Sustainable intensification of food production through resilient farming systems in West & North Africa

D 5.5 TECHNOLOGY SCORE (1)

Analysing technology and practices for gender, nutrition, climate resilience, environmental, economic and social impact.

Contents

SustInAfrica WP5: Analysing technology and practices for gender, nutrition, climate resilience, environmental, economic, and social impact.

In the context of SustInAfrica project, the deliverable D 5.5 reports the tools and indicators used to assess each innovation proposed by the project against a number of factors (parameters) aiming to analyse and score each technological innovation for climate resilience, environmental and social impact.

In the SIA project proposed innovations respond to different needs and problems, have different requirements and also show have differentiated TRLs. Their stage of development in some cases doesn’t allow to gather a proper amount of information to build a full business plan for each one, then the present document aims to provide information about the current state of development, reason for adopting them in relation to climate resilience and environmental and social impact issues and questions that may hamper their adoption.

1. Bluleaf app

Bluleaf (https://www.bluleaf.it/en/home-eng/) is an Italian-made complete and smart technology-based solution developed through collaboration between research institutions and the private sector designed to optimize the agronomical input to help the farmer to take the best possible decision during farming activities.

Gender	Women in many countries face greater constraints to production through a lack of access to assets, resources, and services than men and face different challenges and unequal opportunities in accessing and benefiting from irrigation technologies. BluLeaf could improve women's involvement in local decision-making structures regarding water management, however this will be dependent on women's phone ownership levels and the type of phones owned by women, which varies significantly by country. BluLeaf requires a smart phone, which limits use to women who can afford a smart phone and access to data. Poorer women are more likely to own basic \$10 phones or \$50 "feature phones". Emerging evidence suggests that women are more likely to use irrigation technologies to grow nutritious crops for household consumption. The tool could reduce the time required for irrigation and ultimately reduce women's workload. Access to improved irrigation systems should positively impact women farmers' productivity. BluLeaf optimises the use of irrigation water based on agronomic principles, but it does not take into account the power and status issues that often govern water allocations in larger irrigation schemes.
Nutrition	Bluleaf has a positive impact on food production. Bluleaf produced 41.76% higher biomass and 67.14% higher yield in wheat compared to rainfed production (Saab et al., 2019). Therefore, Bluleaf DSS can be used to produce higher yield. Bluleaf DSS could be also useful to control excessive vegetative growth and to improve fruit quality with higher nutritional value and without a yield penalty. Overall, BluLeaf has the potential to improve food and nutrition security at the household and comunity levels, however the impact on nutrition will depend on how much of the irrigated land is used for food or cash crops .
Climate	The calculation of hydro-climatic parameters is tedious and time-consuming for local water users. Currently available climate models do not support simulation and downscaling of parameters of interest in irrigation practice, such as crop evapotranspiration and irrigation water demand (Rowshon et al., 2019). The Bluleaf DSS will help growers make climate-resilient decisions as allows the simulation of real-time hydro-climatic parameters (e.g., effective rainfall, reference evapotranspiration, irrigation requirements) based on a daily water balance, calculated on data from the field, weather, and farm features. The tool provides recommendations for daily irrigation and forecast for next week's needs based on plant physiological characteristics and end-user requirements. The technology has been extensively experienced in real environments confirming its robustness and its capability to save water: 25 to 34% in Kiwi production in Italy (Buono et al., 2022), 25.7% in wheat production in Lebanon (Abi Saab et al., 2019), 38.2% to Zucchini in Italy (Canaj et al., 2021). For SustInAfrica the tool is relevant for irrigated crops like Mango in Ghana, super-intensive Olives in Tunisia, and Cotton production in Egypt. The volume of water required to support these crops is estimated at between 7,000 and 8,000 m^3/ha for Mango, and 2350 m^3/ha for Olives (Ben Abdallah et al., 2021), and 5200 m^3/ha for Cotton. If only 10% water saving is achieved, benefits range from 235 to 800 m3/ha. Water-saving irrigation can serve as a useful enabler in dealing with climate change (Zou et al., 2012).
Environment	Bluleaf had 13.5% higher yield-water productivity than traditional farmer practices (Saab et al., 2019), therefore it can be used to achieve higher yields and produce stability or even the same yield with less inputs of resources. For each cubic meter saved 0.239 kWh/m^3 or 0.059 litres of diesel is saved (Nemecek et al., 2020). The benefits in terms of global warming for electricity will depend on national production mixes and electricity at the grid while for each litre of diesel saved 3.66 kg CO_2-eq are saved. Canaj et al. (2021) estimated that Bluleaf can reduce damage to human health by 12%, damage to ecosystem quality by 15%, damage to resources by 11%, and overall environmental impact of Zucchini production by 13%. The combined effect of smart irrigation and fertilization will be higher as fertilizer application is one of the most important contributors to the environmental footprint of crop production. For fertilizers and pesticides 11.6 kg CO_2-eq (nitrogen), 1.88 kg CO_2-eq (phosphate), 1.5 kg CO_2-eq (potassium), and 11.4 kg CO_2-eq

	(pesticides, unspecified) are saved only from manufacturing and transportation at the farm. Fertilizer emissions occur in the field including ammonia volatilization (NH_3) to air, dinitrogen monoxide (N_2O), CO_2 to air from lime, urea, and urea-compounds application, and nitrate NO_3 to water unspecified (leaching from N-fertilizer application. For each kg N fertilizer applied 0.022 kg N_2O is emitted. Nitrous Oxide (N_2O) has a GWP 298 times that of CO_2 for a 100-year timescale, thus 6.55 kg CO_2-eq are saved. The water-fertilizer-pesticides benefits will bring benefits not only from energy and global warming but also in terms of water consumption acidification, eutrophication, resource scarcity, human toxicity, and eco-toxicities when considering a life cycle assessment perspective. Irrigate fields can be a significant source of methane emissions. BluLeaf could be adapted to minimise the soil methane emissions per kg of crop yield but as this is highly soil and crop specific it will require additional research.
Income	The adoption of BluLeaf increases yield stability, income and resilience of communities. Access to irrigation reduces the risks of crop losses, usually high in rainfed systems. Irrigation can boost crop yields as much as three times and can enable farmers to grow multiple harvests per year, also during dry periods. It is demonstrated that access to improved irrigation systems and intensification techniques would dramatically increase the overall benefit of agricultural production in terms of increasing incomes and reducing poverty (Lefore et al., 2017), if equity issues in water allocations can be addressed.
Social	Through better use of water, fertilizer, and plant protection products the increased quality of food, food safety, and security is expected. This can help to have more trust in the quality of food products and better health for consumers and succession and farm continuity. Bluleaf offers a farm recording tool to keep regular records of-farm practices and technical activities, helping growers to measure their efficiency and progress throughout the year and have more data available. Through the adoption of Bluleaf farmers can remotely monitor and engage in agricultural production activities with a mobile phone. These features can be a way to respond to the challenges posed by the COVID-19 pandemic, a crisis that interrupted agricultural operations and triggered reflexivity about the operation of the farming systems (Meuwissen et al., 2021). The tool helps in the identification of critical stages in the production cycle, indirectly contributing to ease of work and reduce stress. Maximising the social benefits of BlueLeaf requires addressing any equity issues in water allocations and ensuring that all users can access a smart phone. The current format requires good literacy and numeracy skills, some ICT and irrigation technical skills, which may limit its use to trained extension workers and better educated farmers, however providing BluLeaf services could provide a micro-business opportunity for tech-savvy youth.
Scaling	Bluleaf is a widely available and versatile tool. It is field-tested and tailored to a real-world setting and for any field. For smallholders farmers forging mutually beneficial ventures between them and local financial institutions is the key to sustainable scaling up efforts to co-finance the initial investment cost. Coherent national and regional irrigation policies are needed to increase water availability and the adoption of irrigation and associated managing tools. Government can support investment in infrastructure, provide irrigation extension services and create policies for the rational use of water. Wider awareness about smart irrigation technologies and practices is needed and can be achieved through training, demonstration fields, visit and campaign. Training tech-savvy youth to provide irrigation advisory services through BluLeaf could be an option for scaling (BluLeaf Agent business model). This would provide a commercial incentive to scale up BluLeaf, create employment in agriculture for educated youth and enable farmers with limited literacy and numeracy skills to utilise BluLeaf.
Replicability	The scale of adoption of Bluleaf are the plots or field units with homogeneous characteristics of climatic conditions, soil confirmation, etc. The required data are soil parameters (texture, chemical-physical analysis, profile), characteristics of the crop (phenological phases, type of plant), typology of irrigation system, water quality and management strategies. The first year requires substantial data collection for calibration. From the second year onwards data requirements reduce. Data collection can be either on PC and smartphone/tablet, which requires basic ICT for successful utilization. Knowledge transfer activities, continuous professional development, and training from agricultural experts and services will be required to optimise the system. Low overall smartphone ownership in rural areas, combined with the high cost of the internet and limited network coverage, also present challenges to the use of mobile agricultural applications and limit the scope to use of social networks (FAO, 2019). Bluleaf requires an agrometeorological station, soil and plant sensors, and flow and pressure

