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IITA
Transforming African Agriculture

CGIAR

Technology toolkit

Completing the integrated soil fertility management equation

Latest trends in research and scaling for organic and auxiliary inputs

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Disclaimer
This publication has been realized under the ProSoil program of GIZ financed by BMZ (project processing n° : 21.2005.3 002.00). The contents of this publication are the sole responsibility of the authors and do not necessarily represent the views of GIZ or BMZ.

Citation
Roobroeck D, Vanlauwe B, 2024. Technology Toolkit: Completing the Integrated Soil Fertility Management Equation – Latest Trends in Research and Scaling for Organic and Auxiliary Inputs. IITA

Design
ARGE EYES-OPEN K15 GmbH und weissbunt GbR

Lead organizations

The International Institute of Tropical Agriculture (IITA), is an award winning, research for development organization, providing solutions to hunger, poverty, and the degradation of natural resources in Africa. Since 1967, IITA has worked with international and national partners to improve livelihoods, enhance food and nutrition security, increase employment, and preserve natural resource integrity. Through membership of the Consultative Group for International Agricultural Research (CGIAR), IITA is taking part in a global partnership that works towards the common goals of alleviating poverty and ensuring food security for millions of farm families. The core mission is to offer leading research partnerships that facilitate agricultural solutions to hunger, poverty, and natural resource degradation.

Support program

ProSoil The Global Programme “Soil Protection and Rehabilitation for Food Security” is implemented by GIZ and intended to help smallholder farmers to learn about climate smart, agroecological methods to protect their land from soil erosion and restore and maintain soil fertility. To that end, ProSoil is cooperating with governmental institutions and entities from the realms of science, research, the private sector and civil society to establish framework conditions that will promote change in agricultural and food systems.

Acknowledgements

In developing the toolkit, valuable contributions from multiple experts have been received that made its content reflect the current state of organic and auxiliary inputs. Additionally, GIZ country packages have played a pivotal role in facilitating connections with diverse stakeholders.

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Abbreviations

ABP	Africa Biogas Partnership
AMF	Arbuscular mycorrhizal fungi
BNF	Biological nitrogen fixation
CH_4	Methane
CO_2	Carbon dioxide
DBE	Development Bank of Ethiopia
EIAR	Ethiopian Institute of Agricultural Research
ERW	Enhanced rock weathering
GHG	Greenhouse gas
IITA	International Institute of Tropical Agriculture
ISFM	Integrated soil fertility management
N, P, K	Nitrogen, phosphorus, potassium
N_2O	Nitrous oxide
ROI	Return on investment
SNV	Netherlands Development Organisation
SSA	Sub-Sahara Africa
VCR	Value cost ratio
WB	World Bank

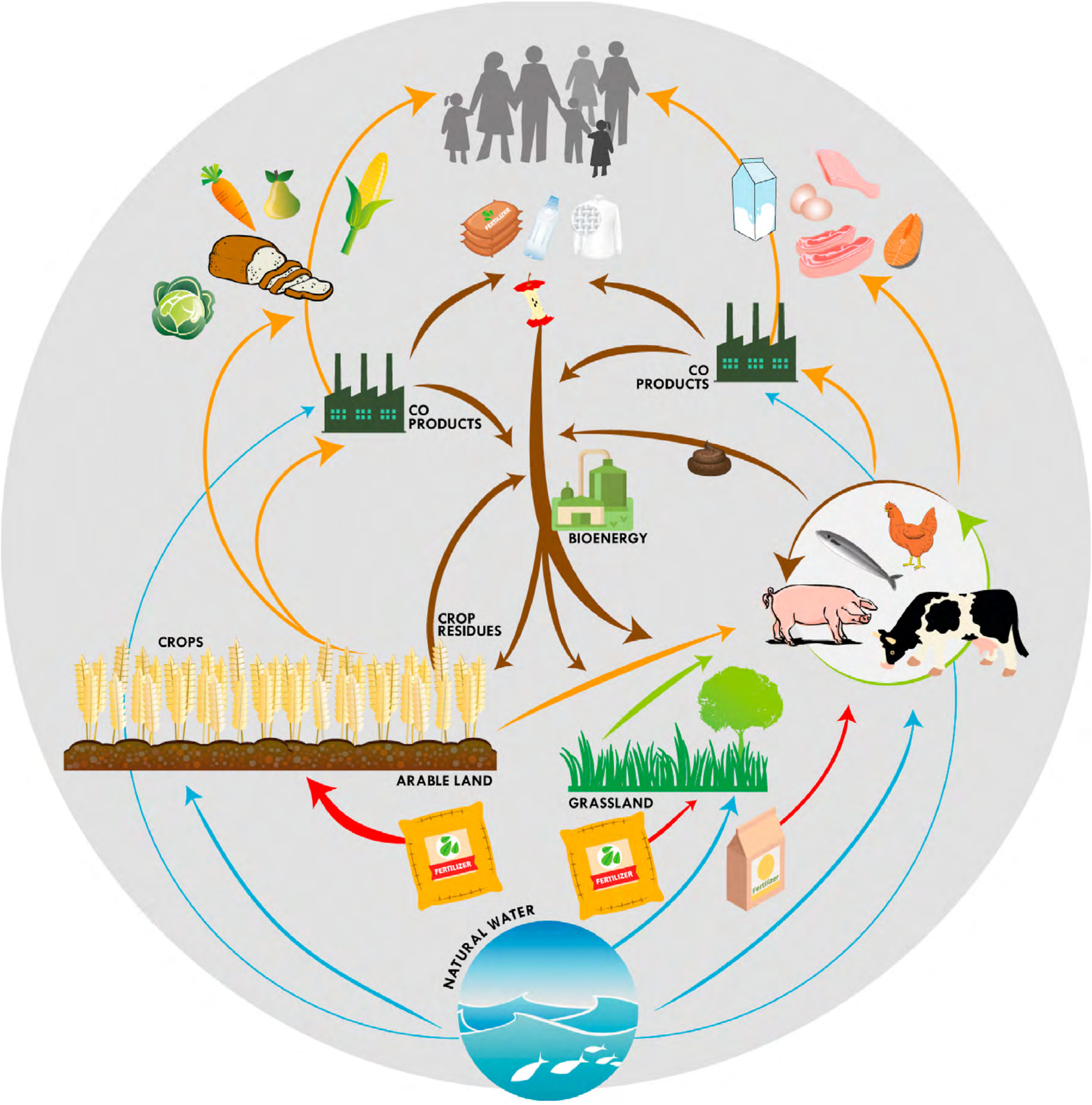
1. Introduction

The effectiveness and sustainability of intensifying agriculture in Sub-Saharan Africa (SSA) through policies focussed on expanding fertilizer alone has been unsettled by price hikes and supply disruptions of synthetic fertilizer combined with lower-than-expected increases of food production and continued environmental degradation. Out of this, consensus is growing among stakeholders that balanced approaches centred around judicious nutrient management are imperative to ensure adequate nutritious food and to protect ecosystem services. Particular attention is paid to the interaction of synthetic fertilizer and soil health as pertains to the roles of organic matter and other amendments for improving nutrient availability, water retention, microbial activity, and carbon sequestration. This is underscored by the Africa Fertilizer and Soil Health Action Plan (2024–2034), which prioritizes mobilization of public and private investment for developing nature-based strategies for soil health rehabilitation and policy frameworks that create enabling regulations and incentives.

This new plan for sustainable agricultural intensification for Africa closely aligns with Integrated Soil Fertility Management (ISFM) which prescribes the necessary co-application of improved varieties, synthetic fertilizer, organic inputs, auxiliary amendments, and weed and pest control following good agronomic practices and specific adaptations (Vanlauwe et al., 2010). Using a system wide lens, ISFM accounts for specific contexts, including agronomic, geographic, social, and economic possibilities and limitations, production objectives, and exchanges of knowledge, labor, and machinery for implementation. Research shows that ISFM strategies lead to greater profitability of investments in seed and fertilizer due to positive feedback loops between bundled technologies (Vanlauwe et al., 2023). Still, most farmers prefer to use no input, inorganic fertilizer only and organic input only even though it leads to lower return rates (Nkonya et al., 2017). When implementing subsidy programs for inorganic fertilizers there is no or even negative impact observed on the adoption of ISFM practices (Smale and Thériault, 2019). The main reasons for this deadlock include weak extension support for judicious application, labour intensity of organic input production, and higher up-front costs that pose significant risks under unfavourable weather or market conditions.

Most smallholder farmers in Sub-Sahara Africa manage soil health with resources and operations that are derived within the field or homestead, such as cultivation of legumes and green manure, incorporation of crop residues and application of animal manure. While these strategies provide some yield increase and soil health improvement when combined with synthetic fertilizer, data shows they are incapable of raising production and efficiency to attainable and desired levels. This is because the practices do not fully address issues like soil acidity, micronutrient deficiency, pest infestation or water supply. Additionally, farmers struggle to apply these practices in sufficient amounts and in the correct manner, and the labour to implement these practices can be prohibitive, especially when yield gains are initially small and take several seasons to reach profitable levels. Because of this, it is essential that inputs from outside the field boundary or farm are more accessible at an affordable cost. In this context, and aligned with green growth and climate action, practices must harness innovative technology and establish circular resource flows (Figure 1).

Figure 1: Circular agrifood system (Source: Dobermann et al., 2022)

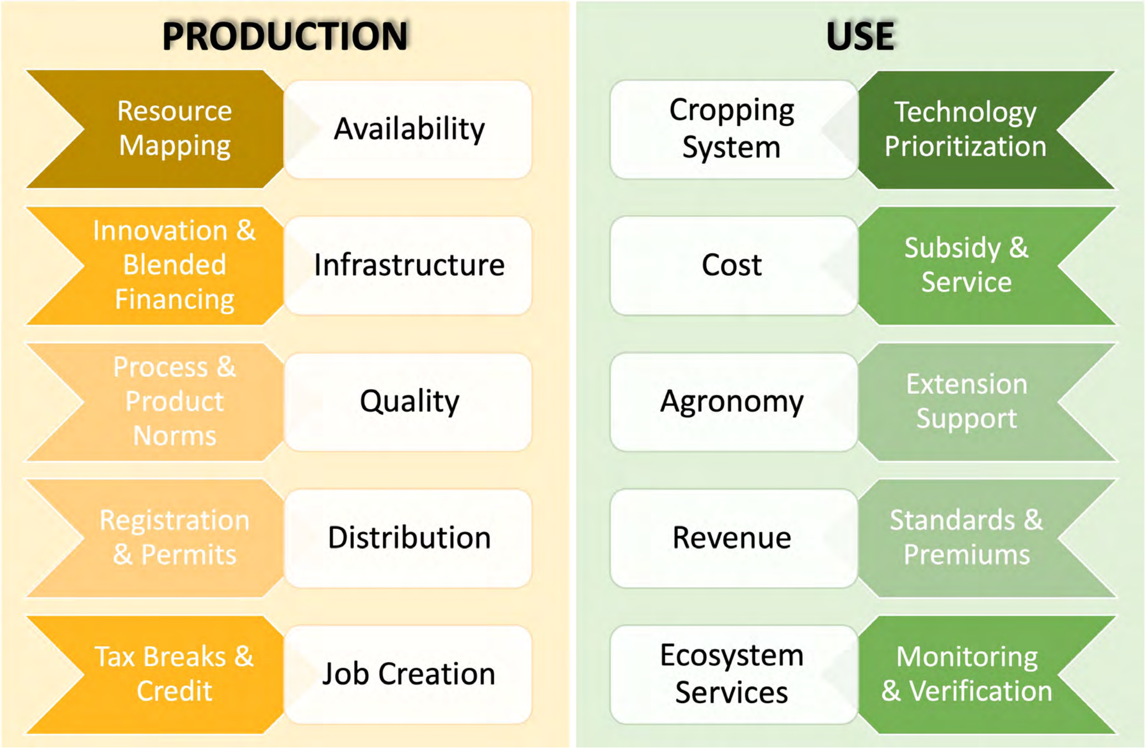


This includes exploiting beneficial interactions of plants and microorganisms, upcycling waste and returning it to farms, and tapping into locally available mineral resources. It is also closely linked to digital tools such as phone advisory services as well as machine learning and image recognition models that are the cornerstone for site-specific agronomy, pest control, monitoring impacts and optimizing supply chains. Shortening transport distance is another key aspect so farmers can easily access inputs and are protected from local and global disruptions. Revenues from sustainability and climate markets for the practices come into play too, and help pricing the inputs correctly and incentivize uptake.

Innovations like these have their own set of complexities that pose a barrier to adoption, but the rewards outweigh the challenges in the form of long-term soil health improvement, producing more food per unit land and inorganic fertilizer, and reducing climate impacts and vulnerability. For optimizing practices and supply chains, and effective scaling of advanced soil health inputs, several aspects relating to their production and use must be marshalled strategically (Figure 2). The promotion of off-farm inputs and service delivery must consider the natural resource base, agronomic and geographic conditions, economic drivers, route-to-market pathways, and stakeholder engagement, as well as the diversity, complexity, and dynamicity therein. Localized production requires comprehensive knowledge of available raw materials, as well as development of processing infrastructure and business models. Engaging farmers in technology adaptation and evaluation is crucial to ensure that their perspectives are incorporated, leading to greater acceptance and demand. Regulatory oversight is paramount for adherence of quality standards and avoid human health hazards and maintain fair pricing for soil health inputs. Bundling advanced technologies has proven to be a powerful mechanism for improving uptake of soil health inputs. Implementing "smart" policies to incentivize and enforce such approach can accelerate progress in this area.

Comprehensive information regarding the technical potential, established delivery models, and incentive structures for organic inputs and other amendments in Sub-Saharan Africa is often constrained by being outdated, fragmented, or scarce. A thorough characterization of their agronomic and climate benefits is imperative to ascertain their integration into the agricultural production cycle. Reviews detailing both successful and unsuccessful scaling efforts of these technologies across the continent or elsewhere, coupled with an analysis of causal factors, are indispensable for gathering insights into how to catalyse uptake effectively, ensuring maximal benefits and sustainability.

Figure 2: Key components of input value chains (inner boxes) and development interventions (outer arrows).



2. Objective

A diverse array of agricultural practices has been developed and validated across various farming systems in Africa and the Global Tropics. Among these, biofertilizers, biocontrol agents, compost, lime, biochar, faecal sludge, and quarry fines stand out as prominent or rapidly emerging technologies. However, it is essential to note that these technologies, while significant, do not encompass the entirety of what is required for systemic transformation. Instead, this selection reflects the agronomic expertise of the International Institute of Tropical Agriculture (IITA) and highlights some of the key products around which scaling engagements with national and international actors are focused.

