season ends.

officers, which was anticipated to be of critical importance in the sustainability of EFO post research project duration, was not fulfilled. Extension officers provide a constant advisory and support service to farming groups throughout the province. It is expected that when all projects reach their exit phase, extension officers will take over to play the role of support structure for all the systems created/established during research project to continue and encourage farmers in using the technologies. Government should develop enabling policy environment that will advance sustainable agricultural technologies like traditional organic farming, infrastructural investments toward improvement of market access and communication channels. Therefore, practical evidence seen at Ezigeni after a decade shows that sustainable agriculture can be achieved and maintained when founded upon appropriate technology adapted by farmers' experimentation; social learning and participatory approach between research team and farmers; good linkages between project/initiative and external agencies, together with the existence of working partnerships between agencies including government departments and strengthened social capital at local level. Despite Ezigeni representing just one out of five villages showing sustainable development over the years, their success is noteworthy as the example to highlight and promote for repetition of best practices elsewhere in the future.

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Correction to: Sub-Saharan Africa Smallholder Farmers Agricultural Productivity: Risks and Challenges

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Correction to:
Chapter 3 in: H. A. Mupambwa et al. (eds.), *Food Security for African Smallholder Farmers*, https://doi.org/10.1007/978-981-16-6771-8_3

This chapter was inadvertently published with an incorrect word in the title, which has now been corrected to "Sub-Saharan Africa Smallholder Farmers Agricultural Productivity: Risks and Challenges".

The updated online version of this chapter can be found at
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H. A. Mupambwa et al. (eds.), *Food Security for African Smallholder Farmers*,
Sustainable Agriculture and Food Security,
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H. A. Mupambwa et al. (eds.), *Food Security for African Smallholder Farmers*, Sustainable Agriculture and Food Security,
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