	meters, which may not be an option in areas of insecurity. The adoption requires an initial investment cost of 80 € per plot/year and about 3.000 € for a complete toolset for crops and weather monitoring. The investment cost could represent a major challenge in developing countries where rates of poverty among farmers are often high (FAO, 2014). Using a cost-benefit analysis Canaj et al. (2021) demonstrated that despite smart irrigation with Bluleaf imposes upfront investment costs, these costs are offset by the benefits to water and energy conservation associated with these practices. In general, irrigation scheduling tools are worthwhile in farms with low water availability, high profitability, and significant technical-economic capacity (García et al., 2020). The BluLeaf Agent model could overcome the problems of investment and security of the equipment - with the Agent owning and operating the equipment as part of the BluLeaf service provided to farmers in the irrigation scheme. BluLeaf is likely to be replicable with medium to large scale commercial farmers/ emerging farmers, large community or cooperative managed irrigation schemes. The break-even size of the schemes will depend on the value of the crops produced.
IP	Bluleaf (https://www.bluleaf.it/en/home-eng/) is a complete and smart technology-based solution designed to help farmers and agronomists manage everyday activities in the field. Bluleaf is based on a Decision Support System (DSS) platform that integrates weather and soil sensors with soil water balance and irrigation scheduling models. Bluleaf was first developed in 2012 through a collaboration between Sysman, CNR, CIHEAM, and a number of academic institutions.
Public/ commercial	**Commercial**. BluLeaf is a commercial product and based on the investment costs and the data needs BluLeaf has greater potential as a commercial opportunity. Adoption as a public good is unlikely in most countries unless a hybrid model is developed, with farmers paying Government Irrigation Extension staff to provide the BluLeaf service. SustInAfrica should develop and test business models where agents (tech savvy youth, cooperatives, agro-input dealers, etc) operate the meteorological equipment and provide a commercial service to farmers.
TRL	TRL > 8; Bluleaf has been continuously developed starting from 10 years ago with help of regional and EU funds.

2. Farmerline

Farmerline Ltd (https://farmerline.co/) is a tool to communicate and collect data to/from smallholder farmers in rural regions of West Africa, by a Ghanaian social enterprise that develops ICTs (web and mobile applications), whose main aim is to create prosperous farmers and thriving agric businesses.. It was launched in 2013 in Ghana and it has been operating for the last 8 years in Cameroon, Malawi, Nigeria and Sierra Leone, reaching 200,000 farmers; Mexico and Peru have shown an interest in the technology.

Gender	Farmerline has recently launched the Women Advancing Agriculture (WAA) Initiative, which will send educational voice messages in local languages directly to the mobile phones of female agricultural workers. Before Farmerline, women had very little access to agricultural information. Farmerline sends to women messages on the weather, the best agronomic practices to maximise yields. Audio content is location-specific and provides actionable information on best farming practices, regional market prices, weather forecasts, maternal health, and financial literacy. The goal is to ultimately improve the yields and incomes of female agricultural workers by providing convenient access to education on agronomy, on how to gain formal financing and to relevant family planning methods. Though Farmerline has used innovative approaches to address literacy barriers to the use of the platform, access to information by women will be dependent on women's phone ownership levels and the type of phones owned by women, which varies significantly by country. Farmerlines services requires a smart phone, which limits use to women who can afford a smart phone and access to data services. Poorer women are more likely to own basic $10 phones or $50 "feature phones". Farmerlines services may be more widely used by women if they can run on the KaOSoperating system used in some feature phones
Nutrition	Increasing farmers' access to high-quality production inputs and education on the best farming practices with help them increase crop yields and quality, increasing the produce nutritional value, increasing availability of more nutritious foods in the household, increasing the household income and, as a consequence, a more nutritious balanced diet. access to Farmerlines services will depend on the affordability of smart phones and mobile data services.
Climate	Farmerline's technology platform helps smallholder farmers to more easily adapt to climate change by increasing their income and reducing their income volatility by providing them with access to inputs and markets while helping them to perform sustainable and climate-smart practices which

	perfectly fit ARAF's investment strategy. Farmerline can be used to provide short term downscaled climate and weather forecasts to farmers in an easy to understand format.
Environment	Famerline improves the farmer's knowledge and skills on farming practices, saving fertilizer and agrochemicals reducing pollution. It helps to rationalise the use of natural resources inputs like water or soil and preserve soil fertility thus reducing environmental impact.
Income	By providing smallholder farmers with timely and relevant agriculture and market information that will increase their yields, income and autonomy. The company estimates that some farmers increased their revenues by more than 50 percent using Farmerline. This is a huge return, seeing that Farmerline only costs farmers $2-3 for a few months[1].
Social	Farmerline provides a way to challenge food insecurity and sustainability in Africa. Farmerline aligns work with technology; it provides a platform recording all the data on activities and operations, thus, staying in touch with farmers and other partners. It helps all actors of a value chain, so that farm input companies know in real-time which input they need to aggregate for farmers, traders get to know where the increase in yield is coming from and can predict harvest time and adequately prepare logistics, and the government can be relieved from providing direct support to farmers because farmers now make more yield and more money, policymakers expand to areas where the focus has not previously been. Additionally, funders know where more funds are going to be required. Farmerline was used also as a tool to reach out to farmers across Ghana through mobile voice messages to give them vital information and awareness of COVID-19 in local languages. There is a risk of "data apartheid", with those able to afford smartphones and data service improving their livelihoods while those without access stagnate. This risk will depend on how much communities share information.
Scaling	Farmerline has been able to orchestrate rapid scaling and innovation while remaining focused on its end beneficiaries. The company has secured US$6.4 million equity investment by Acumen Resilient Agriculture Fund (ARAF) and FMO, the Dutch entrepreneurial development bank, and also features Greater Impact Foundation. Lenders of the US$6.5 million debt include DEG, Rabobank, Ceniarth, Rippleworks, Mulago Foundation, Whole Planet Foundation, Netri Foundation and Kiva.
Replicability	Lack of basic literacy and numeracy often presents a significant barrier to using digital technologies, but in the case of Farmerline, no particular skills are required. Additionally, the linguistic sub-type of cultural capital is high as, besides English, it can be operated in local languages, thus, reaching farmers with low literacy levels and increasing usability. Availability of cash money/Liquidity can easily limit the adoption of innovations; this can be a prohibitive disincentive, especially in the absence of secure land rights and access to financing and credit. Expensive or inaccessible credit restricts the capital available for farmers to invest in their crops, contributing to low yields and profits. Credit is very hard to obtain for most smallholders in rural Africa due to the creditworthiness of most farmers, administrative costs and to the associated risks in farming, moreover, the lack of absolute ownership of the land implies insecurity. Farmerline operates in a context where local communities and smallholders have little cash for much of the year, therefore it has embraced a digital finance program that facilitates rapid credit rating and loan provision. The App Farmerline tracks loan repayment and integrates biometrics like voice and fingerprint recognition to increase credibility and remove the literacy-related issues surrounding contracts. Moreover, to maintain its success, instead of charging the farmers for access to information, Farmerline derives 90% of its revenue from the food companies, exporters, big buyers, and by the businesses that are working with farmers. Weak network coverage and access to electricity for charging the phones is a problem that app-builders can't resolve. Farmerline provides services also in offline mode, so it's ideal for areas with low connectivity. Another threat to ICT and agricultural technology adoption is the prevalence of poor-quality or counterfeit seeds and other inputs in the market. Trustworthy agro-dealers are forced out of the market when they cannot compete with cheap, counterfeit manufacturers. After continuing to buy counterfeits, farmers may lose trust in the efficacy of genuine inputs. Farmerline delivers quality farm inputs through partner agribusinesses (retail shops).
IP	Launched in 2013, Famerline is one of the largest private employers in the Ghanaian agricultural sector and the intellectual property owner of Mergdata and all other digital solutions offered. Mergdata is Famerline's cloud-based mobile and web software application that enables