This toolkit aims to provide nuanced information about key entry points of the six featured technologies within the broader context of ISFM (Figure 3). By compiling up-to-date evidence from research and case studies we discuss the potential benefits for crop production and complementarity with synthetic fertilizer. Critical reflections are made of lessons learned and innovative incentive mechanisms that can help production and use. We also provide examples of how policies and investments can be designed to create practical ways for farmers to access and use technologies that enhance soil health. This toolkit is intended for development organizations and the policy sector to accelerate dissemination and uptake at scale of organic inputs and other amendments with proven ability to maintain and enhance soil health in food production systems of SSA. In light of the Fertilizer and Soil Health Strategy for the next 10 years, the insights provided in this toolkit can aid decision-makers. By assessing the technical aspects and scalability, the toolkit advances understanding to leverage and guide research, commercial investments and policy design. The scope of the assessments in the toolkit includes upland annual and perennial cropping systems such as grains, roots, tubers, and bananas because they represent the largest geographic area and staple food in smallholder systems of SSA.

Figure 3: Entry points of toolkit on value chains for organic inputs and other amendments.

Technology profiles in the toolkit discuss pertinent aspects that influence the suitability and viability, as well as incentivizing policies. First, an overview is given of the soil health problems addressed by the technology, along with its characteristics, its composition, its place in the production cycle, and the steps for manufacturing and application. The compatibility of regenerative inputs with synthetic fertilizer and other agro-industrial inputs is described, touching on uptake efficiency, nutrient substitution, pest/disease control, climate resilience, and/or carbon removal. Here the size and persistence of effects is related with the application rate and other controlling factors. Technical and scaling ability is evaluated in terms of resource availability at continental and local scale, and the requirements and challenges to production, distribution, and use, including infrastructure, financing, and extension support. Examples of scaling pathways are given through selected cases that achieved commercial operation in SSA or other representative countries, looking at their business models and what aided in success or failure. Important support for development, financing and extension needed for increased production and improved marketing by private/public sector and widespread uptake by farmers are discussed. This includes approaches to boost adoption at early stages, e.g., farmer co-design, participatory field evaluation and technology transfer. Also feature there are digital tools for capacity building, decision support, resource tracing along chain of custody to avoid unsustainable exploitation and forest-free production. Under enabling policies, we describe means like product regulations, tax incentives interventions, market prices norms, and carbon offset schemes through which the technology can scale in an environmentally sustainable and financially viable manner. We also look at means whereby markets for advanced inputs can be self-regulated with minimal involvement of national or local governments.

Table 1: Description of content in technology profiles

Main features	Soil health problems addressed by the technology; characteristics, composition, place in the production cycle, and the steps for manufacturing and application.
Complementarity	Synergies and trade-offs with synthetic fertilizer and other agro-industrial inputs, i.e., yield gain use efficiency, nutrient substitution, pest/disease control.
Availability & scalability	Quality and quantity of raw material feedstocks; requirements and challenges to production, distribution, and use, including infrastructure, financing, and extension support.
Costs & benefits	Production costs and market prices for inputs; economic returns from yield gains and fertilizer substitution at recommended application rates.
Mitigation & adaptation	Production costs and market prices for inputs; economic returns from yield gains and fertilizer substitution at recommended application rates.
Growth pathways	References of commercialization and scaling in SSA or other representative countries, looking at their business models and what aided in success or failure.
Support functions	Development, financing and extension function for promoting wider uptake, approaches to boost adoption at early stages, e.g., sensitization, participatory evaluation and technology transfer.
Enabling policies	Regulations and incentives through which the technology can scale in an environmentally sustainable and financially viable manner, with minimal administrative burden.

It is important to note that the toolkit has caveats and limitations relating to:

- Geographic and agronomic contexts – This toolkit does not assess the technical and commercial scaling potential of the practices for specific geographies and agronomic contexts. Policies and recommendations that support auxiliary inputs should not be applied uniformly across regions. Variations in availability, suitability, and financial viability must be considered.
- Practical considerations – We have not explored practical aspects of managing combined fertilizer and soil health restoration. This is crucial in smallholder farming systems in Africa, where fertility conditions can vary significantly within a single holding. Practices should be optimized for diverse and challenging environments where traditional methods may fall short. Tailored recommendations and policy frameworks at the sub-national level are essential to address these needs effectively.

3. Technology profiles

To use and interpret the toolkit correctly, users must understand the agronomic and economic context of their specific situation. This background is crucial for assessing the relevance of the toolkit's recommendations and for effectively planning the adoption process. Before starting, gather and evaluate information on factors such as soil types, climate, water availability, existing agricultural practices, as well as attitudes, production objectives, infrastructure, organizational structures, and the financial capacity of farmers or enterprises. These insights will help ensure that the technology description is applied appropriately and effectively.

3.1. Microbial inoculants to manage nutrients and pests

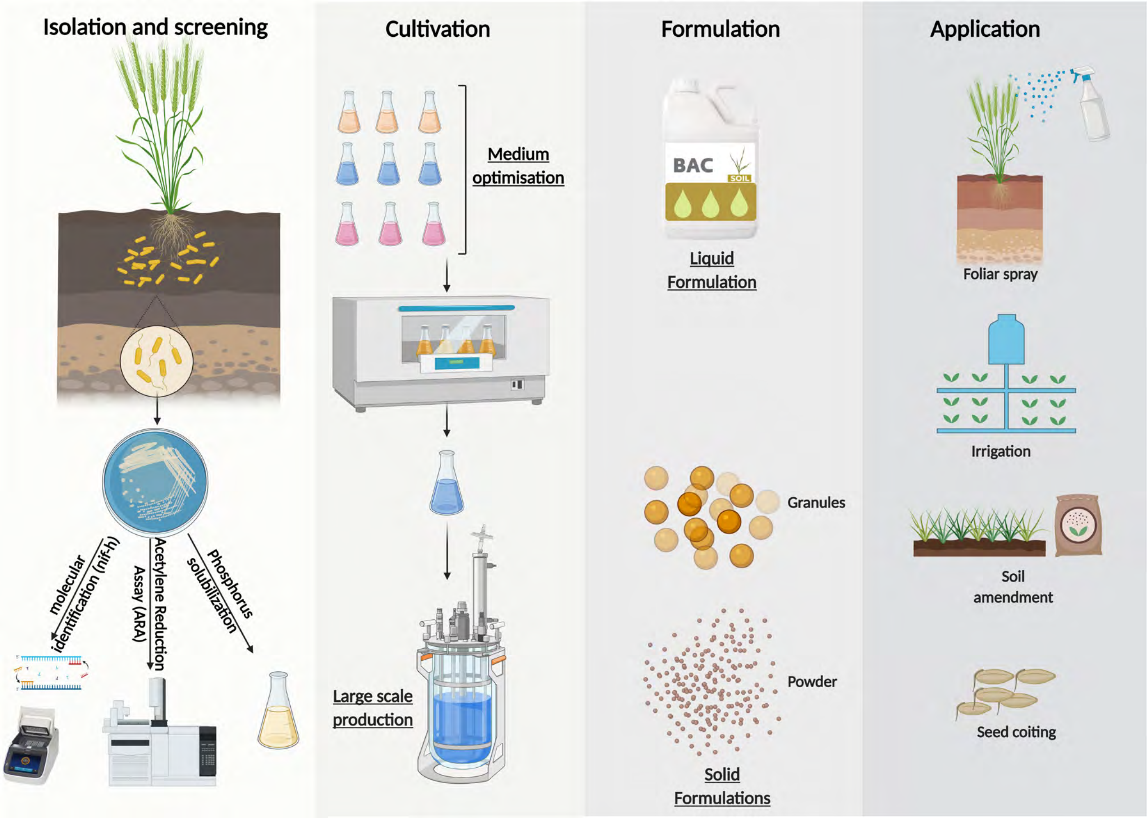
Main features

Crop growth and resilience can be enhanced by beneficial microorganisms like bacteria and fungi that facilitate nutrient supply, tolerance to drought or salinity and protection against diseases and pests. Adding biological fertilizer and control agents fosters a healthy and active microbiome in soil and crop that whereby reducing input costs and environmental impacts. The process of inoculation can involve dressing seed or plantlets, soil, or foliage after which the microbes colonize the plant. Different microorganisms offer specific functions and associate with particular crops, varieties, as well as climate and soil types. Symbiotic Rhizobium and free-living Azobacter perform biological nitrogen fixation (BNF) from the air and transfer these resources to plants via the root system, and commonly serve as biofertilizers for legumes. Arbuscular mycorrhizal fungi (AMF) enhance nutrient uptake in crops, particularly phosphorus, copper, and zinc, by increasing the root surface area and reaching into the smallest soil pores. BNF and AMF biofertilizers are highly relevant for smallholder farming systems where low amounts of fertilizers are used, soils strongly bind nutrients and naturally occurring species have been lost. With a vast diversity of AMF, these fungi form symbiotic relationships with more than 70% of terrestrial plant species, providing a broad spectrum of application in agriculture. Endophytic bacteria or fungi are useful for plant protection, these microorganisms live between plant cells where they produce or modulate hormones that govern productivity and stress responses, some release antibiotics or compete with pathogens, and others build up substances that adds an extra layer of defense. Microbial agents are used for controlling nematodes and weevils in banana plantlets (Figure 4; Dubois et al., 2006), suppressing parasitic weeds in cereal crops and soil-borne diseases in horticulture.

Figure 4: Banana plantlets with Fusarium endophyte inoculant (left) and without (right). Credit: T. Dubois & D. Coyne.

Expanding the use of inoculants on large area of cropland in Africa is hampered by challenges in the selection of strains for crops, the commercial viability of manufacturing, the shelf-life of products, and the dissemination of best agronomic practices (Figure 5). A key bottleneck is ensuring consistent yield gains from biological fertilizers and control agents under diverse on-farm conditions. There is large variability in effectiveness of Rhizobium for legumes, mycorrhizal fungi, and endophytes, due to soil types, climate, and pest pressures. Microbial inoculants may perform differently in various environmental contexts, making it difficult to predict their effectiveness across different farms and regions. Other management practices, such as the amounts of fertilizers, pesticides, and irrigation, can interact with microbial inoculants in complex ways, affecting their performance and overall impact on crop yields. Decision support tools that ensure stable and effective yield gains from biofertilizers and biocontrol agents across diverse agricultural contexts is critical for encouraging farmer adoption. There is a lack of such recommendations and integration of biofertilizer in fertilizer use advisory services that are being scaled across the continent.

Figure 5: Process of development, production and field application of N-fixing inoculant (Credit: Aasfar et al., 2021).



Complementarity

Nitrogen-fixing bacteria and mycorrhizal fungi can work in conjunction with synthetic fertilizers to improve nutrient availability to plants. This combination can boost crop growth and yield more effectively than using synthetic fertilizers alone, not only increasing profitability but also minimizing environmental impacts. Use of inoculants can allow legume production with minimal or no use of N fertilizer input. Promoting N fixation in legumes also generates more nutrient-dense residues that can be incorporated into the soil for the subsequent crop to realize higher yield. For instance, estimates show that advanced legume integration may save up to 10% of N input on maize and wheat in Ethiopia and Malawi, equivalent to more than 30,000 tons of synthetic N fertilizer (Snapp et al., 2023). Biocontrol agents can be integrated with artificial pesticides to create integrated pest management systems that are more sustainable and delay resistance development. In many cases, other inputs are needed so biofertilizer and biocontrol agents work effectively, for instance phosphorus fertilizer and agricultural lime (see Profile 3.3.) for N-fixing Rhizobium, and organic matter from compost, manure and biochar for mycorrhizal fungi or Fusarium. In N-deficient soils there may be need to add inorganic N fertilizer as a starter. For AMF, the use of pesticides, herbicides and acidic mineral fertilizers might block effectiveness so there is need for judicious management in time and space to avoid that the biofertilizers will not be blocked.

Availability/Scalability

Naturally occurring microbial strains with potential benefits for crop growth can be found for most legume, cereal, root, and tuber crops and bananas that are adapted to agro-climatic conditions in farming systems of Africa. Scaling such technologies across agricultural production zones is not straightforward because of variability in yield gains at farm and regional level, as well as different microbial strains used by manufacturers. Existing N-fixing inoculants are most effective for soybean, cowpea, pigeon pea and groundnut, whereas for common bean and chickpea they are less effective. Regions in SSA where legumes and cereal are rotated or intercropped are the most opportune for use of N-fixing inoculants. The quality of marketed products, i.e., number of viable colony-forming units, strongly influences the yield response of legumes. A major constraint for suppliers is the absence of awareness and distribution channels while sufficient volumes must be sold to achieve affordable prices and keep the technology attractive to investors. Ensuring that marketed inoculants are sterile and deliver the promised benefits is critical for farmers to gain trust and purchase the alternative input, putting great importance on norms and regulatory oversight for products. The benefits of biofertilizers can be less predictable than synthetic fertilizer, and biocontrol agents less predictable than chemical pesticides since factors like weather conditions, the presence of other organisms, and the adaptability of the target pests can influence their effectiveness. To warrant activity and persistence of beneficial microorganism in soils, farmers must apply appropriate management practices, hence extension services are needed so attainable benefit is realized. Scaling up production and use of microbial technologies can be a challenge and costly as the multiplication and storage requires expert knowledge and intensive management.

Costs and benefits

Microbial inoculants are inexpensive, for instance a NoduMax package of 100-gram costs US $4-5 in retail and can inoculate 10 kg of seed and will plant 0.25 ha with soybean. Compared to mineral N fertilizer, the use of rhizobial inoculation does not result in higher yields, but by reducing the rate of application of mineral N can achieve greater profit margin. A farmer who spends US $20 per hectare on the inoculant and US $5 on seed treatment, and harvests an additional 200 kg of grain, would receive net return of US $175 at common market prices. Additionally, the fodder quality of haulms from faba bean, common bean, and soybean is enhanced when combining N inoculation with mineral P fertilizer (Belete et al., 2019), leading to increased livestock production or sales. Furthermore, the benefits of Rhizobium and P fertilizer extend to subsequent maize crops, improving yields and accruing benefits over time. With the fungi-based Striga weed control technique farmers need 2.5 kg of the biocontrol product to treat one-acre farm of maize, sorghum or millet, a kilogram of the product costs US $1 and after three seasons of treatment, the farm will be free from Striga which otherwise decreases yield by 30% or more. In demonstrations, maize grain yields were increased from 50-150 kg per acre to 350-450 kg per acre. Biopesticides containing a naturally occurring fungi that protect cotton production from damage of bollworm and leafhopper cost between US $226 and $602 per hectare, achieving a return rate of 0.9 to 1.7, whereas for the same area chemical products are cheaper at US $28 to $59 and provide a benefit cost ratio of 1.6 to 2.0 (Malinga et al., 2023). For controlling weevils in banana crops, treating plantlets in tissue culture is more cost-effective than conventional field application by spraying the biopesticides on mats. Dipping the rhizome of young plantlets can give season-long protection, killing larvae internally, protecting the biopesticide from drought, requiring less product, and reducing labor costs (Akello et al., 2009). The practice of endophyte priming to protect banana plantlets against weevils and wilt demonstrates economic viability compared to chemical control and reduces environmental and occupational safety risks.