[1] https://borgenproject.org/farmerline-food-security-in-ghana/

	organisations to digitally collect data from farmers, farms, and farming communities. It is compatible with all commercial browsers.
Public/ commercial	Farmerline is a commercial enterprise, with farmers paying a monthly fee (€2-3) and generating additional revenue from food companies and large buyers using its services.
TRL	TRL > 8; Developed 8 yrs ago;

3. InsectaMon

Pests, diseases and weeds can be a major constraint to the intensification of cropping system in sub-Saharan Africa (Ratnadass, 2020) and IPM is an approach that allows to assure equitable, secure, sufficient and stable flows of both food and ecosystem services (Bottrell and Schoenly, 2018). InsectaMon is an AI-based pest insect monitoring system proposed for the SustinAfrica project currently calibrated and tested on different sustainable farming system and agricultural practices in Ghana (on pineapple), Burkina Faso (on cotton) and Tunisia (on olive). The project aims to make InsectaMon technology available via an app.

Gender	Women usually participate actively in crop protection, doing manual weeding, hand-picking insects and applying crop protection products. Therefore women farmers are probably responsible for a majority of pest management activities in African agriculture and may be exposed to crop protection chemicals. Notwithstanding the persistent gender disparities in access to productive resources, InsectaMon will increase the control of women on agricultural production and marketing. The impact on women’s workloads and health will depend on the business model adopted for Insectamon. An Insectmon smartphone app will be limited by women’s access to smartphones and data services, however small businesses could provide local InsectaMon - based crop protection services that are accessible to women, and InsectaMon could be incorporated into CABI’s Plant Clinic/ Plant Doctor services that have been scaled out across many countries in Africa.
Nutrition	The main benefit from the adoption of InsectaMon is improving of the quantity and quality of food products and of its nutritional value, due to temporal and spatial monitoring of insects up to the species level that allows farmers to better decide how to implement crop protection over the season reducing residues on food. This should reduce damage to crops and therefore increase availability of nutritious food at household level and in the market. By enabling farmers to apply crop protection measures at the most appropriate time (Integrated Pest Management) Insectamon should reduce crop protection chemical residue levels in harvested crops.
Climate	InsectaMon improves farmer's knowledge and the planning of preventive farming practices and pest management practices. Insectamon should help identify and track invasive species that are spreading as a result of climate change and could be used to understand how variations in weather parameters can impact pest settling, multiplication and distribution.
Environment	Benefits for the environment may derive from the reduced and more rational use of chemicals that leads to a decrease of pollution but also for the possibility to reduce impact of treatments on pollinators and on beneficials with great advantage for the functional and overall biodiversity
Income	InsectaMon should decrease the cost of production by reducing the use of chemical crop protection products, reducing incidence of plant pest damages and also reducing the amount of low quality produce, and of crop wasted/ rejected at harvest. The tool will maintain or improve crop yields while saving on agricultural production costs. Randomised control trials of a similar app, Plant Village Nuru, for detecting cassava viruses in cassava plants developed by Penn State University and IITA reduced the levels of cassava viruses in cassava used as planting material, increasing crop yields.[2]
Social	Farmers and agricultural workers are exposed to crop protection chemicals when they mix and spray pesticides and poisoning is well documented (Jeyaratnam, 1990). Contamination of the soil, air and water exposes the wider community and consumers to pesticides and pesticide residues. The tool is expected to increase quality of work (less work intensity and better working quality), the level of satisfaction of producers, increasing also trust in the safety and quality of food products. It can also contribute to reduce stress due to pest management as decrease pest development unpredictability.
Scaling	The tool offers help to generate new knowledge and share information with farmers. It relies on future-oriented ICT combining affordable sensor technology with a smart intelligent design based on machine learning. If Insectamon can be developed as a smartphone app scaling should be rapid, however the app will need to compete with, or merge with similar AI-based apps like Plant Village

[2] PlantVillage Nuru – Apps on Google Play. PlantVillage (psu.edu)

	Nuru. Scaling will depend on the business model adopted by the developers.
Replicability	New insects can be added to the Insectamon software as required, however this requires a large set of training and testing images for the AI algorithm and expert support for classifying the images. InsectaMon will have the greatest impact when used as part of an Integrated Pest Management Strategy. The adoption of IPM principles and tools limited by insufficient training and technical support to farmers, lack of favourable government policies and support, low levels of education and literacy among farmers and the challenges of pest scouting (Parsa et al., 2014). InsectaMon can reduce the work required in pest scouting. IPM requires a substantial understanding of crop-pest-environment interactions. Farmers often have a limited understanding of unintended effects of plant protection products and that leads to excessive use, reduced cost-benefit and subsequent environmental and safety hazards. On the other hand, under-dosing might create problems of pest resistance development. A specific expertise of user is also required for product training and technical training that can be done by local experts trained by technology developers.
IP	The technology is experimental. The core development will be done during the SustInAfrica project lifetime and subcontracted to a digital solution developer. It will be calibrated and tested on different sustainable farming practices in Ghana with pineapple, in Burkina Faso with cotton, and Tunisia with olives.
Public/ commercial	**Commercial**. Like similar AI-based pest identification software/ apps, Insectamon will only move beyond the R&D phase if a suitable business model can be developed. The development of a smartphone app is the obvious solution but the app will need to generate sufficient revenue to update and expand the app. Small businesses could provide local InsectaMon - based crop protection services, and InsectaMon could be incorporated into CABI's Plant Clinic/ Plant Doctor services that have been scaled out across many countries in Africa.
TRL	TRL > 2; Experimental proof of concept

4. Application of Remote sensing

Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring it's reflected and emitted radiation at a distance, typically from aircraft, UAV (Unmanned Aerial Vehicles) or satellite. Satellite remote sensing of land plays a role in many aspects such as the exploration of mineral resources, the monitoring of floods and droughts, soil moisture, vegetation, deforestation, forest decline, forest fires, carbon storage, or land cover, road monitoring, and urban and agriculture planning. In agricultural systems, satellite observations can be used to assess a wide variety of geophysical and biophysical parameters, including precipitation, temperature, evapotranspiration, soil moisture, and vegetation health.

The agricultural UAVs use has expanded across all areas of agriculture, including pesticide and fertilizer spraying, seed sowing, and growth assessment and mapping. UAVs have resulted in increased stability, measurement accuracy and productivity. They are less expensive than most other agricultural machines and also they are easily operated and their applications have contributed to the expansion of many areas of agriculture, including insecticide and fertilizer prospecting and spraying, seed planting, weed recognition, fertility assessment, mapping, and crop forecasting.

Gender	Not clear at this stage.
Nutrition	High-resolution satellite imagery can be used to make predictions of smallholder agricultural productivity, i.e. to estimate and understand yield variation at the field scale across African smallholders. The satellite can support increasing agricultural output to support modest gains in income and food security (Burke and Lobell, 2017).
Climate	Satellite remote sensing has provided major advances in understanding the climate system and its changes, by quantifying processes and the Spatio-temporal states of the atmosphere, land, and oceans. Several types of tools and indices by the satellite remote-sensing have been developed for

	monitoring drought occurrence and stress, changes in land use, and crop–soil water relations. Satellites can monitor agricultural conditions to detect soil and crop conditions and features, monitor growth, and analyse soil and irrigation requirements (Jindo et al., 2021).
Environment	Remote sensing can be used for precision agriculture with farmers utilizing satellite data in deciding how much fertilizer/water to put on their crops and how to distribute it. Remote sensing can be used in environmental impact assessment in agriculture systems. SHA and others have proved the potential to combine AI and remote sensing to track crop pests, enabling targeted control that could reduce the costs and risks of chemical control measures and improve the efficacy of non chemical control approaches for smallholder farmers.
Income	Evidence of profitability to farmers remains unclear. Some government agencies, for example the European Space Agency (ESA) Copernicus programme, NASA's LANDSAT, TRMM, and MODIS missions provide free access to medium resolution satellite data that could help to reduce costs to the user.
Social	Remote sensing helps in Food security (land use[3] biofuels, productivities, nitrogen contamination, desalination, climate change), water quality (nutrients, land use change, access, urban/rural, oil spills), Air pollution, and health (particulates, urban pollution), biodiversity management (land use change), information for society (Impact of regional SDIs) and disasters (typhoons, heat waves and pest outbreaks).
Scaling	Remote sensing is most needed when it is difficult or expensive to collect data in other ways, such as for smallholder farmers, many of whom live in remote areas. Most farmers do not have the skills to utilize these technologies effectively. Lack of knowledge and/or financial means, incompatible equipment, or small plot sizes reduce the financial attractiveness of the technology for the farmers (Blasch et al., 2021), but the adoption of such tools can be possible by creating a connection between researchers and extension services to allow better planning of crops and resource use. Though UAVs can be used when and where required, satellite imagery is not always available for the appropriate period, region and resolution, particularly for those regions of SustinAfrica that have little economic, strategic or security value, where satellite passes may happen less than once per year. UAVs are limited by national regulations (see D5.2 IP Frameworks). Though UAV regulations are widely ignored[4] or are unenforced/ unenforceable in practice this project assumes that the regulations will restrict the use of UAVs in some countries.
Replicability	Remote sensing is highly replicable but requires expert support, favourable government policies and support from government officials.
IP	Remote sensing satellite systems produce images that are subject to copyright and, unless the imagery is provided free, the sharing and use of images is restricted by the licencing agreements. The technological process to acquire the data is under a patent regime because every satellite system uses proprietary technology. Processed data or value added to the raw data on the other hand can be protected by copyright rights.
Public/ commercial	**Commercial**: new/ high resolution satellite imagery is a commercial product and can be very expensive. Lower resolution imagery and imagery more than six months old is often released free of charge by satellite companies as a public good. Operating UAVs in Africa is a commercial business, with small UAVs operated by professional photographers contracted to record social events. Potential for UAV operators in rural areas to provide services to farmers.
TRL	TRL 6 – technology demonstrated in relevant environment

5. Farming system technologies and practices

In order to achieve a sustainable intensification of African Countries, beside technological innovations ***SustInAfrica*** (SIA) will integrate also some knowledge intensive innovations promoting various mixed cropping approaches also based on introducing farming system technologies and agroecological practices that are new to the specific area of interest. The introduction of specific farm producing technologies and practices in areas where they are new or not widely adopted contributes to the innovation potential promoted by the SIA project.
Table 1 summarizes the farming system technologies and practices proposed by the SIA project to be tested for each crop, area and AEZ. The information was extracted from Deliverable D3.2 of Work Package 3

[3] OneSoil | Free Farming App for Precision Agriculture

[4] Small UAVs are widely used across Africa for wedding photography, football matches and other social events, regardless of national laws.

(“Multiple Agro-Ecological Zone – [AEZ] - and crop-specific demonstration trials utilizing various agro-ecological tools and approaches”).

Table 1. Farming system technologies and practices to be tested proposed practices for each crop and region within the SIA project.

	Mango (GH)	**Pineapple (GH)**	**Maize-Push pull (GH)**	**Olives (TN)**	**Cotton (EG)**	**Olive (EG)**	**Date Palm (EG)**	**Cotton (BF)**	**Millet (NG)**
Management	Organic	Organic	Conventional	Conventional	Conventional/Organic	Conventional/Organic	Conventional/Organic	Conventional/Organic	Conventional/Organic
Compost	x	x	x	x	x	x	x	x	
Biochar	x	x	x					x	
Cover cropping		x		x					
Intercropping	x	x	x		x	x	x	x	x
Pest control					x	x	x		x
Flower strips		x							
Biofertilizers					x	x	x		x
Chemical fertilizers			x						x
Tillage				x					
Bluleaf	x			x	x	x	x		
InsectaMon	x	x		x					
UAV remote sensing	x	x		x					
Satellite remote sensing	x	x		x					
Farmerline									

6. Compost

Compost is the product of artificially controlled bio-oxidation and humification of a mix of organic materials such as solid organic waste from green and woody biodegradable plant residues as pruning waste, manure, and sewage waste. Composting is generally achieved by converting solid wastes into stable humus-like materials via biodegradation of putrescible organic matter (Huang et al., 2000). Compost has been used to improve agricultural soils for hundreds of years, but only in the last few decades have we begun to understand the science behind this practice.

Gender	In small-scale agriculture, where stabling/ kraaling or tethering of small livestock is common, women are involved in the management of soil health via composting and other techniques to improve soil fertility. Composting is not a new technology, and most farmers are already aware of the benefits, however the main barriers to the greater use of composting is the availability of compostable materials and the need to transport the compost to the fields. Small farmers, <0.5 ha, in the dryer tropics rarely generate enough biomass to produce enough compost for more than the vegetable beds. Livestock may consume much of the material that could be used to make compost (crop residues and roadside grass), and research in Zimbabwe has shown that the Gross Margins for feeding crop residues to cattle are higher than using the residues for mulch or compost. Where landholdings are fragmented poor farmers may not own carts, donkeys or other options for transporting the compost to distant fields. Concentric “soil fertility rings” around homesteads are a common phenomenon in Africa, with the fields nearest the homestead receiving the greatest amount of compost/ kraal manure. There is a risk that compost will increase women’s workloads, as women may be expected to collect additional compostable materials from community resources (forests) and transport the compost to fields on their heads[5].
Nutrition	When compost is added to soil, it has multiple positive effects on its physical, chemical, and biological properties, which result in improvements in the productivity and quality of crops

[5] This is common practice in the Mid Hills of Nepal, with women collecting leaves from community forests and roadsides to make compost and transporting the compost up hillsides in “dokos” - baskets carried on their backs with a headband..

	(Ho et al., 2022). A paper of 2013 reports an extensive literature review and lists benefits arising from the use of compost; among those a gain in crop nutritional quality (Martínez-Blanco et al., 2013). The impact of compost will be dependent on the quantities that can be produced, the nutrient levels in the materials used to make the compost, and any nutrient leaching from the compost heaps.
Climate	Using agricultural by-products, predominantly manure, as compost may also be an effective way to sequester and stabilize carbon in soils: a trial ran for 19 years showed that the use of compost and cover crops boosted soil carbon content by 12.6% (Tautges et al., 2019). Where animal manure is used for compost production NOx may be released from the compost heaps and lost to the atmosphere unless the compost heap is covered.
Environment	The use of biowaste compost on land can have beneficial effects on the plant-soil system. Nine environmental benefits were identified in an extensive literature review: nutrient supply, carbon sequestration, weed pest and disease suppression, increase in crop yield, decreased soil erosion, retention of soil moisture (blue water is saved), increased soil workability, enhanced soil biological properties and biodiversity and gain in crop nutritional quality (Martínez-Blanco et al., 2013). Environmental burdens from over-irrigation, overuse of herbicides and pesticides and fertilizers are reduced and when pesticides are considered, environmental benefits are related to both the avoided production/transportation and the avoided use in the field, that can consequently be credited to the system as an environmental saving.
Income	On-farm production of compost has many economic benefits for the farmer. It is low cost or inexpensive to produce, can be made with locally available materials, improves soil fertility, is environmentally friendly, does not require a great deal of skill or technical know-how, is inexpensive to purchase, and boosts food production. All those aspects reduce costs or save money for production or increase income. Farmers with larger landholdings, livestock and access to transport will realise greater benefits from compost than resource poor farmers. Commercial production of compost from urban waste and organic industrial waste has struggled to compete with synthetic fertilisers due to the high transport costs of the high volume/ low nutrition density of compost compared to synthetic fertilisers. There is a large range in the nutrient content of organic fertilisers but as an example 4 bags of organic chicken manure (4.5:03:03) would be required to replace 1 bag of synthetic NPK fertilizers (16:06:12)
Social	Compost is not just beneficial only to farming, because it is produced from waste, it also helps the circular economy process and leads to more sustainable production methods. It improves contaminated, compacted and marginal soils through better soil water-holding capacity, nutrient retention and soil structure. It provides cost savings over conventional soil, water, and air pollution remediation technologies. Economic barriers to the production, purchase and transportation of compost may limit the use of compost by resource poor farmers.
Scaling	The most prevalent barriers are either financial, institutional, or informational (Viaene et al., 2016) and may arise in case of purchase. Barriers to using compost in case of purchase include high cost, the uncertainty of product availability when it is needed, complex regulations, lack of knowledge and experience with using compost, quality of compost, and the perception of the risk of spreading weeds and diseases. The economic viability of the composting plants depends on several factors, such as the availability of compostable materials, the selection of suitable processing methods, technologies, scale, quality of product, and marketing strategies (Pandyaswargo and Premakumara, 2014). The current very high price of synthetic fertilisers may make the production, sale and transportation of organic compost made for urban and industrial waste economically competitive
Replicability	The financial stimulus for on-farm composting to compensate for the high production cost associated with compost is needed. Also, a certain degree of flexibility in current policies and institutional arrangements could stimulate compost production and application (Viaene et al., 2016)
IP	N/A
Public/ commercial	Public and commercial. Training in on-farm compost production is a public good and there are opportunities for entrepreneurs to produce commercial organic fertilisers from waste streams.
TRL/SRL	TRL 9 – actual system proven in operational environment