Climate mitigation and adaptation

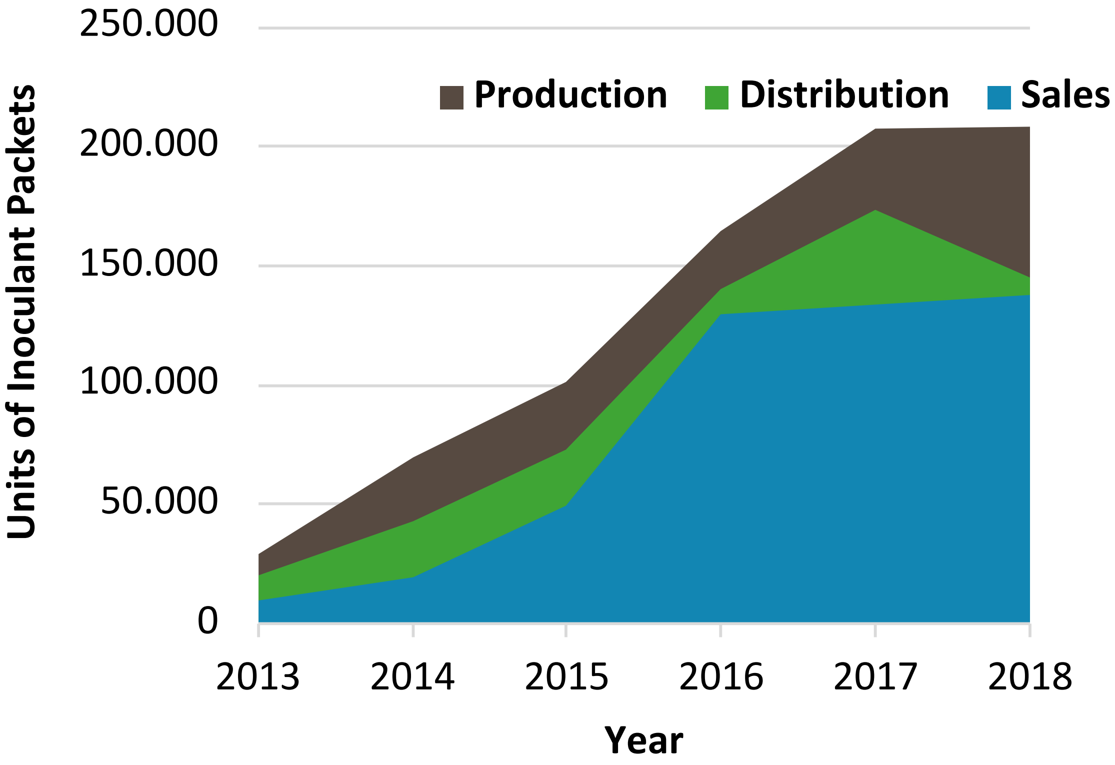
By rule, microbial inoculants and control agents have a low environmental footprint, and often their effectiveness exceeds that of synthetic products under climatic stress. The energy demand for the manufacture of Rhizobium inoculant to treat 1 hectare of land is less than 1% of that corresponding to the production of mineral-N fertilizer. Use of biological nitrogen fixation contributes to reducing the soil-derived nitrous oxide (N_2O) emission (Minamisawa, 2022). Since biofertilizers reduce the need for synthetic fertilizers they lower the climate footprint of agriculture that is associated with fertilizer manufacture. Increased root growth through a healthy root microbiome leads to higher soil organic matter content which aids in storing CO_2 and improved soil water retention for resilience to drought. A global study found that Rhizobium inoculation of common bean was more efficient than mineral N fertilizer during the dry season particularly under no-tillage system and in soils with high organic matter content thus being a more resilient choice (dos Santos et al., 2022). Chemical pesticides are derived from fossil fuels and thereby contribute substantially to greenhouse gas emissions which can be avoided fully through biocontrol agents. Distribution is less emission intensive because inoculants can be produced locally.

Growth pathways

The first step of identifying and isolating elite microorganisms for inoculants is done by researchers from the public and commercial sector. Manufacturing and marketing of the biofertilizer products involves commercial input suppliers and agro-dealers, or alternatively national programs. Different enterprise models have led to sustained production of N-fixing inoculants for legumes with some degree of commercialization, either as a semi-commercial government operation, or a combination of government and private sector involvement. Small scale inoculant production has been initiated in many countries throughout Africa, but few have gone on to large scale. “NoduMax”, a nitrogen fixing inoculant for legume crops developed by IITA, is registered and produced in Nigeria, and commercially distributed to soybean growers through agro-dealers across the country and neighboring countries with annual sales exceeding 110,000 units. In Zambia inoculant production is performed by a government institution to meet demands of farmers.

The main barrier for privately owned inoculant manufacturers is poor sales due to limited awareness of farmers on the benefits from bio-fertilizers, lack of effective input demand information, inefficient distribution infrastructure, and poor business planning. In Ethiopia, another scaling model was adopted through “Farmers’ Cooperative Unions” which are entities mandated that can reach a higher number of farmers, work hand in hand with bureaus of agriculture in forecasting input demands, can more easily bulk purchase and deliver back to buyers through the unions and link farmers to better grain markets. The partnership is designed in such a way that business and technical support is obtained from other legume value chain actors which is driving expanded purchase and use of N-fixing inoculants. Critical to achieving expanded use in this case was the bundling of inputs where legume seed was pre-treated with Rhizobium, this increased farmer convenience and ensured effective dressing and storage. Since 2016 Ethiopian company Menagesha Biotechnology Industry PLC managed to double its output capacity by acquiring modern equipment that reduces risk of batch contamination and consolidated that increase in distribution and sales through the marketing via unions (Figure 6). These interventions also benefited overall enterprise efficiency, where the three-year average ratio of distribution to production went up by 12%, and the ratio of sales to distribution by 34%.

Figure 6: Trends in output and sales of legume inoculants by Ethiopian commercial enterprise (Wolde-meskel 2019).



The identification of biological control agents for controlling diseases and pests has seen major progress over the past decade. Isolation, lab screening and field testing of indigenous endophytic microorganisms is carried out in multiple countries across SSA. Commercialization of Trichoderma fungal strains has happened in Kenya by Real IPM Company Ltd. Nurseries and demonstration gardens serve as hubs for sales and training and have been a highly successful route-to-market for biocontrol manufacturers in Uganda and Kenya. The ’Toothpick’ project[1] is scaling the local manufacture of a microbial inoculant that reduced yield loss by Striga in maize and sorghum through simple techniques and training of which keeps prices for farmers low and boost the rural economy. Field testing and training of Village Inoculum Producers under this program has happened in Kenya, Côte d’Ivoire, and Benin. Enhancement of tissue culture banana with commercially available mycorrhizal fungi is practiced by multiple enterprises in Kenya, Uganda, and Tanzania.

Commercialization of biological control methods for managing pests and diseases in agriculture, such as weevils and wilts in bananas, faces

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[1] *https://www.toothpickproject.org/toothpick*

significant challenges. The variability within microbial species and the lack of standardized taxonomic descriptions and comprehensive testing results can indeed complicate regulatory approvals and widespread adoption. Effective communication between scientists and regulators is crucial to address these complexities, mitigate misconceptions, and establish robust monitoring and evaluation frameworks (Ochieno et al., 2020). This dialogue can help streamline the regulatory process and ensure the safe and effective deployment of biological control agents in agriculture.

Support functions

- **Development:** Preservation centres and reference banks for elite microbial inoculants isolated from local environments are needed so producers and regulators have quick access. Research on the rapid fingerprinting of microbial products, the mechanisms of action and their persistence in the soil will drive quality control and marketing. At the manufacturing side, design of low-cost and effective inoculation techniques, and embedding with seed and input supply systems must be advanced for realizing large scale adoption so minimal additional investment and labour is incurred by farmers. Decision support tools for aligning biofertilizers and biocontrol agents with soil conditions and other inputs must be constructed to improve stability and predictability of effect sizes.

- **Financing:** Funding for plant-microbial research and policy formulation for promoting the use of microbial inoculants is needed for advancing product development and attracting private sector investment. On the side of commercialization, financial mechanisms like grants and preferential loan to purchase of modern automated laboratory equipment which allow high production capacity and low staff cost, bringing down price for farmers and achieving a return on investment that is investor friendly. Instead of flat tax benefit or subsidy, the government can use this incentive specifically for enterprises that encourage farmers to expand the use of inoculants or pre-inoculated plantlets through a "buy-one get-one-free" model which has led to increased sales by agro-input suppliers elsewhere.

- **Extension:** Promotional campaigns among farmers to demonstrate benefits on crops and the low cost of the technology compared to synthetic nutrient inputs and control agents that make it attractive for reducing costs of production. Agronomic advisories and participation in farmer groups have been demonstrated as effective means to promote the use of Rhizobium inoculant on grain legume. This is because it ensures profitable use by guiding application techniques, mineral fertilizer use and crop management that improve activity of the microorganisms and efficacy of the product. Applications of microbial fertilizers and biocontrol agents should be strongly integrated into educational programs to ensure students gain a deeper understanding of this biotechnology.

- **Surveillance:** The status of soil microbial health and occurrence and severity of pests must be closely monitored at local and national scale to inform and promote preventative use of inoculants before economic damage happens. For biological control to be effective in the short-term it is important that pest pressures do not become excessive, otherwise chemical control agents must be used.

Enabling policies

Regulatory environments play a key role in driving expanded use of microbial inoculants, but many countries of SSA have unfinished or interim frameworks that obstruct development, production, distribution, and sales. One of the key challenges is that a wide range of microorganisms and biological mechanisms are used to improve plant nutrition and defences which requires laws with clear definitions and specific registration and monitoring procedures. The complexity of terminologies, and non-uniformity at global scale, pose a challenge, particularly for new players. Navigating these intricacies demands significant resources and acts as a barrier to entry into the inoculant market. Legislation must, at the same time, enforce penalties for non-compliance, so the market is protected from fake and substandard. Institutionalizing and strengthening regulatory frameworks on biofertilizers and biopesticides is pivotal, as showcased by the progress made in Ethiopia, Ghana, Kenya, Nigeria, Tanzania, and Uganda by IITA. Regional harmonization of policies, laws, regulations, and standards is key to promote technology transfer and trade, else these can hamper uptake and access. The key aspects of governance frameworks for biofertilizer and biocontrol agents have been summarized in Figure 7.

Figure 7: Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T) of policy and regulation for microbial inoculant products (Adapted from: Ghorui et al., 2024)

Pipelines for development and market release of microbial inoculants by public or private sector can be accelerated through standard screening procedures across the sector and offering support to producers through the registration which enable harmonized and rapid review by regulators and bureaus of standard. In many parts of the world, quality control is transferred from government agency to independent industry control body operating voluntary certification schemes which set benchmarks, protocols, and independent testing standards for evaluating and labelling inoculant products. Manufacturers are attracted to this model since they can display a label that offers confidence to farmers that the product fulfils stringent. The curation of such codes falls onto a panel of experts who reviews the protocols so that it continues to provide the right quality assurance program for advancements in strains and product development. Barriers to registration and commercialization for enterprises after investment in development or acquiring licenses can be circumvented through open and reliable information exchange via innovation platforms with representation from science, government, and business sectors, where biological agents can be classified into readiness and risk levels on an objective and multi-disciplinary basis that determine specific registration and commercialization roadmaps.

The enforcement of policies and legislature on synthetic fertilizer and chemical pesticides, and strengthening norms, would spur agro-input suppliers and farmers to consider microbial inoculant as alternative.

3.2. Compost for nutrient recovery and value addition

Main features

Composting offers an effective strategy to recycle nutrients from agricultural crop residues, and food scraps and yard trimmings in municipalities by adding value through production of farm inputs. Application of compost to farmland has well-documented benefits for soil health, crop production and the environment. The conversion process can be done with and without oxygen, by earth worms (vermicomposting), each requiring specific equipment, labor, energy, land, and types of materials. Composting generates nutrient-rich solid that is applied to soil or beds, and liquids that can be used as foliar spray. Operations can take place on different scales and locations.

- On-farm: This involves converting material near the homestead, field or livestock barn using crop residues, manure, straw, hedgerows clippings, agroforestry resources and other feedstocks. It may also take in materials from nearby residents or businesses to increase production and labour-effectiveness or generate revenue in tipping fees. Typically, the compost would be used close to its production site.

- Off-farm/Municipal: This refers to local government programs where food scraps and yard trimmings are collected from homes and businesses or separated at landfills sites. Usually this is done by contracted haulers and commercial facilities. Produced compost is sold to input suppliers, horticulture producers or used in green spaces.

It is estimated that food and green waste from households can annually produce between 50,000 tons of compost in Malawi and 500,000 tons in Ghana (Freyer et al., 2024). Several challenges however limit the adoption in rural and urban settings of SSA and use as fertilizer substitute. On-farm production faces labor constraints and inadequate supply of N-rich material such as animal manure, human and vegetable waste. Smallholder farmers have trouble aggregating food scraps and green waste due to management regulations and certification requirements, and therefore do not use off-farm materials for composting. Uncertainty about nutrient content due to process variation at the farm level undermines appropriate management decisions and causes that farmers apply too much, leading to low profitability and pollution of water bodies. When farmers apply too little crop yields are unsatisfactory. The number of composting plants in cities across SSA is very limited, especially if compared to the status of municipal organic waste recycling operations in South-Africa (Figure 8)[2]. For municipal composting the main constraints are high transport costs, the risk of heavy metal or biohazard contamination and intensity or cost of segregating refuse. For instance, removing plastic from biodegradable solid fraction can take 12% of the active labor time spent to achieve a compost that meets biosafety standards (Yesaya et al., 2021).