7. Biochar

Biochar is defined as a carbon-rich material produced during the pyrolysis process that is a thermochemical decomposition of biomass (crop and forestry residues, manure, municipal and industrial wastes) occurring with a temperature of about ≤700°C in the absence or limited supply of oxygen. Smallholder farmers can use biochar to increase crop production and improve food security, when aiming to generate income as well as reduce emissions to improve sustainability. It represents numerous opportunities for synergies in different areas of biomass production and its utilization.

Gender	A project run by the World Agroforestry Centre (ICRAF) and partners in rural Kenya describes women's participation in the improvement of cooking systems using biochar-producing gasifier cooking stoves that use firewood and crop residues as fuel; producing biochar while cooking would attract more women to engage in biochar production and application.(Kinyua et al., 2018). If gasifier stove technology is not available, the production of biochar may force women to travel further in search of fuel for traditional stoves.
Nutrition	Biochar is among the environmentally friendly bio-products possible to enhance agricultural productivity due to its inherent properties. Several studies have reported positive effects of biochar application at the rate of 5-50 t ha^{-1} on crop yields, with appropriate nutrient management (Kapoor et al., 2022). The project assumes that better uptake of soil nutrients from the biochar by plants will result in higher levels of micronutrients required for human health (Fe, Zn, Se) in the crops, but this needs to be tested. To combat micronutrient deficiencies in the diet some countries have mandated the addition of micronutrients to fertilisers (Se in Finland, Zn in Malawi) so fortifying biochar with Zn (using a liquid Zn fertiliser) could have nutritional benefits.
Climate	Biochar can help build resilience to climate change. It may contribute to revitalizing the fertility of degraded soils by sequestering carbon and reducing greenhouse gas emissions, thereby mitigating climate change and global warming (Abdelhafez and Abbas, 2020; Rogers et al., 2022). Additionally, biochar application enhances water retention and water use efficiency (WUE) in plants facing high temperatures (Kapoor et al., 2022) and improves overall soil health and biodiversity, resulting in healthier crops that are more resistant to disease and pests.
Environment	The review of published environmental life cycle assessment (E-LCA) studies by Mohammadi et al. (2020) showed biochar has the potential to mitigate the carbon footprint of farming systems through a range of mechanisms. Yet, the importance of clean technology selection for biochar production in terms of particulate matter and fugitive greenhouse gas emissions is important in the overall life cycle environmental assessment impact of biochar systems (Joseph et al., 2015). Because of its porous nature, biochar can improve your soil's water retention and water holding capacity, so plants will have more water available for a longer period, thus reducing irrigation requirements and frequency (Ndede et al., 2022). Using biochar soil retains more water, however, if biochar is not produced and applied correctly it could have a negative effect on soil. Most countries require cotton crop residues to be burnt at the end of the season to prevent pest carryover. The production of biochar from cotton stalks would return the carbon in the crop residues to the soil, while protecting crops from pest carry-over, though this may require evidence-based policy changes to current regulations.
Income	Biochar could become a completely new income source for farmers and rural regions as increased crop yields are expected. (Rogers et al., 2022) found that food security and family income were cited as the main reasons to engage in biochar production and use in Tanzania. It is argued that biochar can increase revenues (e.g. by increasing yields and crop quality) and reduce farming costs (e.g. reduce requirements for other costlier inputs such as fertilizer and agricultural lime). The use of biochar on commercial farms has required unaffordable high application rates. SustInAfrica will test if the precision application of much smaller quantities can be cost-effective for smallholder farmers.
Social	Biochar provides social benefits in the form of carbon sequestration (climate change mitigation), reduced agricultural water runoff, higher nutritional value, conservation of biodiversity, and higher food security (better yield predictability in the face of weather change), and waste management.
Scaling	The economic viability of biochar production and utilization is still a significant challenge as the cost associated with the feedstock acquisition and transportation, capital, operations and transportation of biochar to application sites significantly affects the economic feasibility of biochar. Feedstock cost is the most critical component of the biochar supply chain and is largely responsible for determining economic feasibility. Biochar-based bioenergy system is economically viable when life cycle costs and environmental assumptions are accounted for (Homagain et al., 2016).
Replicability	Replicability can be reduced by the lack of prior licensing of pyrolysis/gasifier systems in many countries, limited in-practice know-how about pyrolyser/gasifier/biochar systems, lack of skilled labor/technicians and operators for pyrolysers/gasification systems, and risks not sufficiently

	understood, are not additional deployment barriers (Möllersten and Naqvi, 2022).
IP	N/A
Public/ commercial	**Public**. It is unlikely that biochar will be a commercial product, though the production of biochar kilns from old oil drums will create work for local blacksmiths.
TRL/SRL	Biomass pyrolysis and gasification systems TRLs range from 3 – 7 and biochar for soil impact TRLs range from 1-2 (Möllersten and Naqvi, 2022).

8. Intercropping

Intercropping is defined as the agronomic practice of growing two or more crops on the same field at the same time. Intercropping is widely practiced by smallholders in Africa but is less frequent in the more commercially oriented production systems of Latin America and Asia. The major benefits of intercropping are (1) increasing the rate of crop production, with the advantage of simultaneously decreasing the risk of total crop reduction, and (2) controlling weeds. Intercropping is considered by its advocates to be a sustainable, environmentally sound, and economically advantageous cropping system (Khanal et al., 2021). The benefits of intercropping are dependent on the selection of appropriate crop mixtures. With the ideal mix of crops the total production per ha exceeds the production of a monocrop from the same plot (Land Equivalent Ratio). Less effective crop mixes will depress the yields of one or both crops.