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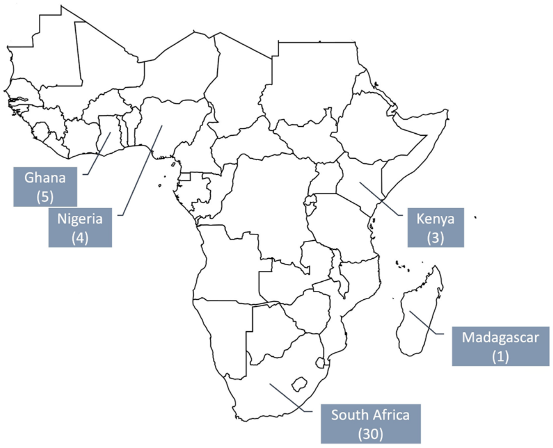
[2] *https://www.enfrecycling.com/directory/organic-plant/Africa*

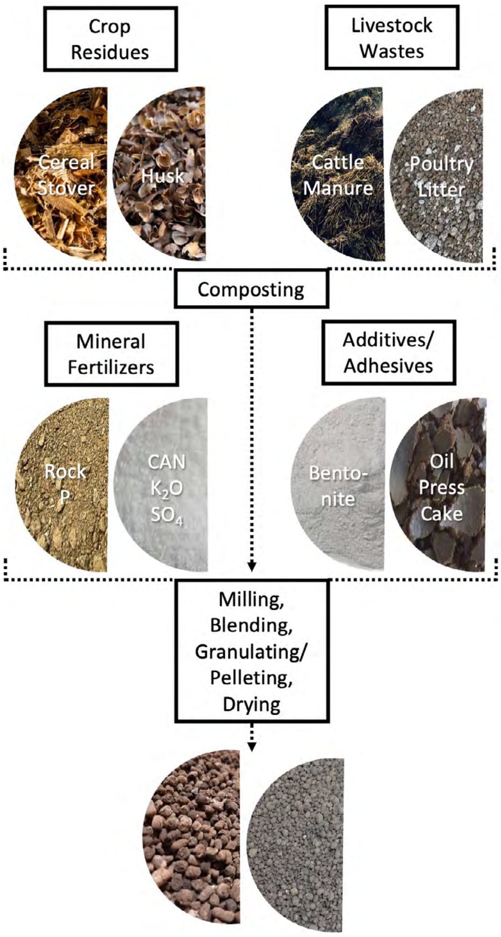
Figure 8: Number of registered organic recycler plants in SSA countries (Source: ENF, 2023)



Complementarity

Combining synthetic fertilizers and compost allows to strike a balance between the immediate nutrient needs of plants and the long-term health of soils. More nutrients from fertilizer are taken up by crops when compost is co-applied due to improved soil structure, water retention, and microbial activity. The application of compost alone is often criticised as inefficient for crop yield compared to synthetic fertilizer. It is observed that the combined application of compost with synthetic fertilizers allows for a reduction in the latter, while achieving similar or better crop yields and reducing soil erosion risk. The mechanisms leading to greater yield when compost is applied together with fertilizer, are faster breakdown of organic matter, balanced nutrient supply, and improved synchrony between release and crop demand. Compost can be used as a baseline soil conditioner and synthetic fertilizers as supplements. Micronutrients like zinc, boron, manganese, copper and molybdenum are found in compost that address widespread deficiencies of these elements, compensating for their absence in standard fertilizers and promoting crop growth. However, at farm level the micro-nutrient inputs from compost are not balancing their actual removal rates through harvest. Because of this, deficiencies of one nutrient can arise that limit the effectiveness of others. This imbalance may result in the yield responses to combined applications being smaller than the sum of the benefits from individual applications, a phenomenon that is widely observed (e.g., Essel et al., 2021). Compost restores or maintains soil biotic communities through bacteria, fungi and fauna it carries inside which compete with or prey on harmful rots, wilts, and nematodes (Oka, 2010). At the same time, compost supplies the organic substrates that beneficial species need to survive. Incorporating compost makes soil easier to work and more resistant to compaction, prevents clay soils from becoming waterlogged which alleviates loss of soil by erosion. Innovative organo-mineral fertilizers (Figure 9), offer the advantage of balanced nutrient content and ease of application for farmers.

Figure 9: Source materials and processes of orgno-mineral fertilizer manufacture



Availability/Scalability

Farm households in rural communities generate solid organic wastes such as manure, tree trimmings, grass clippings and crop residues, which can amount to 80% of the total solid waste that is generated. Urban households in SSA generate 91 to 531 kg of solid waste each year, which is for 50–75% organic material (Bougnom et al., 2014). A project in a municipality of Côte d'Ivoire with twenty thousand inhabitants collected 59.4 tons fresh weight of cassava, banana peels and kitchen waste that yielded 14.2 tons of mature compost at a 36% dry mass conversion (Yeo et al., 2020). At a commonly recommended application of 2 tons per hectare derived from field trials in SSA this would be sufficient for 7 hectare of land each year. Major field crops like maize, wheat, millet, sorghum, sugarcane, cassava, rice and barley regenerate millions of tons residues annually which could supply thousands of tons NPK when turned into compost.

Technical and operational aspects strongly influence production capacity. For one, the carbon to nitrogen ratio, which must be 25 – 30 for a composting process to work, requires that sufficient N-rich material like legume stover, kitchen waste, animal manure and human waste is mixed with C-rich material. In terms of infrastructure and labour, smallholder farmers are limited to turn crop residues into compost. Here service delivery and automation systems are needed to increase the volume of organic waste that is composted.

Costs and benefits

A project in Durban, South Africa, that diverts 398 tons organic wastes per year from a municipal-run market to decentralized composing sites,[3] reported a total investment of US $ 387,486 for the equipment and infrastructure, including truck, shredder and chainsaw, and concrete base with roof. Monthly staff costs are US $ 760 and operating costs like water, fuel, safety gear and maintenance are US $ 2,159. Sales of compost generate US $ 95,305 per year making that the venture reaches break-even with the capital investment and interest payment by year 3. Several other benefits were recorded by this project, such avoidance of 16.6 tons CO_2 emissions per month, transport reduction of 14 km per haul, and savings on disposal fees that were reinvested into the market. For a windrow system with automated pile turning that has an output capacity of 5,678 tons compost per year the facility and administration are costing US $ 222,247 with machinery, labour and fuel costing US $ 84,664 and compost testing, depreciation of the plant, and repair and maintenance costing US $ 55,427 (Askarany & Smith, 2014). Common wholesale price for quality compost ranges from US $ 1 to $ 1.5 per kg. The main factor influencing profitability of a composting business and affordability for farmers is the distance between the source of organic waste, the processing site and the cropping field. Another factor is minimizing the proportion of plastics and metal since fewer workers and personal protective equipment is needed to sort the solid waste, and the compost quality is higher.

Climate mitigation and adaptation

Organic wastes dumped in landfills or pits on farms are producing large amounts of methane (CH_4), a potent greenhouse gas that is hard to remove from the air. An estimated 50% to 60% of methane emitted from landfills in SSA originates from compostable food waste. Improved separation of organic solid waste in municipal refuse and on-farm composting is effective strategy to abate CH_4 emissions, of which many African nations are signatories. Nutrient-rich compost allows farmers to swap synthetic fertilizers that have a large carbon footprint from energy intensive manufacturing, overseas importation and road haulage. It is estimated that moving

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[3] **LUMEC, 2023 ; available here:** *https://africazerowastehub.org.za/wp-content/uploads/2023/11/MunicipalSavingsCompostingCBA.pdf*

a ton of organic waste from landfill to compost reduces CH_4 emissions by 6% to 26% (De Silva & Taylor, 2024). A study in Madagascar by GIZ showed that liquid compost saves 5.3 kg CO_2 per ton, whereas solid and vermiculture compost save 17 kg CO_2 per ton, through the replacement of synthetic fertilizer.[4] Nonetheless, liquid compost can be transported to crop fields more efficiently than solid compost, thereby reducing transport-related emissions. Incorporating compost increases into the stable carbon pool of soil and each ton removes 25 kg CO_2 from the atmosphere. On top of that, the resilience of agriculture is increased, with models showing that the potential to offset losses of crop yield and soil carbon due to El Niño in Ethiopia is higher for composted manure than fresh untreated manure (Smith et al., 2019).

Growth pathways

Programs in Africa have established and sustained community-based composting on farms by offering training and business plans via information sheets, videos, and webinars. A radio show with tips on improving compost piles and soil quality that was produced by Farm Radio International in collaboration with farmers increased adoption from just over 25 % to over 89 %.[5] Listeners reported greater level of comfort with local extension officers after hearing testimonies on the broadcast, the power from word of mouth. Agri-service providers like One Acre Fund offer hands-on capacity building for compost production to thousands of small-scale farmers through field officers in Burundi, Kenya, Rwanda, and Tanzania. Composting by farmers with low amounts of crop residues and vegetable wastes can be made more efficient and profitable through community facilities. Another potential alternative for on-farm compost production is outsourcing the process to a service provider where a cooperative or commercial enterprise is contracted so individual farmers do not need to invest in equipment or labour. In such cases, the farm supplies feedstocks to the processor at no or limited cost. Agricultural residues and food waste is composted by the contractor, who then owns and distributes the final product for agricultural land application, the urban market, or the soil reclamation industry. In India, production of city compost and use in rural agricultural landscapes has been successfully achieved by capacity building and financial support to urban local bodies, linkage with farmer producer organizations, and a government subsidy on purchased volumes.[6]

Several successful enterprises exist in SSA that produce compost in agro-industrial and municipal settings. In Ghana, Sabon Sake has set up a facility near farmer fields that takes residues from sugarcane and sells compost back to farmers.[7] In Kenya, Taka Taka Solutions Ltd. operating in Nairobi has successfully entered into composting, with about 60% of refuse from households, offices, restaurants, schools, malls, hospital and factories existing of organic materials and now sells 800 tons of compost annually.[8] For achieving this scale, the company sought investment and support to grow the number of sorting and recycling centers, elevate logistical and processing efficiency, and expand sales of compost. Buy-in from commercial customers and the local government was leveraged through sustainability analyses and reports demonstrating how organic recycling profits everyone in the waste value chain. A shift to windrow-turning technology decreased composting maturation time from 6 months to 4 months, and contracts with export-oriented horticultural farms in a radius of 75 km from Nairobi ensured offtake, interventions that were critical for the company to attain financial sustainability and profitability. The comparatively higher service charge than other waste collection enterprises was not prohibitive for customers due

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[4] *https://www.giz.de/de/downloads/giz2023-fr-emissions-gaz-compost-madagascar.pdf*

[5] *http://www.worldcitizens.org.tw/awc2010/eng/F/1870.pdf*

[6] *https://www.giz.de/de/downloads/giz2023-en-URNCC-broshure.pdf*

[7] *https://www.dw.com/en/ghana-turns-sugarcane-farming-waste-into-organic-fertilizer/a-59730966*

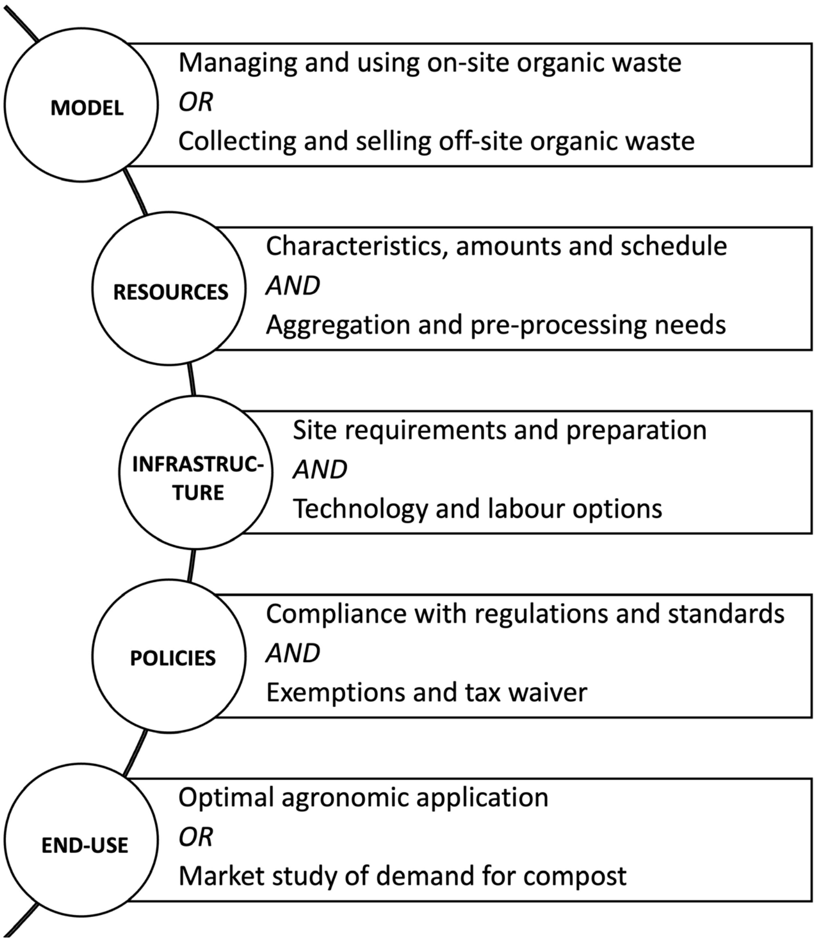
[8] *https://www.repic.ch/wp-content/uploads/2020/07/TakaTaka-Solutions-Improving-Resource-Efficiency-in-Waste-Management.pdf*

to more punctual collection, more bin liners per month, better quality of vehicles and collectors, and higher recycling rate. By collecting and processing of plastic, paper, metal, glass, and textile helped Taka Taka Solutions to overcome costs of segregation and limited compost quality.

Support functions

- **Development:** There is need for broader assessment of the agronomic and economic value of compost-based inputs to determine fair market pricing and guiding the production chain. Contextualized decision support tools are crucial for farmers and enterprises to select suitable composting technologies (Figure 10). These tools should consider factors such as the availability of crop residues, food waste, and animal waste, as well as the ease of collection, management, labor requirements, next to regulations, permitting and exemptions, and potential uses or outlets for the finished compost products. For companies in markets where the consumer's ability and willingness to pay for waste collection is low it is critical to utilize the low-tech solutions compared with cheaper labour make sense. Research on techniques to increase nutrient retention, water regulations and pathogen control is also needed for enhancing process efficiency and food safety.

Figure 10: General steps in planning a compost operation under various settings.



- **Financing:** Grants to local governments or private firms can help promote composting programs and tax waivers for enterprises and compost products, with assistance for 50 % of the capital cost or a certain maximum level, whichever is less, can be a viable incentive opportunity. Government services or funding for technical advisory from experts can help achieve prerequisite efficiency levels at separation, composting and marketing. To understand the economic viability of a composting process the time that each activity takes must be quantified so targeted modifications can be implemented and tested to reduce overall costs and increase output efficiency. Such information is not widely available for commercial operations on the African continent. Production costs and output increase with the level of process sophistication, with an ascending order for passive piles, turned windrows and in-vessel systems.

- **Extension:** Distributing pictorial brochures and radio shows on composting have shown to be effective channels for increasing awareness and level of uptake by farmers. Technical support and training by officers from local governments and other support organizations, onsite and remotely, is needed to help ensure appropriate management of food scrap and agricultural organic waste as well as composting systems and procedures. For urban waste producers that are environmentally conscious it is important that complex information like offsets in CO_2 emissions are translated into simpler concepts like 'how much litre of petrol this equates to'. The primary financial incentives for composting are waste tipping fees and compost sales, about which farmers and operators must be informed and supported in how such revenues can be earned.

Enabling policies

On-farm compost is a key part of government efforts to maintain soil health and substitute synthetic fertilizer, which is reflected in the Agricultural Soil Management Policy of Kenya.[9] In Ghana, the inclusion of compost in the national fertilizer subsidy programme (MoFA, 2017) led to a 50% price reduction. Transport between urban recycling centres and rural areas remains a barrier to access for farmers, which must be addressed by policies and promotion of on-farm or collective composting facilities. For cities, savings in disposal fees at landfills measuring US $ 24 to $ 113 per ton of organic waste,[10] become available for financial support to community-based and private waste dealers, and capacity building programs. National agricultural research institutions, extension agencies and universities play a key role in building evidence and developing compost value chains. Policies and laws related to permitting, siting, design and operation of facilities; product quality; controlled tipping, and restrictions of landfilling or combustion; enterprise taxation; and recycling goals can be leveraged to promote on-farm and commercial composting. Ownership of composting programmes by local or regional institutions will ensure long-term sustainability, tailored solutions to local conditions, and increased community engagement. It allows for better alignment with local agricultural practices and waste management needs, leading to more effective use of resources. Moreover, local ownership can foster a sense of responsibility and accountability, promote capacity building within the community, and enhance the likelihood of successful adoption and scaling of composting initiatives. This approach supports the development of policies and incentives that are responsive to the specific challenges and opportunities of the region.

[9] *https://kilimo.go.ke/wp-content/uploads/2021/01/Draft-National-Agricultural-Soil-Management-Policy-NASMP-September-2020.pdf*

[10] *https://revistas.unam.mx/index.php/aidis/article/view/79068/72914*

As a first essential step, legislation must mandate that municipal, institutional and industrial actors track the amount of organic waste generated, which helps secure quick wins in guiding interventions and value chain design. By banning disposal of garden and farm waste in landfills and introducing "pay-as-you-throw" schemes, governments can increase recovery of organic material and attract investors into composting enterprises. Results-based financing where payment is contingent on the achievement and verification of pre- agreed targets has been a powerful mechanism around the world to improve municipal solid waste collection and recycling. Governments can aid growth of the composting sector by setting procurement policies for its agencies involved in landscaping, erosion control and road construction. Certification of composts and agronomic advisory services are important for farmers to gain trust in the value chain and will elicit greater willingness to pay.

3.3 Liming products to counteract soil acidity

Main features

Crop production on large swathes of land across Africa is limited due to acidity, occurring when the pH value is below 5.5 (Figure 11)[11]. In Ethiopia, more than 3.5 million hectares, or 40% of agricultural land, is classified as acidic. In Rwanda, the pH value of soil is below 5.2 on 43% of farmland. In Kenya, 17% to 24% of land in key maize cultivation area at the west of the country have a pH value below the threshold of 5.5. Acidification of soils is attributed to natural processes such as high concentration of aluminium oxides, leaching of calcium and magnesium, and low populations of symbiotic bacteria, as well as agronomic practices including excessive use of acidifying ammonium-based fertilizers and depletion of organic matter by residue removal. Below a pH value of 5.5, several constraints arise to crop growth such as reduced phosphorus and micronutrient uptake and aluminium toxicity. The economic impact is massive, in Ethiopia alone, acidity of soils is estimated to cause a loss of close to US $350 million annually across maize, wheat and barley production systems. Low use efficiency of mineral fertilisers on acidic soils further results in losses of US $67 million per year for the country.

Applying agricultural lime is key solution to overcome the problem and can be derived from local deposits of calcitic limestone (calcium carbonate) and dolomitic limestone (calcium magnesium carbonate). Carbonates in lime react with hydrogen ions in the soil and thereby raise the pH value. It is processed in three stages involving extraction, crushing, and milling to a powder. Agricultural lime is manufactured as co-product in quick and hydrated lime, cement, mineral fillers and/or aggregate ballast industry, or can be obtained from purpose deposit. The use of lime across SSA is very low, for example, in Kenya only 3% of smallholder farmers apply it. This is attributed to several aspects such as lack of knowledge, high lime prices, lime bulkiness, lime quality, and lack of streamlined liming policies and guidelines. Another overlooked problem is acidity deeper down the soil profile (20-50 cm), which requires the use of more expensive gypsum to be alleviated. Given the costs of reclaiming acid soils, proper analysis and targeting of lime interventions is of utmost importance. To close knowledge gaps, the project "Guiding Acid Soil Management Investments in Africa (GAIA)", is building a portal with map resources that shows where crop yield losses due to the problem are most prevalent, what application rate is required to remediate soil health, and how profitable the use of lime can be for specific crops. This interactive dashboard enables farmers, policy makers and industry to make better informed decisions and plan investment strategies.

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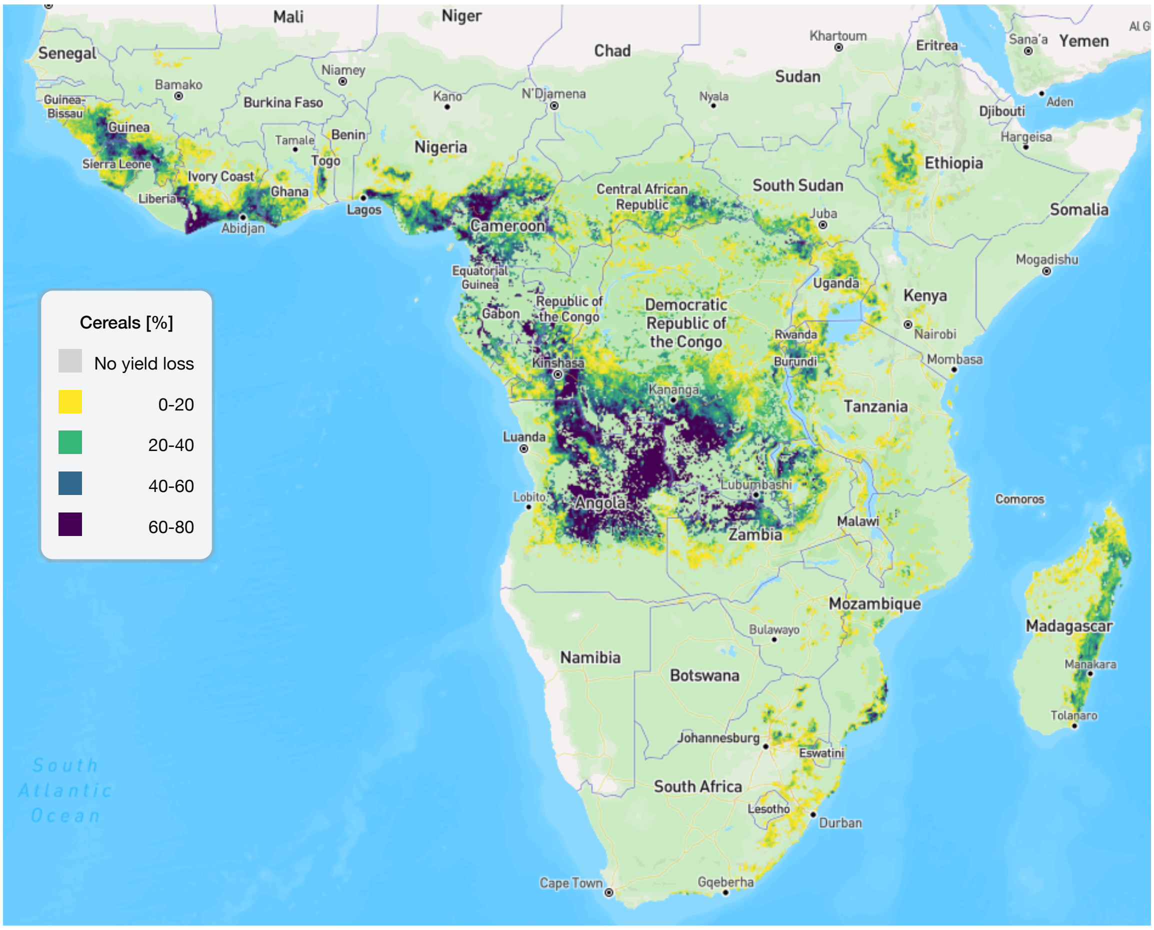
[11] **GAIA project;** *https://www.acidsoils.africa/data*

Figure 11: Soil acidity induced yield loss in cereals across SSA (Source: GAIA project, Silva et al. 2023)



Complementarity

Liming is an effective method for reducing soil acidity, but for benefits to occur, it must be complemented with inorganic and organic inputs, quality seed and good agricultural practices. When soil acidity is reduced, phosphorus availability is higher as its reaction with iron and aluminium is reduced, and increased use efficiency and uptake of P fertilizer is achieved. Adding lime to soil also influences the supply of P to crops by upregulating the activity of enzymes responsible for nutrient recycling from residues (Margenot et al., 2018). Essential nutrients like calcium and magnesium become more available to plants through release from lime and pH correction which leads to higher yield, nutritional value, and resistance to pest and disease. Soils with a pH value of 6 or above have greater activity of earthworms and other fauna, leading to better soil structure and enhanced efficiency of added nutrients. Applying magnesium-rich agricultural lime improves the nutritional value of pasture forage which prevents acute neurological conditions in livestock and dairy cows due to low intake of magnesium. Application to bring pH up to a desired level varies from rates of 1 to 8 tons per hectare, and these must be repeated at intervals of 2 to 5 years. Many factors determine lime requirements and therefore blanket recommendations are not advised. The choice of liming material and when to apply them depends on their effective neutralizing value (Table 2) and fineness. At the same time, a shift to non-acidifying or less acidifying nitrogen fertilizers, and recycling of crop residues, should be considered in conjunction with appropriate liming so a desired soil pH value is maintained for longer and lime inputs are reduced.

Table 2: Properties of common liming agents. *Relative to pure calcium carbonate.

Liming agent	Acid neutralizing capacity (%)*
Calcitic lime	80 – 100
Dolomitic lime	95 – 120
Burnt lime	150 – 175
Hydrated lime	120 – 135
Slag	60 – 90

Availability/Scalability

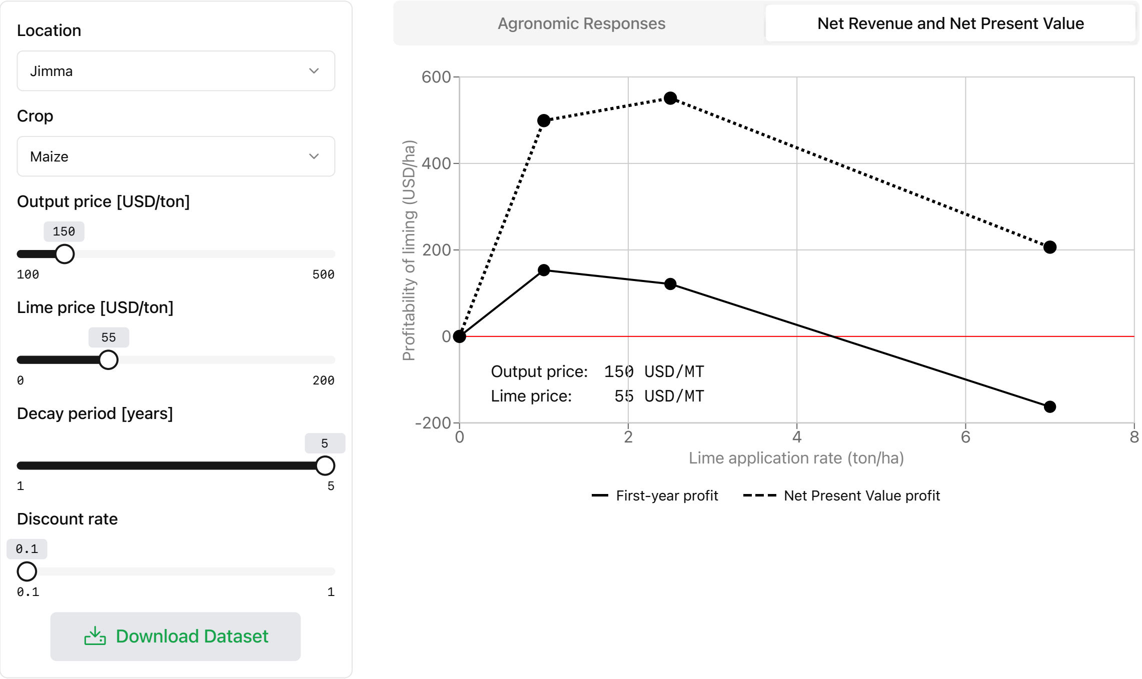
The volume and cost-effectiveness of geological lime formations that are suitable for agriculture are poorly documented in African countries. In some cases, like Rwanda, the amount of lime required for addressing acidic soils is estimated to be lower than the total quantity of lime deposits in the country (Nduwumuremyi et al., 2013). Where the challenge lies, is the exploitation since liming materials are often scattered in smaller pockets across the landscape making it difficult and costly to assess and mine. The number of lime producers where soil acidity constrains crop production are limited or non-existent. Costs and potential returns of production must be well understood beforehand to ensure investments will be profitable. Many questions must be answered, like what are the available sources and quality, where are the processing units, how can you assess the transport cost to the farms, and what is the crop yield response depending on the lime application? Large cement producers have the potential to manufacture great volumes of agricultural lime as limestone or as a by-product from industrial lime production, yet most producers of agricultural lime in SSA are relatively small and few offer a varied range of limestone products for farming, building and tanneries.

Transportation costs substantially increase the price of lime so production should take place near its marketable area and points of use, so areas with high lime requirements are ideal locations for these industries. Another limitation of powdered lime is that it is difficult to evenly apply on farmland and can be easily blown away by wind. These challenges are avoided when lime is granulated. This technology avoids difficulties in handling and spreading powdered lime, but the additional manufacturing steps make granulated lime considerably more expensive. Some specialty granulated lime products are ground to ultra-fine powder before it is pelleted into granules, which is more costly but provides a very fast-reacting product that is capable of being used in drip irrigation without clogging emitters.