Gender	Intercrops are usually more labour-intensive than sole crops because options for using machinery are usually fewer in intercropping (Hong et al., 2020), however women often manage and benefit from annual intercrops as they are expected to provide nutritious food to their families. They also sell surplus production for income generation. Women's labor share in African agriculture amounts to 60-80%, thus intercropping may increase women's labor constraints.
Nutrition	In Africa, a meta-analysis has shown that intercropping increases crop yields by 23% (Himmelstein et al., 2017). The increased production of quality protein and essential amino acids is also achieved by intercropping (Htet et al., 2021). Intercropping increases production diversity and the availability of more diverse foods at household level which in turn can impact on improved dietary diversity and ultimately improve nutrition outcomes.
Climate	Intercropping also enhances the competitive ability of crops for nutrients and water related to monoculture systems. It provides year-round ground cover, or at least for a longer period than monocultures, to protect the soil from desiccation and erosion. It improves soil health and delivers multiple ecosystem services. by increased yield, better soil quality, and soil C sequestration (Cong et al., 2015) through decreasing tillage frequency and soil disturbance, and increasing soil organic matter and carbon storage. In traditional cropping systems intercropping with crops with different water requirements or maturity periods is often used as "insurance" against total crop failure as a result of drought or floods.
Environment	Intercropping with complementary crops has shown significant potential to increase resource efficiency and resilience against biotic and abiotic stresses, thereby allowing to deliver yield gains without increased inputs or stabilizing yields with decreased inputs. Most research findings showed that the yield of intercropping is often higher than sole cropping (Bitew et al., 2021). Intercropping has been considered a sustainable agricultural practice that can reduce the environmental impacts of agriculture (Fung et al., 2019). Intercrop systems have been indicated to use resources differently and more efficiently, especially N-fertilizers (Louarn et al., 2021) compared with mono-cropping. Losses of reactive N from agricultural systems also have major environmental impacts through ammonia volatilization, nitrate leaching, and the emission of greenhouse gases (direct N_2O emissions and indirect CO_2 emissions from the manufacture of synthetic fertilizers) that affect global warming, air quality. Intercropping can reduce insect pest infestations, though the effects of intercropping on pest control depend on the pests and crop mixes. Intercropping maize with soybean or other legumes reduces damage by the Fall Armyworm (*Spodoptera frugiperda*) while intercropping with pumpkins increase damage.
Income	Economic analyses (Arsyad et al., 2020; Huang et al., 2015) of the different intercropping systems have indicated that farm incomes were increased from intercropping as it is leading to on-farm cost savings and reduced reliance on external inputs. In Africa, a meta-analysis has shown that intercropping increase gross income by 172 USD/ha (Himmelstein et al., 2017).
Social	By growing more than one crop at a time in the same field, farmers maximize water use efficiency, maintain soil fertility, minimize soil erosion and reduce the occurrence of diseases, insects, and weeds.

Scaling	Cost of implementation is the largest barrier identified. Farmers also need strong technical and financial support during the adoption process to help them troubleshoot the site-specific complexities and challenges of managing polycultures.
Replicability	The main barriers to adoption by farmers include uncertainty in profitability, increased labour requirements, increased management complexity, risk of competition/yield loss, and risk of pest reservoirs (Huss et al., 2022).
IP	N/A
Public/ commercial	**Public**. No commercial opportunities.
TRL/SRL	8/9: Ready For Implementation Technology is developed and qualified. It is readily available for implementation.

9. Biofertilizers

The term "biofertilizers" has different meanings across Africa, including fertilisers made from organic wastes. In SustInAfrica Biofertilizers are defined as substances that contain microbes which help in promoting the growth of plants and trees by increasing the supply of essential nutrients to the plants through increasing the availability of soil nutrients to plant roots, or stimulating the plants own nutrient uptake mechanism (bio stimulants). The best known biofertilizer are rhizobium species used to inoculate soybean and other legumes to ensure N-fixation. Biofertilisers, are considered environment-friendly and safe for the user, however the cost efficiency is highly dependent on the crop variety, the soil ecology and how well the biofertilizers have been manufactured, stored and transported. The production of novel biofertilizers is a fast-growing industry and farmers and extension staff have limited independent information on the efficacy and cost- effectiveness of new products.

Gender	Women are healthier (significant health impacts from the substitution of synthetic fertilizers) and will be able to take up more income-generating activities.
Nutrition	Biofertilizers can help to increase the quantity and quality of yield, though this depends on the soil conditions and the crops. It is reported a 30% increase in yield (L. Zambrano-Mendoza et al., 2021) as farmers can reduce the application of synthetic fertilizers and sustainably increase crop yield through the use of this technology (which microbes?).
Climate	Biofertilizers help to minimize the over-dependence on synthetic chemicals, thus reducing carbon emissions, though this will depend on using the right microbial strains for the soil conditions. It is possible that biofertilizers that promote the rapid decomposition of soil organic matter could increase the release of NOx and C from the soil, but this is unlikely to happen at an environmentally significant scale.
Environment	Biofertilizers protect the environment from pollutants since some are natural fertilizers. Biofertilizers complement, but cannot replace synthetic or organic fertilisers, as they either make existing soil nutrients available to plants, or, in the case of rhizobium required adequate soil phosphates for N fixation. The carbon footprint of production biofertilisers is insignificant compared to the carbon footprint of synthetic fertilisers. It is found that the reduction of GHG emission in organic fertilizer production in comparison with the emission in mineral fertilizer production was on average 78% for N and 41% for P (Havukainen et al., 2018). There are concerns that the rapid growth of the industry could result in "invasive" soil microorganisms being introduced.
Income	When appropriate biofertilizers are used the crop Gross Margins will improve, however there is a risk that farmers will waste their money on inappropriate products.
Social	Appropriate Biofertilizers are considered a feasible and sustainable attractive biotechnological alternative to increase crop yield, improve and restore soil fertility, stimulate plant growth, and reduce production costs and the environmental impact associated with chemical fertilization (L. Zambrano-Mendoza et al., 2021).
Scaling	Government interventions and strategies impact African biofertilizer development. Investments in current and future technologies are critical for the development and success of biofertilizers in Africa (Raimi et al., 2021).
Replicability	Some of the challenges identified for impeding adoption in Africa are (Raimi et al.,

	2021): 1 Lack of biofertilizer quality control system; 2 Limited capacity to expand production; 3 Lack of advanced production technology; 4 Lack of storage facilities; 5 Ineffective bio fertilizer standards; 6 Lack of farmers' biofertilizer awareness; 7 No regulatory framework; 8 Lack of experienced personnel; 9 Inadequate funding. The effective use of biofertilizers is also dependant on local soil analysis services to ensure that the right products are purchased by farmers.
IP	N/A most biofertilisers are made from naturally occurring soil microorganisms that cannot be patented, however the production process may be subject to patents.
Public/ commercial	Commercial: Most biofertilisers are commercial products that require microbiology skills and equipment to produce. Various projects have proven the viability of producing microbial plant protection products and rhizobium inoculants by small and medium scale enterprises (SMEs) so biofertilisers production by SMEs may be viable. There are also a range of "home-made" biofertilizer options for farmers to experiment with at little or no cost.
TRL/SRL	7-9: Technology is demonstrated in operational environments and it is ready for implementation but the market is not entirely familiar with the technology.

10. Cover crops (CCs)

Cover crops which include legumes and cereals are another effective soil conservation practice to reduce runoff and water erosion. Cover crops are not a new practice, but there is renewed interest in using cover crops to conserve soil and improve soil productivity (Baumhardt and Blanco-Canqui, 2014).

Gender	Cover crops decrease labour for weeding, one of the activities women are frequently responsible for.
Nutrition	Cover crops may have a yield effect on the following main crop (Smit study on wheat). Adopters in different case study regions in Europe (Smit et al., 2019) have estimated that growing CCs increases in yields of the following main crops by 4.2%. Different cover crops have different impacts on soil fertility and therefore crop production and quality. Growing cover crops instead of cash crops can reduce income and this could impact on nutrition outcomes.
Climate	If correctly managed, catch and cover crops can mitigate climate change through soil carbon sequestration (building up the soil organic carbon content of the soil), by reducing emissions from fertilizer production (Smit et al., 2019) and by increasing water availability to the crop. By reducing the area of bare soil cover crops increase infiltration rates, reduce runoff and surface evaporation. By shading the soil cover crops reduce organic matter oxidation and NOx volatilisation and increase soil nutrient cycling.
Environment	As well as climate change mitigation, cover crops can have other environmental benefits including reducing nitrogen leaching (cover crops also trap excess nitrogen, erosion) and improving soil health (better water infiltration and water holding capacity. Thus, cover crops reduce aquatic and terrestrial eutrophication due to water pollution and remove CO_2 from the atmosphere.
Income	Despite the benefits and their positive perception by farmers, there is little information on the cost-benefit trade-off of adopting CCs (Lamichhane and Alletto, 2022). Cover crops are grown for the protection and enrichment of the soil, can be also grown for harvest or to sell. The sowing of CCs can increase farmers' costs (purchase of seeds, cost of cultivation) and additional labor or can decrease costs in case seeds are available on farm and tillage are decreased by the soil cover. Smallholder farmers prefer to use cover crops with a clear economic value (fodder crops for example) and adoption of cover crops, like Mucuna / Velvet Bean and crotalaria, for purely soil fertility reasons is low.
Social	Cover crops serve environmental protection and climate change mitigation goals and have a role in pest management as they can break pest cycles and control weeds.
Scaling	Economic, sociological, and psychological factors influence the decision of farmers to grow or not grow CCs (Smit et al., 2019). To date, seed cost represents one of the most significant barriers to using CCs (Lamichhane and Alletto, 2022). Moreover, there are no subsidies, a lack of awareness, and high labor requirements.