Costs and benefits

Upscaled assessment in Ethiopia estimates that treating 300,00 hectares of acidic land would require 0.9 million tons of lime which, with a 50% subsidy, would incur a total cost of US $ 100 to $ 120 million for supply distances of 100 to 200 km (unpublished policy brief: EIAR and GIZ). Field studies showed that the application of lime at rates of 2 to 5 ton per ha on wheat and barley in conjunction with ISFM provides net added value of US $ 1,320 to $ 1,420 per hectare. The total benefit in the first year from additional grain yield by use of lime on 300,000 hectare amounts to US $ 410 - $ 430 million. If the same average returns hold true and current input-output prices remain, the net present value added to the economy from the use of lime on 300,000 hectare of land is estimated at US $ 1.61 billion over five years. Since the effect of lime lasts for at least 5 years it is possible to reduce the costs to farmers by reclaiming 20% of their land each year which for a farm size of 1 hectare would come to US $ 39 - $ 45 annually. A study in western Kenya found that for all levels of soil pH (4.5 to 5.5) and varying fertiliser application (0-100 kg N ha-1 an 0-50 kg P ha-1), the economic optimum amount of lime application on maize is between 1.5 and 2 tons ha-1 (Hijbeek et al., 2021). These authors also found that maize farmers with a soil pH value of 5 need to invest more than US $ 272 on lime inputs for 5 years to make a profit and achieve better result than using fertilizer alone. To facilitate decision-making, the GAIA project offers interactive profitability assessment where users can select specific settings, such as the geography, crop and cost (Figure 12)[12].

Figure 12: View of ROI analysis tool for lime from the GAIA project (response functions for more locations and crops to be added).


Location: Jimma

Crop: Maize

Output price [USD/ton]: 150

Lime price [USD/ton]: 55

Decay period [years]: 5

Discount rate: 0.1

Output price: 150 USD/MT

Lime price: 55 USD/MT

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[12] GAIA project; *https://www.acidsoils.africa/agronomy*

Climate mitigation and adaptation

The manufacturing of lime, which involves crushing limestone and heating it to high temperatures, is energy-intensive and typically relies on fossil fuels, contributing significantly to greenhouse gas (GHG) emissions. Integrating renewable energy sources, such as concentrated solar power, wind turbines, photovoltaic panels, geothermal or biomass, can substantially lower its carbon footprint but require large investment. Agricultural lime does not directly contribute to climate mitigation but yield increases and higher fertilizer use efficiency can lower emissions per quantity of food and compensate for emissions from the manufacture and transport of lime. The choice of liming agent does matter here. It is found that the application of calcitic lime on maize for a soil with pH value of 4.5 and low fertilizer use can decrease the GHG footprint per ton of maize (Hijbeek et al., 2021). With dolomitic lime, the GHG footprint per tonne of maize would be increased due to higher release of CO_2 upon reaction in the soil.

Growth pathways

In the Oromia Region of Ethiopia, the regional government is owning the production and distribution of lime and fully subsidizes the input where farmers get lime free of charge through the district Board of Agriculture. The public sector is responsible for 85% of supply and distributes 91% to farmers. In the Amhara Region of Ethiopia, there is partial support from the regional government in transporting lime from the factories to the stores of cooperative unions, and farmers are paying a normative share of the actual price of lime. Through the government's role in the value chain the number of farmers applying lime doubled or tripled, the quantity of lime used was increased two to seven times, and land area treated rose two- to ten-fold across both regions (Oumer et al., 2023). While government-controlled lime crusher plants have a capacity of 7,200 to 400,000 tons per year they operate only at 2% to 29% of production. This is mainly due to limited demand and operational inefficiencies arising from maintenance problems during the peak lime processing seasons, storage problems and electric power interruptions. Free handing out of lime and subsidized transport are effective mechanisms for awareness and demand creation among farmers, but at the same time actors realize that such intervention discourages private sector investment and farmers may not purchase at fully loaded cost. Lack of autonomy on financial management and key decisions by the government-owned lime crushers also contribute to low production even when there is demand.

In Kenya, 10 firms produce and/or sell powdered calcitic and dolomitic lime and five companies offer granularized products which are mostly imported into the country. Data on soil pH levels and crop production for Kenya puts the expected demand at approximately 187,000 tons whereas currently less than 50,000 tons are sold. Increased awareness on soil acidity and liming among farmers are projected to raise demand to 319,000 - 532,000 tons in the next five to 10 years totalling a worth of US $ 9 million in sales. By shifting to local production of powdered and granulated lime Kenya could save of about US $ 2.07 million per annum in importation costs and foreign exchange. Recognizing the importance of information on soil acidity and liming application in Kenya, the Ministry of Agriculture and Livestock Development, research institutions, universities, the private sector, and development partners collaborated through the Kenya Fertilizer Roundtable (KEFERT) to produce a reference handbook (Esilaba et al., 2023). In Mali, a project was launched as part of the Sahel Irrigation Initiative Program where technical and business capacity building is offered for mining sector to prepare the critical early stages of the development of the aglime market. Agronomic, financial and value chain experts share information on aglime properties with the public but also with thought leaders who can help amplify the message about the benefits for managing soil acidity and to connect with education centres to build a network of specialists across the country.

Support functions

- **Development:** Strategic research is needed to design effective and lowest cost strategies such as micro-dosing, and identify interactions with other management practices of crop, soil, water, and fertilizer on acidic soils. Maps on the lime requirement to achieve a target soil pH level in a specific region are critical to aid decision making and effective use that incentive adoption by farmers. Regulations and laws should be formulated as part of a comprehensive policy framework on lime use and application to bolster investments in the value chain. Improving information exchange on the available products, and nurturing collaboration between manufacturers, distributors, and stockists is key for coordinating efforts to grow the industry.

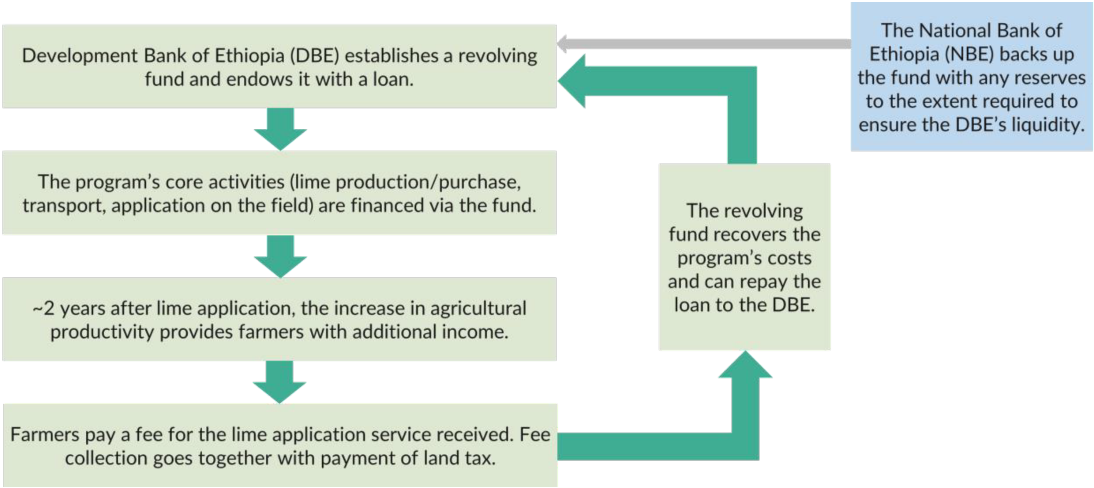
- **Financing:** Governments should make an upscaled economic assessment and farm-specific business cases of the benefits from liming agricultural soils to understand returns on investment and attract funding for value chain growth. Increased budgetary allocation is also required for agricultural research and knowledge dissemination on soil acidity, as well as the design of tax incentives that enhance the financial viability of commercial lime enterprises. Higher investment by both the public and private sectors in awareness creation, through nationwide platforms and funding for research will galvanize demand from farmers.

- **Extension:** Standardized knowledge about soil acidity and lime application methods can improve access for farmers, extension staff, input suppliers, and policy makers. For instance, research shows that the pH buffer method alone cannot be relied on as indicator but must be combined with exchangeable acidity for better mapping and targeting of lime interventions. Manuals with guidance on soil sampling, laboratory procedures, and lime application need to be developed for different crops. The source, rate, method, and timing of lime input play a key role, and farmers must adhere with recommendations for profitable usage. Ensembles of spatial datasets on soil properties, weather, long-term agronomic trials, and crop modelling tools can allow to generate at scale, specific estimates of crop yield responses at different lime applications. Such are being developed in Ethiopia for the Amhara region through a collaboration of international and national research institutions, funded by development cooperation agencies.

Enabling policies

Promoting the use of lime on croplands to improve acidic soil requires coordinated information and incentives for farmers which can be done by geographically differentiated subsidy programs for the input. Because lime is a new agricultural input that comes with substantial upfront costs it is proposed to subsidize lime and the transport of lime to enhance farmer adoption and use of lime, applying an approach similar to the very successful introduction of inorganic fertilizer. In conjunction with subsidies, governments and suppliers must invest in demand creation like in northern Rwanda where a campaign was launched in 2023 bringing together communities for discussions and answering questions about lime stimulating uptake of the sales voucher that was put in place. The Ethiopian government, to achieve its target of treating 4 million hectares of land with lime, without relying on taxes or foreign investment, is exploring the option of a revolving fund with the Development Bank of Ethiopia (Figure 13). The fund would finance all the core program activities such as lime production and purchase, distribution, and application. Farmers will enjoy higher incomes and improved livelihoods due to the restoration of their farmland productivity. Once this happens, they can start making their contribution to recovering the program´s costs. In practice, farmers are charged with a fee to remunerate the lime application service they received. The repayment can be collected via the annual land tax by adding a line to the receipt expressing the respective amount. A farmer would pay a fee when lime application reaches its maximum effect after two years. The revolving fund recovers the costs. At the end of the program, no open balance will be left such that the fund can repay its loan to the Development Bank of Ethiopia (DBE). The proposed revolving fund has significant advantages compared to a scheme where the costs are covered by the government tax revenues. First, the expenditures of the program do not have to compete with other expenditures. Second, cutting other expenditures to secure the resources for the soil acidity program has a contractionary effect on the economy as it constrains aggregate demand. The credit financing of the program is expected to contribute to lower rather than higher inflation since the fund increases economic activity, and the amount of money relative to output from agriculture will remain the same.

Figure 13: Functioning of the proposed financing scheme to promote lime use (Credit: Global Green Growth Institute).



A key step is for lime to be classified as an agricultural input, so it is not subjected to value added tax, and this is not yet the case for many countries in SSA. Guidelines on quality norms and labelling are needed that relate to neutralizing value, calcium and magnesium percentages, the form of carbonate, oxide or hydroxide, and particle size (fineness). Financing and pricing policies for aglime are critical for farmers’ ability to pay back loans, agricultural extension and advisory services, mechanization services for application, and soil testing for agronomic recommendations. Enactment of such a conducive value chain environment will attract investment in lime production. Manufacturers required comprehensive information about the prospects for the market, investment opportunities, and value chain analysis. Most importantly, lean supply chain management must be promoted because of low profit margins, seasonality in demand, costs for crushing into fine powder and requirements for storage. To achieve this downstream and upstream flows of products, services, information, and finances must work together, and manufacturing cost and wastage reduced. Government, research, and private agencies should create lime market observatories for soil acidity and quality and price of lime products to compile and supervise regional level datasets for rapid desk-based assessments on areas of demand and competition which can steer policy development and change. Such observatories would be national or regional, and can be modelled on those for export crops, milk, and fruit and vegetable, and can be linked to those for synthetic and organic fertilizers. Its board would be composed of representatives from stakeholder organizations active within the national or regional lime supply chains and chaired by the Ministers or Directorate-General from Agriculture and Rural Development. The mandate of the observatory would be to provide first-hand information about the market’s situation, as well as factors affecting it, and exchange experiences and good practices. Such value chain bodies are important for real-time monitoring of data on price, production, and trade, increase market transparency and examine ways to promote industry and adoption.

3.4. Biochar as Structural Organic Amendment

Main features

Biochar refers to carbonized material that is destined for application in agriculture and derived from renewable sources, not primary forest. It is produced through pyrolysis, i.e., thermal decomposition under low oxygen, which simultaneously generates heat and synthetic gas that can be used to offset wood and fossil fuel consumption. A wide array of technologies exists for turning biomass into biochar without and with captive energy use, these include simple artisanal kontiki, drum kilns and cookstoves, and high-tech commercial electricity and green hydrogen generators (Figure 14). Converting excess fibrous agricultural wastes into biochar can be an effective way to stop field burning, which curbs soil organic matter depletion and air pollution from smoke and particulate matter. Nutrient and water retention coupled with carbon credit earnings from long-term sequestration provide a compelling advantage whereby biochar can bridge both the biophysical and financial requirements needed for challenging restoration cases, even the reclamation of rangelands infested by invasive species. Logistical and financial aspects present challenges when it comes to the widespread adoption of soil biochar amendment. Deploying a mix of dispersed artisanal and centralized industrial models can be a practical approach to address these challenges.

Figure 14: Biochar production systems: top left – cookstove, top right – artisanal kiln, and bottom – air dryer system (Credit: IITA & partners)

The number of research papers on the use of biochar for soil fertility management and yield improvement in SSA has sharply increased in the last 10 years, and several enterprises are deploying the technology to farmers and agribusinesses. The biochar value chain begins with the collection of biomass at the lowest possible cost and emission penalty, then matched with appropriate pyrolysis systems, and lastly optimized use in farming systems, tracing materials along the way for accessing carbon credits. Implementation models are dynamic and can be moulded depending on regional and local factors, feedstock availability, and market demands. On-farm experiments in various agroecosystems of Kenya showed that one-time amendment of biochar at 1 to 10 tons ha-1 combined with micro-dose fertilizer input increased agronomic efficiency of nutrient input by 50% to 70% over three years (Kätterer et al., 2022). Biochar is also known to reduce soil-borne diseases to acceptable levels and enhance plant resistance to pathogens in staple crop and horticulture production. Under intensive maize-soybean rotation, it was found that 48% of carbon from low quality biochar was recovered 15 years after its application and without recycling of crop residues (Kätterer et al., 2019). Because of high permanence of biochar under tropical agricultural conditions, and low cost of production and verification there is rapid growth, reaching 93% of all delivered carbon removals in 2023.[13] Strong interest for biochar exists from farmers and governments in Africa owing to the benefits on crop production and fertilizer saving, and the entry point it offers into climate finance, renewable energy and human health.

Complementarity

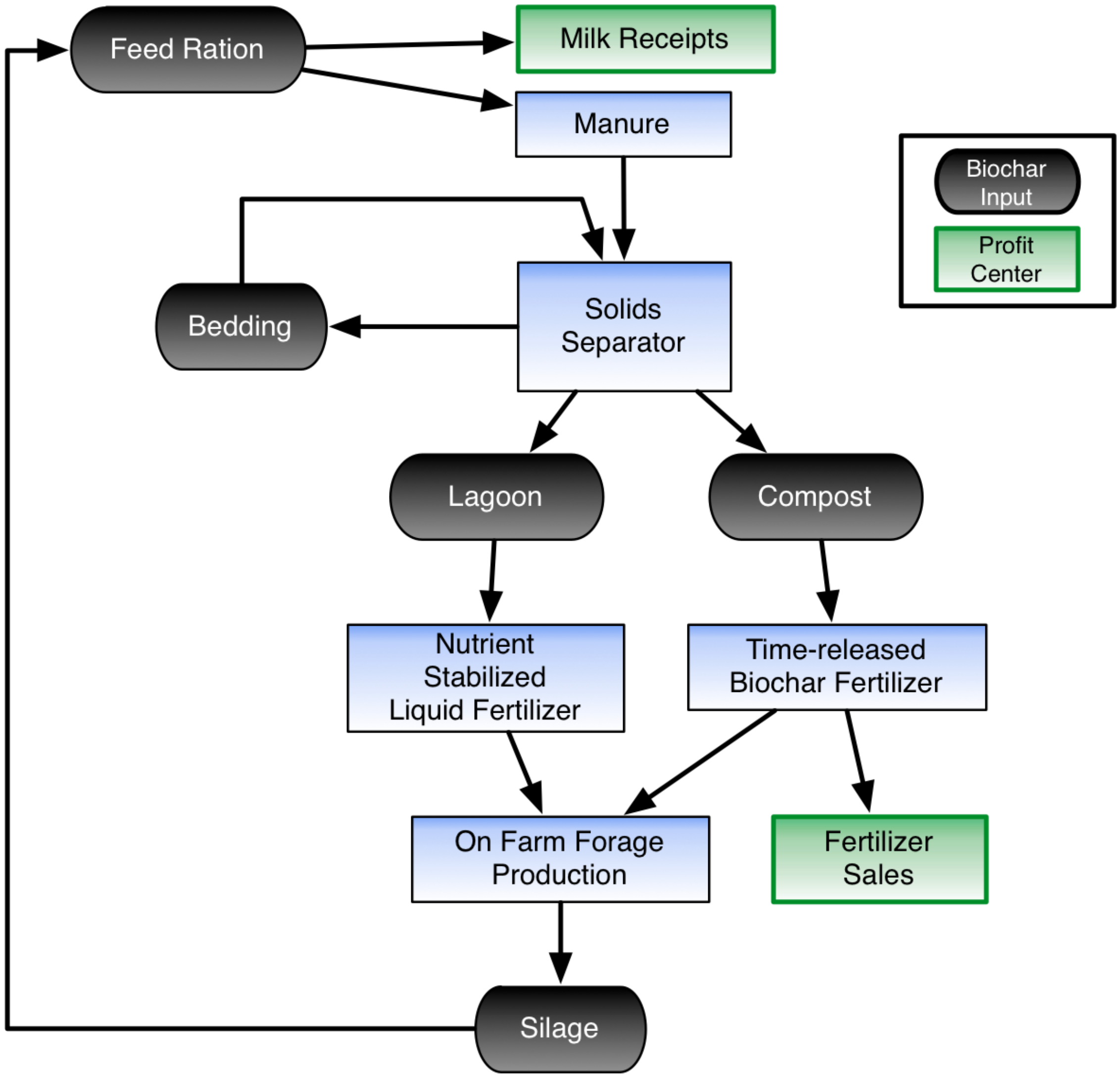
Biochar is a “structural” input, best compared to a sponge, it is not a “functional” input like inoculants, fertilizer or compost in the strict sense. There are beneficial cascading uses of biochar in farming system (Figure 15)[14], as stabilizing agent for synthetic and organic inputs and as soil conditioner for field production. Mixing biochar with urea-based fertilizers can decrease ammonia volatilization, and increase nitrogen use efficiency by 20% compared with regular urea (Jia et al., 2021). Adding biochar to manure and compost during thermal processing and curing is known to substantially reduce nitrogen losses and greenhouse gas emission, conserving more nutrients for the crop when these are applied to the field. Combining biochar with synthetic or organic inputs offers a slow-release agent so the synchronicity of nutrient supply with demand from crops throughout the growing cycle is improved.

[13] *https://www.cdr.fyi/blog/2023-year-in-review*

[14] *https://www.agproud.com/ext/resources/2022/08/03/WBA-2014*

Biochar also adsorbs heavy metal substances that may enter the soil through other inputs and pose a risk to public health. High porosity and surface area in biochar enhances soil aggregation and water retention, leading to better crop root development, reduced soil erosion, and increased water-use efficiency. Mixing biochar with cattle manure and maize stover during composting has been shown to reduce losses of nitrogen and organic matter, enhancing the fertilizer potential of the final product (Bello et al., 2019). Functions of microorganism and inoculants, as well as their longevity, are enhanced through biochar amendment since it offers a habitat for colonization and survival. The structural stability and slow decomposition rate of biochar offer a unique opportunity for rehabilitating soil fertility in that farmers can apply biochar to their fields incrementally over time. Biochar can be a one-time input at higher rate or a repeat amendment at lower rates, yet under each scenario enhancing crop production and agronomic efficiency over the short and long run.

Figure 15:



Availability/Scalability

The selection of biomass materials and the amount diverted for biochar production must consider the broader context of nutrient recycling, soil health, and sustainability in farming systems. Nitrogen-rich materials like legume stover, vegetable waste, and animal manure are not appropriate in this respect since a large proportion of this nutrient escapes as gas during pyrolytic conversion. Biomass resources like stover or straw should neither all be turned into biochar since they provide functional organic matter for soil health. A balanced approach for selecting biomass must compare the benefits as structural organic matter input and carbon sink against the need for other soil fertility functions. Nonetheless, in most cases there is an excess of such fibrous high-carbon residues in field crops, municipalities and agroforestry that make good candidates for biochar production. Total biomass stocks from farming can be quantified through the ratios of economic yields to residue and aggregated production, or via geospatially explicit and dynamic crop growth modelling. Availability of specific resources can be assessed through farm surveys, livestock densities and standard factors for other organic matter management strategies like composting and mulching as part of scenario analysis.

A study in smallholder maize, millet, sorghum, and rice growing systems of Uganda showed that the potential biochar yield from unused residues with cookstoves ranges between 1 and 1.6 tons per hectare (Roobroeck et al., 2019). When extrapolating based on the land coverage for those four cereal crops in the country, the total potential amount of biochar is 2.1 million tons per year under existing competitive pulls. At a biochar application rate of 5 tons per hectare this would suffice to treat 419 thousand hectares of land each year, equivalent to 21% of the cultivated areas for the crops. Other biomass resources that are suitable for biochar production and currently used in projects are cassava stems, legume pods, sisal boles and pulp, cacao husks, coconut shells, coffee husks, tea pruning, tree litter and hedge clippings. Other good candidate resources are invasive encroacher species for instance, in Namibia 45 million hectare of land is affected by sickle bush or other types which represent an estimated biomass stock of 400 million tons[16]. Animal bone waste from slaughterhouses also presents a valuable resource for producing P fertilizer through pyrolysis, also called bone-char, but this technology is underutilized. Livestock herds in Ethiopia generate between 192 and 330 thousand tons per year, that when recycled can provide 28-58% of current P fertilizer inputs, worth US $ 50 to $ 104 million (Simons et al., 2014).

Costs and benefits

In artisanal systems the cost of biochar production ranges from US $ 65 to $ 100 dollar per ton, whereas in industrial systems it is between US $ 200 and $ 400 per ton, but the permanence and carbon credit value is higher. Average prices for carbon credits on voluntary offset markets are US $ 120 per ton biochar (Puro.Earth; see CORCHAR index[16]), with 30% going to overhead for monitoring and certification. Prices for the biochar as farm input at bulk quantity are near US $ 200 or lower per ton, and large-scale market demand would likely support wholesale prices in the range of US $ 80 to $ 150 per ton (author knowledge). If biochar is produced with own labour and applied at 1 ton per hectare, the maize grain yield gains can translate into an immediate return rate of 32% to 207% under smallholder practices with varying rates of fertilizer and manure use. If farmers purchase biochar for the same input rate, the best-case yield gain would give an immediate return rate of 53% but the worst-case scenario would take two growing seasons to reach a 32% return. The economic benefit of biochar must be assessed over a longer period since the effect on crop production is lasting and recurrent. As shown

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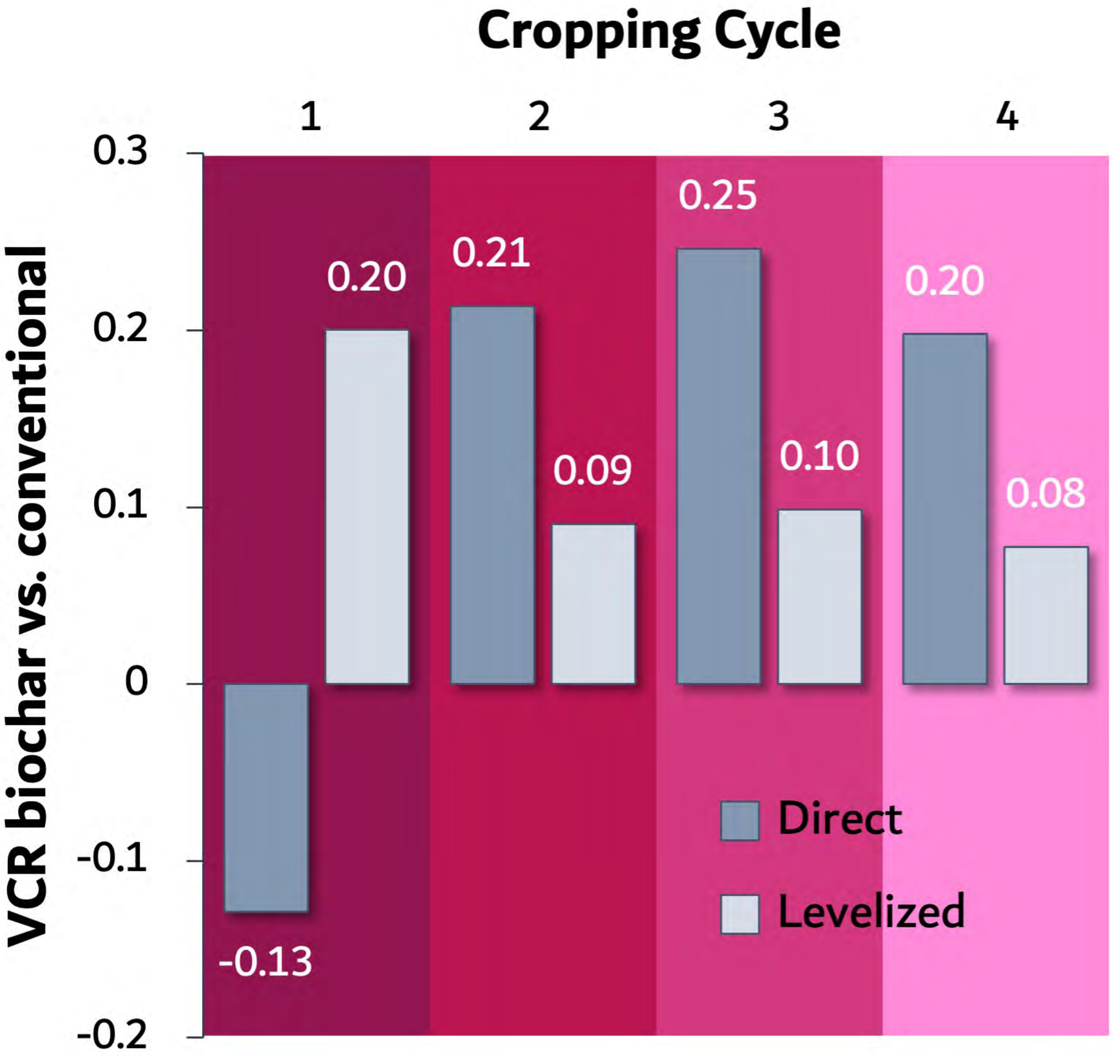
[16] *https://puro.earth/corc-carbon-removal-indexes*

by data from irrigated rice in Ghana, when purchase and labour costs for applying biochar is wholly factored in the first season the value cost ratio is lower than the conventional practice with synthetic fertilizer only (Figure 16). Writing off the costs of biochar use across the yield gain horizon draws a more representative picture and shows a lower stable profit level from the second season onwards.

Use of biochar as feed ration in dairy has a VCR of 4.67 through savings in additives, reduced disease and mortality, and increased milk quality.[15] Use in bedding, through decreased pathogen load and respiratory ailment, has a VCR of 1.45. Including onward benefits in manure storage and its fertilizer quality would increase these metrices.

Figure 16: Difference in value cost of paddy rice cultivation with and without biochar over multiple growing seasons, under direct and levelized attribution of purchase and labor expenses (Adapted from: MacCarthy et al., 2020).



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[15] *https://www.n-big.org/download/Brochures/Biochar-from-Namibian-Encroacher-Bush.pdf*

Climate mitigation and adaptation

It is estimated that biochar production from available crop residues, discounting for harvest efficiency, livestock feed usage and emissions during production, can offset a large proportion of greenhouse gas emission from countries ranging from 44% in Ghana, 35% in Rwanda and 23% in Malawi (Karan et al., 2023). A global meta-analysis for paddy rice demonstrates that biochar applications at 9 tons ha^{-1} combined with 140-200 kg fertilizer N achieved the lowest greenhouse gas intensity of production, i.e., methane and nitrous oxide per unit yield, which is more than 2.5 lower than without biochar application (Iboko et al., 2023). Emission measurements for production of biochar-enriched substrate under a GIZ project confirmed a large negative carbon footprint due to limited methane and nitrous oxide being generated by pyrolysis systems and compost piles. A recently concluded study from the International Livestock Research Institute in collaboration with IITA, found that manure mixed with biochar at 10 to 30% weight ratio had a lower CH_4 emission intensity by 10 to 44%, lower N_2O emission intensity by 50%, and less ammonium volatilization by 50 to 84%.