Replicability	The exploitation of CCs faces three key drawbacks: 1 lack of publicly funded CCs breeding programs to ensure that farmers have market access to high-quality seeds; 2 remunerating systems (i.e., public incentives) for farmers (possibly based on the type and extent of ESs they produce e.g., carbon storage); 3 proved cost effective management practices.
IP	Some varieties of cover crops may be protected by breeders rights.
Public/ commercial	Commercial: farmers will probably need to but their initial stock of cover crop seeds, creating an opportunity for SME seed enterprises.
TRL/SRL	TRL 6 – technology demonstrated in relevant environment

11. Pest control

Pest control is a process that maintains nuisance organisms below economic thresholds of damage and builds on complex ecological processes often mediated by biodiversity. A pest control program to reduce pests (e.g., birds, rodents, reptiles, and insects) disease vectors and pathogen includes good prophylaxis and management practices.

Gender	Women spend their time in field-hunting pests and killing them as they are responsible for routine management (Kawarazuka et al., 2020), improved pest control strategies will come with a positive impact on their agricultural labor as will help women to save time for other more rewarding activities. Women farmers and other women farmworkers are frequently exposed directly when working as pesticide applicators or indirectly during harvesting, planting, and soil preparation (Mrema et al., 2017), therefore better safer pest management approaches would improve health conditions.
Nutrition	Pest control contributes to increased farm productivity and food availability by reducing pre-and post-harvest crop losses. Animal pests are a severe threat to global crop production, leading to an estimated average yield loss of about 20% without crop protection (Schneider et al., 2015). Up to 40% of the world’s food supply is already lost to pests (Heeb et al., 2019). A more rational use of chemicals would also improve the produce quality and food safety.
Climate	Improved pest management contributes to the mitigation of climate change by improving overall greenhouse gas (GHG) balance. A reduction in pest-related yield losses decreases the GHG emissions intensity per unit of food produced. Integrated Pest Management stratergies reduce the need for plant protection products, thus reducing GHG due to manufacturing, transport, and application. The production of synthetic pesticides is energy intensive and can emit even more greenhouse gases (GHG) per kg than the production of synthetic fertilizers (Cech et al., 2022).
Environment	Pest control contributes to food and water safety, as reducing the number of pesticides used in turn reduces residues in food, feed and fibre, and in the environment decreasing point and non-point pollution. A more sustainable pest control is fundamentally important for biodiversity-friendly agricultural production, to maintain ecosystem balance and mitigate environmental impacts.
Income	Improved pest control can decrease production costs through reduced levels of input use and normally increases yield and yield quality. Higher quality crops and with fewer residues can command better prices in markets and contribute to increased farmer profitability.
Social	Pest control inevitably has a multitude of unintended effects on the environment, public and worker health, as well as on the productivity and produce safety of neighbouring farms. A sustainable management of adversity is fundamentally important for biodiversity-friendly agricultural production, to improve food security, farm resilience and public health benefits.
Scaling	Adoption levels of various IPM practices varied across the sample depending on a range of factors relating to both farm and farmer characteristics (Creissen et al., 2021).
Replicability	Successful replicability of pest control strategies requires positive farmers’ perception of the benefits and collective action within a farming community (Parsa et

	al., 2014). In developing countries, the most frequent obstacle is "insufficient training and technical support to farmers (Parsa et al., 2014)
IP	IP only relevant as it relates to commercial pesticides which are the intellectual property of the respective companies that have developed them.
Public/ commercial	Public: Integrated Pest Management requires considerable support from extension services (government, cooperative, private). Commercial: There is potential for the production of biological pest control agents by SMEs. Smallholder farmers in Kenya produce predators and parasitoids for the horticulture industry, SMEs in India produce the fungal antagonist *Trichoderma viridus* for the control of soil pathogens.
TRL	TRL 6 – technology demonstrated in relevant environment

12. Tillage

Tillage is the mechanical manipulation of the soil for crop production. It significantly affects the soil characteristics such as soil organic matter, carbon stocking, water conservation, infiltration, and evapotranspiration processes and soil temperature. The impact of tillage depends on the techniques used. Several of the SustInAfrica trials involve reduced tillage techniques, classed as "Conservation Agriculture" if they follow the 3 principles of CA: Reduce soil disturbance, maximise soil cover and include crop rotation. The use of Zaï holes, demi-lunes, ripper furrows and direct seeders in the field trials are all examples of CA.

Gender	Across Africa women do much of the field preparation, with a Zambian woman moving 6 tonnes of soil per ha when "split ridging". Tillage practices that reduce women's workloads are therefor critical. The academic world is split on the impact of CA on women's workloads, with some papers reporting an increase in workload and others reporting a significant reducing in labour peaks, with women often being early adopters of CA as it enables them to engage in multiple livelihoods activities.
Nutrition	Crop yields in eroded soils are lower than those in protected soils because erosion reduces soil fertility and water availability. Tillage also influences the distribution of water and aeration in the soil profile, the soil organic matter and the carbon content (Curci et al., 1997). Tillage alters the physicochemical properties of soil by mixing the upper fertile profile with the lower profile richer in leachates (Rahman et al., 2008) and affects the soil enzymes and biomes. It may significantly reduce quantity and quality of food crop leading to food insecurity. Little work has been conducted on the impact of soil tillage on the level of micronutrients important for human nutrition (Fe, Zn, Se) in crops. A study in Serbia found that fodder maize grown under CA had higher nutrition levels, but the study looked at animal, not human nutrient requirements. Plants obtain most of their micronutrients through root associations with soil fungi (mycorrhiza) and rhizosphere bacteria. Numerous studies have shown higher levels of mycorrhiza forming fungi (Glomus. etc) in soils under CA, so it is plausible that crops grown under CA should be able to access more micronutrients through mycorrhizal associations than crops grown under inversion tillage.
Climate	Tillage systems and methods of seedbed preparation may also impact N2O emissions. In general, N2O emissions are greater under CA/NT than in conventional tillage systems and may negate any gains of soil organic carbon (SOC) sequestration. However, several studies also show no significant effect of tillage systems or even a negative effect of NT on N2O emission (Lal, 2021). The use of crop residues as mulch increases soil carbon, but the levels sequestered are hotly debated, and crop residues are an important source of fodder in livestock producing communities. CA/NT is highly effective at protecting crops from dry spells during the growing season and there is general agreement that CA/NT the most appropriate tillage technique in the semi-arid and sub humid tropics. CA/NT is less effective in the humid tropics, where weed growth quickly dominates crops, or in waterlogged soils.
Environment	Environmental benefits of a proper tillage management include improved water quality; reduced nutrient losses, increased water availability, improved air quality and overall improved soil quality, meaning increased organic matter and improved soil structure, porosity, and tilth.
Income	Tillage operations require considerably inputs in machinery investment and maintenance, fossil combustibles, and labor inputs as compared to Conservation Agriculture. When farms convert from conventional tillage systems to conservation tillage systems, there is potential to lower production costs and improve farm profitability. The agronomic benefits associated

	with conservation tillage practices, such as improved soil health and productivity, may improve yields, thereby increasing net returns.
Social	Tillage is one of the most significant disturbances for soil biodiversity (Van Capelle et al., 2012). Societal benefits of rational tillage include improved quality of life (reduced labor, greater flexibility in planting); improved profitability (reduced wear and tear on equipment, saved fuel and fertilizer, improved productivity and possibility for higher carbon credits) and improved wildlife habitat. https://www.sare.org/publications/conservation-tillage-systems-in-the-southeast/chapter-2-conservation-tillage-systems-history-the-future-and-benefits/benefits-of-conservation-tillage-systems/
Scaling	Scaling CA is limited by long held beliefs that a clean ploughed field = a good farmer. Numerous projects have promoted CA but most have not invested sufficient time and extension resources to achieve scale, with some notable exceptions.
Replicability	CA is most appropriate for the semi-arid and sub humid areas of Africa, with several CA techniques originating in the Sahel. It is not appropriate for the humid tropics and waterlogged soils. Women are often early adopters of CA in “women’s crops” and should be targeted by extension systems. CA can be used at all economic levels, though the technologies are very different. Poor farmers lacking animal traction can use hand tools to make Zaï holes, demi-lunes, etc, or use jab planters. Richer farmers with livestock can use ox drawn rippers and direct seeders. Emerging Farmers, with access to mechanised equipment, can use tractor-drawn rippers and direct seeders.
IP	N/A
Public/ commercial	**Public**. Significant investment in extension services is required to scale CA. **Commercial**: Increasing adoption of CA creates a market for locally manufacturers of hand, animal drawn and mechanised CA equipment,
TRL/SRL	TRL 9 – actual system proven in operational environment

13. Fertilizers use trials

Fertilizers can be classified as mineral or organic. Mineral fertilizers, also known as chemical fertilizers, since they are manufactured by the chemical fertilizer industry, are mainly nitrogen (N), phosphate, and potash. Most organic fertilizers originate from animal manures – either from the faeces and urine of livestock animals, from the faeces of poultry, alone or mixed with bedding material (e.g., farmyard manure, chicken manure).

Gender	Unknown at this stage is not clear if women have equal access to fertilizers. This needs to be assessed during the baseline. Labour constrained smallholder farmers often use fertilisers as a substitute for labour, with the extra yield from the fertilisers compensating for the yield lost due to competition from weeds. Because women have unequal access to both financial and knowledge resources, women tend to use less fertilizer. Therefore if women receive more education about and access to fertilizers, nitrogen-use efficiency would increase, benefitting food security and climate change mitigation. Moving towards a more balanced and efficient use of nitrogen fertilizer will significantly improve gender and social equity outcomes. Micro-dosed fertilisers may be an effective way to reduce womens labour.
Nutrition	Potentially good in terms of addressing P deficiencies that limit crop growth across much of Africa and can improve N-fixation by legumes. Are there any critical micronutrient deficiencies in soils in Ghana? Zn for example. Malawi now mandates Zn fortification of fertilizers to address Zn deficiencies in the diet. Fortification of fertilisers with micronutrients to improve both crop growth and human nutrition could be an option for these trials. Without the addition of fertilizers, crop yields and agricultural productivity would be significantly reduced. 30–40% crop yield increase could be achieved through balanced (recommended) nutrient use practice (Islam et al., 2022).
Climate	Nitrogen fertilizer produces nitrous oxide, a potent greenhouse gas, which contributes to climate change. For each kg N fertilizer applied 0.022 kg N_2O is emitted. Nitrous Oxide (N_2O) has a GWP 298 times that of CO_2 for a 100-year timescale, thus 6.55 kg CO_2-eq are saved. Carbon footprint

	from fertiliser production: (https://www.interregir2ma.eu/images/IR2MA/deliverables/244_Guidebook/D244_Guidebook.pdf) ● N generic fertilizer 10.86 kg CO_2-eq/ kg N ● N ammonium nitrate (27.5% N) 8.55 k kg CO_2-eq/kg N ● N urea (46% N) 3.5 kg CO_2-eq/ kg N ● N calcium nitrate (11.86% N) 3.2 kg CO_2-eq/kg N ● N urea-ammonium nitrate (32% N) 6.5 kg CO_2-eq/kg N ● N ammonium sulfate (21% N) 2.04 kg CO_2-eq/kg N ● N ammonia liquid (82% N) 2.09 kg CO_2-eq/kg N ● P generic fertilizer 2.10 kg CO_2- eq/ kg P_2O_5 ● P triple-superphosphate (48% P_2O_5) 1.73 kg CO_2-eq/kg P_2O_5 ● P superphosphate (21%) 1.85 kg CO_2- eq/kg P_2O_5 ● P di-ammonium phosphate (46%) kg CO_2-eq/kg P_2O_5 ● K potassium fertilizer 0.75 kg CO_2-eq/ kg K_2O ● K potassium sulfate (50% K_2O) 1.49 kg CO_2-eq/kg K_2O ● K potassium nitrate (46% K_2O) 2.45 kg CO_2-eq/kg K_2O ● K potassium chloride (60% K_2O) 0.55 kg CO_2-eq/kg K_2O
Environment	Not clear at this stage. The trials could address underlying soil fertility issues but risk harming soil structure and health if not part of integrated soil fertility management that includes soil testing, crop rotations, pH correction, and soil organic matter.
Income	Not clear at this stage. It will depend on the Gross Margins for fertilizer use. Fertilizers can aid in making profitable changes in farming, however the current world price of fertilisers makes fertiliser too expensive for smallholder farmers and beyond the capacity of most governments to cushion the shock to farmers through fertiliser subsidies.
Social	Labour constrained smallholder farmers often use fertilisers as a substitute for labour, with the extra yield from the fertilisers compensating for the yield lost due to competition from weeds. The current price of fertilisers will make fertiliser use uneconomic for most farmers.
Scaling	The current fertilisers prices will prevent the scaling of fertiliser use.
Replicability	Current agricultural practice in many countries is to provide blanket fertiliser recommendations, an approach that is highly inefficient. Replicability will require detailed soil analysis for each location and fertiliser response trials to ensure that the recommended rates are effective and economically viable.
IP	Most chemical fertilisers are generic products. Some more specialised fertiliser products or formulations (slow release) may be protected by patents.
Public/ commercial	Commercial: chemical fertilisers are a commercial product. Public: Chemical fertiliser use should be based on accurate soil analysis by soil fertility extension agents.
TRL/SRL	TRL 9 – actual system proven in operational environment

Appendix A. Matrix and key performance indicators to score each technology for nutrition, environmental, economic, and social impact.

Dimension	Categories	Indicators	Name of technology/practice
Nutrition	Household Dietary Diversity	Household Food Consumption Score	
	Food availability	Food calendars/ seasonal availability	
	Malnutrition	Stunting rates	
	Productivity increase	Crop Yield increase	
Economic	Productivity increase Efficiency improvement	Higher productivity per employee	
		Higher Return-on-Investment	
		Water productivity	
		Work time use efficiency	
	Efficiency improvement Benefit-costs	Pesticide use reduction	
		Water use reduction	
		Water use efficiency	
		Water delivery performance	
		Resource use efficiency	
		Increased production efficiency	
		Amount of yield losses from pests	
		Fertilizer use reduction (N-use)	
	Benefit-costs Quality	Production costs reduction	
		Phytosanitary measures	
		Increase in turnover/income	
		Increase in sales	
		Benefit/Cost ratio	
		Economic viability	
		Investment payback period	
		Quality improvement (food safety)	
	Quality Lower Input	Quality improvement (yield quality)	
		Improved traceability	
		Fertilizer use reduction (N-use)	
Environmental	Lower Input Lower emissions and leaching	Nitrogen use reduction	
		Fungicide use (late blight control)	
		Herbicide use reduction (Haulm killing)	
		Soil herbicide use reduction	
		Pesticide use reduction	
		Nitrogen and water use efficiencies	
		Water use efficiency	
		Water balance	
		Energy use	
	Lower emissions and leaching Waste reduction	Nitrogen leaching reduction	
		Greenhouse reduction reduction	
		Reduction of crop wasted/ rejected at harvest (%)	
	Soil health	Better soil structure	
	Soil health Ecosystem services	Soil fertility and erosion	
		Water quality	
	Ecosystem services Gender and social equality	Air quality	
		Workload of Women	
Social	Gender and social equality Ease of work	Female Energy Expenditure	
		Effective time use	
	Ease of work User satisfaction	Stress reduction	
		Disseminate to farmers directly	
		Increased level of satisfaction of producer	
	Public health	A lower level of pesticide active ingredients	
	Public health Transparency of food chain	Increased quality food and food safety	
		More data available	
	Transparency of food chain	Trust in the quality of food products	

Annex B: Technology readiness levels (TRL)

EU definitions for TRL:
TRL 1 – basic principles observed
TRL 2 – technology concept formulated
TRL 3 – experimental proof of concept
TRL 4 – technology validated in lab
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space

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