Biochar can hold up to four times its weight as water and plants can easily access the moisture even when soil is dried out; this sponge-like effect reducing vulnerability of rainfed farming systems and increases water productivity for irrigated systems. The stability of maize yields across ten years, an indicator of climate resilience, was found to be 12% higher when biochar was combined with fertilizer by the IITA long-term trial in Kenya (Kätterer et al., 2019). The process of biochar production also generates energy in the form of heat, syngas, or bio-oil, which can substitute fossil fuels, electricity and fuelwood, whereby reducing greenhouse gas emissions associated with energy production and consumption, further contributing to climate mitigation. Assessing the net climate mitigation impact of biochar must consider emissions from aggregation, pre-processing and transport of biomass, alongside the reduced footprints of agricultural production and the persistent carbon removal following recognized life-cycle analysis protocols.

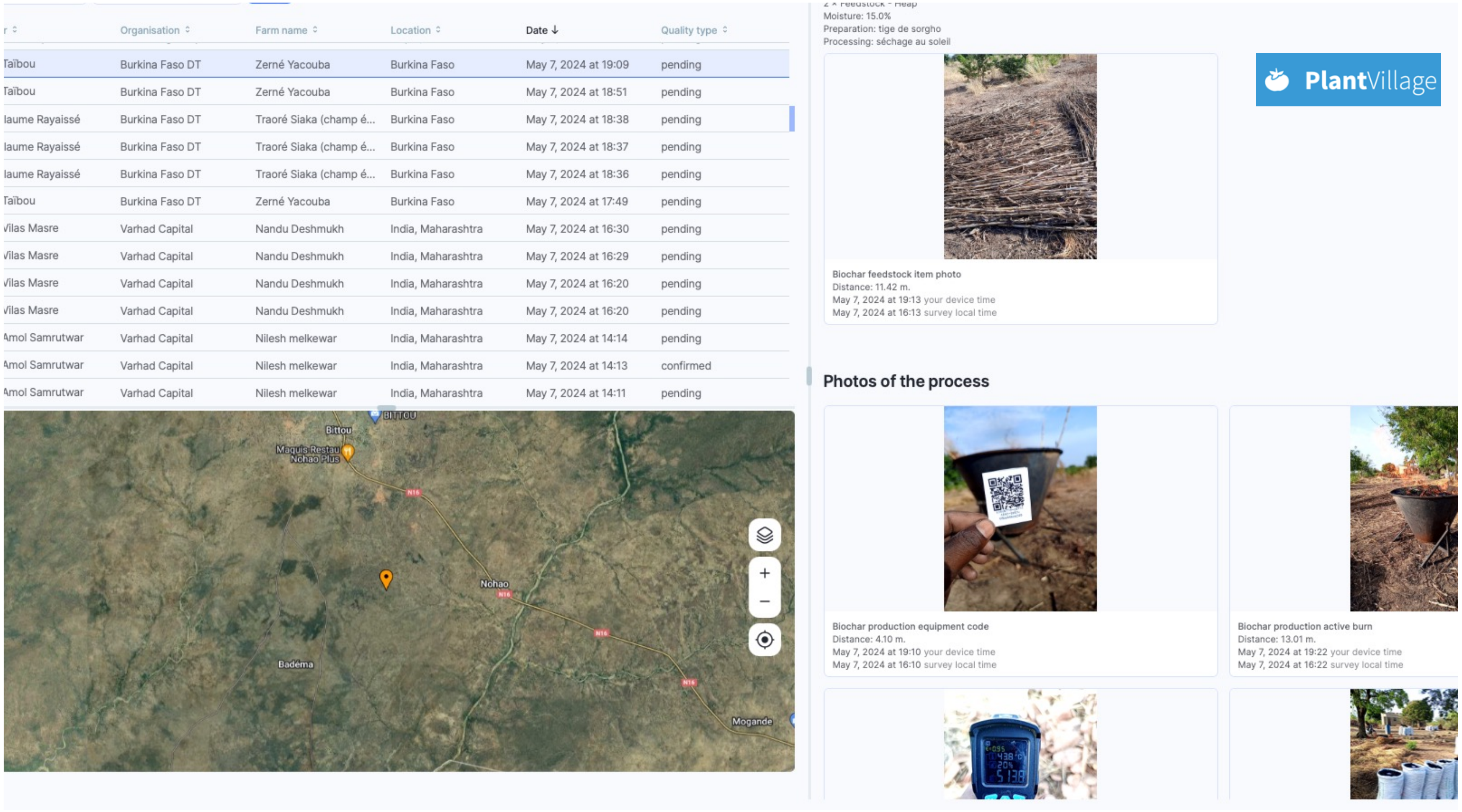
Growth pathways

Artisanal biochar production can take place on or near farms, making it cheaper to source feedstock and use biochar in a timely manner. Cookstoves that implement pyrolysis are actively promoted in many countries of SSA owing to their health benefits, fuelwood saving and biochar output. Industrial biochar production facilities are suitable for agribusinesses since they can utilize heat and power for offsetting energy costs. The number of social and commercial ventures in Africa that produce biochar for soil amendment and carbon credits is rapidly growing. PlantVillage through BiocharLife[17] enables production of biochar through kilns or dug pits on farms in Kenya, Malawi, Burkina Faso, and Tanzania linking the farmers with carbon markets via the Artisan standard and paying US $ 80 per ton of biochar. The role of PlantVillage is to start-up and maintain production and agronomic use through extension and offering a digital chain-of-custody tool for tracing resource flows, critical go-between services for farmers. BiocharLife certifies the production and sinking process by checking rule compliance and reported amounts, they then directly pay out to the farmer. Small-scale biochar production is bundled into clusters of 500 ton per year or more for the climate services to become marketable and the administrative costs sustainable. Jointly, PlantVillage and BiocharLife have produced more than 5,000 tons biochar between 2020 and 2023, and now are entering into purchase agreements of 30,000 tons with international buyers like Carbon Future. To access the market these companies, make use of chain-of-custody tools that integrate digital fingerprinting techniques and lower overhead cost of monitoring, reporting and verification (MRV; Figure 17). Revenue from carbon credits is retained to repay for services provided to farmers. Input supply companies are also marketed biochar mixes with compost or other organic input, where the model is underpinned by sales to farmers as a nutrient source. For instance, SafiOrganics[18] is a Kenyan manufacturer which uses rice husk as feedstock for biochar and mixes it with frass from black soldier fly derived from urban solid waste. The technology allows to downsize and decentralize fertilizer production, add value to local wastes and create new employment. This reduces the logistical cost and produces a high-quality product at the same price or lower than imported synthetic fertilizers.

In Cameroon, the first African pilot facility for industrial biochar production was built by NetZero[19] next to a large coffee processing plant. This location gives a direct and cheap access to husks, an abundant biomass waste, and gives a one-of-a-kind platform to distribute the biochar to small coffee growers. Its production capacity can reach 2,000 tons of biochar per year and since 2022, the project was certified by Puro.earth, the world’s leading certification standard for high-permanence carbon removal. A similar enterprise model is followed by BioSorra[20] in Kenya. Several engineering and financial viability studies ongoing for captive heat and electricity from biomass gasification with small and large industrial systems. One involves cassava chip drying where technology is being transferred to local equipment suppliers and cooperative processors which will shorten the time to dry and achieve market final moisture through a hybrid greenhouse setup. Another is linked to the tea sector where the supply chain and suitability of pruning residues and other biomass is tested, and business and environmental blueprints are developed for attracting investors to operate as independent electricity and heat generators. Each of these enterprise models is directly linked with on-farm biochar trials which elicited demand from farmers to deploy the technology.

[17] *https://www.biochar.life/certificates*
[18] *https://safiorganics.co.ke/our-products/*
[19] *https://netzero.green/en/production-sites/*
[20] *https://www.biosorra.com/copy-of-about*

Figure 17: View of MRV platform for biochar production developed by PlantVillage, with in-built geotagging, barcoding and picture logging.



r ⇕	Organisation ⇕	Farm name ⇕	Location ⇕	Date ↓	Quality type ⇕
Taïbou	Burkina Faso DT	Zerné Yacouba	Burkina Faso	May 7, 2024 at 19:09	pending
Taïbou	Burkina Faso DT	Zerné Yacouba	Burkina Faso	May 7, 2024 at 18:51	pending
laume Rayaissé	Burkina Faso DT	Traoré Siaka (champ é...	Burkina Faso	May 7, 2024 at 18:38	pending
laume Rayaissé	Burkina Faso DT	Traoré Siaka (champ é...	Burkina Faso	May 7, 2024 at 18:37	pending
laume Rayaissé	Burkina Faso DT	Traoré Siaka (champ é...	Burkina Faso	May 7, 2024 at 18:36	pending
Taïbou	Burkina Faso DT	Zerné Yacouba	Burkina Faso	May 7, 2024 at 17:49	pending
Vilas Masre	Varhad Capital	Nandu Deshmukh	India, Maharashtra	May 7, 2024 at 16:30	pending
Vilas Masre	Varhad Capital	Nandu Deshmukh	India, Maharashtra	May 7, 2024 at 16:29	pending
Vilas Masre	Varhad Capital	Nandu Deshmukh	India, Maharashtra	May 7, 2024 at 16:20	pending
Vilas Masre	Varhad Capital	Nandu Deshmukh	India, Maharashtra	May 7, 2024 at 16:20	pending
Amol Samrutwar	Varhad Capital	Nilesh melkewar	India, Maharashtra	May 7, 2024 at 14:14	pending
Amol Samrutwar	Varhad Capital	Nilesh melkewar	India, Maharashtra	May 7, 2024 at 14:13	confirmed
Amol Samrutwar	Varhad Capital	Nilesh melkewar	India, Maharashtra	May 7, 2024 at 14:11	pending

Moisture: 15.0%
Preparation: tige de sorgho
Processing: séchage au soleil

Biochar feedstock item photo
Distance: 11.42 m.
May 7, 2024 at 19:13 your device time
May 7, 2024 at 16:13 survey local time

Photos of the process

Biochar production equipment code
Distance: 4.10 m.
May 7, 2024 at 19:10 your device time
May 7, 2024 at 16:10 survey local time

Biochar production active burn
Distance: 13.01 m.
May 7, 2024 at 19:22 your device time
May 7, 2024 at 16:22 survey local time

Support functions

- Development: Biochar agronomic recommendations must be formulated that guide farmers on effective dosage for different crops, accompanying inputs, water stress conditions and production targets. Other soil and water management practices should be included as part of this so their complementarity can realize benefits which exceed economic thresholds. Mechanical and thermal engineering of pyrolysis systems is needed for making them suitable for specific biomass materials and allowing easy and robust operation while maximizing biochar quality and minimizing emissions. Constructing, validating, and scaling digitally mediated tools for tracking biomass sourcing, pyrolytic conversion, and farm application is essential for regulating and incentivizing biochar production. These tools can integrate geographic and remote sending information, data analytics, energy management, and internet-of-things telemetry to ensure transparency, quality control, and compliance with environmental and sustainability standards. Advancing the knowledge for biochar production and use involves multidisciplinary research and collaboration across natural, social, and business-related fields.

- Financing: The economic viability and return on investment are critical drivers for the adoption of biochar technology in agriculture, regardless of whether it is applied in artisanal, domestic, or industrial contexts. Enterprise models must be formulated for scaling that consider a broad range of benefits, including saved fertilizer costs, increased crop yields, reduced energy expenses and improved ecosystem functions like water retention. Blockchain technology can be used to create transparent and immutable records of transactions, reducing the risk of fraud or misreporting. Cooperative models where smallholder farmers or local communities collectively invest in and benefit from biochar production and application, as well as industrial utilities with energy generation for agri-processing should be piloted and scaled. Financing options for the purchase of pyrolysis systems and biomass processing equipment could involve partnerships with financial institutions or government-sponsored incentive programs. Investment insurance plans can be utilized to alleviate risks and promote innovation and early adoption.

- Extension: Initiatives by national agricultural agencies and civil society to educate the masses about biochar and its numerous advantages in agriculture must be broadened. This involves needs assessment to understand the specific requirements and challenges of the target audience. Information materials and research-informed recommendations should also be tailored in line with knowledge and literacy levels, and the contexts and practices of farming systems. Demonstration sites and farmer evaluations where communities see the benefits of biochar firsthand can serve as learning hubs and help refine application methods. Integrating biochar agronomy, pyrolysis, and gasification technology into university curricula for science and engineering is essential to develop a skilled workforce equipped to advance these fields.

Enabling policies

Most nations in SSA have not yet included biochar as a soil input in agricultural and waste management policies. Inherent linkages of biochar with various policy domains, such as food production, environmental, energy, and industry, require a harmonized approach between entities and frameworks. Cameroon is the first on the continent to have integrated industrial biochar production into its climate and sustainable development strategy. Regulations play a central role towards ensuring responsible practices that safeguard food systems, biomass sourcing and societal benefits. Currently, producers in SSA must register biochar under existing national legislation for fertilizers, soil improvers and composts, but the standards on nutrient content and acidity contained in these do not fit with its characteristics or that blended product. Quality norms formulated by industries in Europe, China and the US offer a valuable starting point for developing national legislations and issuance of certification. Specific guidelines and governance structures for the removal of invasive species and biochar production to restore communal grassland and fodder production are missing. In early 2024, Kenya enacted its milestone “Carbon Credit Trading and Benefit Sharing Bill”[21] which provides for:

i. Permits for persons intending to carry on carbon credit trading business in either the voluntary carbon market or the carbon compliance market.

ii. Benefit-sharing ratios of project proponent with the designated authority, the national and local government, the community; distinguishing private and public land.

iii. A registry for carbon credit trading permits, carbon credit trading projects, community development and benefit-sharing agreements, as well as purchase agreements.

iv. Litigation against false declarations in environmental and social impact assessment; and misrepresentations or concealment of material facts.

Multiple schemes for monitoring, reporting and verification of biochar production are recognized, including the European and World Biochar Certificate, British Biochar Quality Mandate and International Biochar Initiative Standard, and Verra’s Verified Carbon Standard. The Global Artisan C-Sink certification guidelines are eligible for low, lower middle and higher middle-income countries and pertains to kiln and dug pit systems that are suitable for on-farm production (Figure 18). Overall, the three components that govern biomass sourcing are: monitoring the source of the biomass, evidence of legal and sustainable management, and use of Life Cycle Assessment methodology to ensure a minimum greenhouse gas saving. When using less than 4 tons feedstock per day the operators are exempt from sustainability reporting. Technological development targets are also embedded in regulations, in that when a C-sink project exceeds a production of 1,000 tons per year it must develop and demonstrate a trajectory towards integration of energy-captive pyrolysis systems. Emissions from pyrolysis systems must be recorded and, if necessary, compensated.

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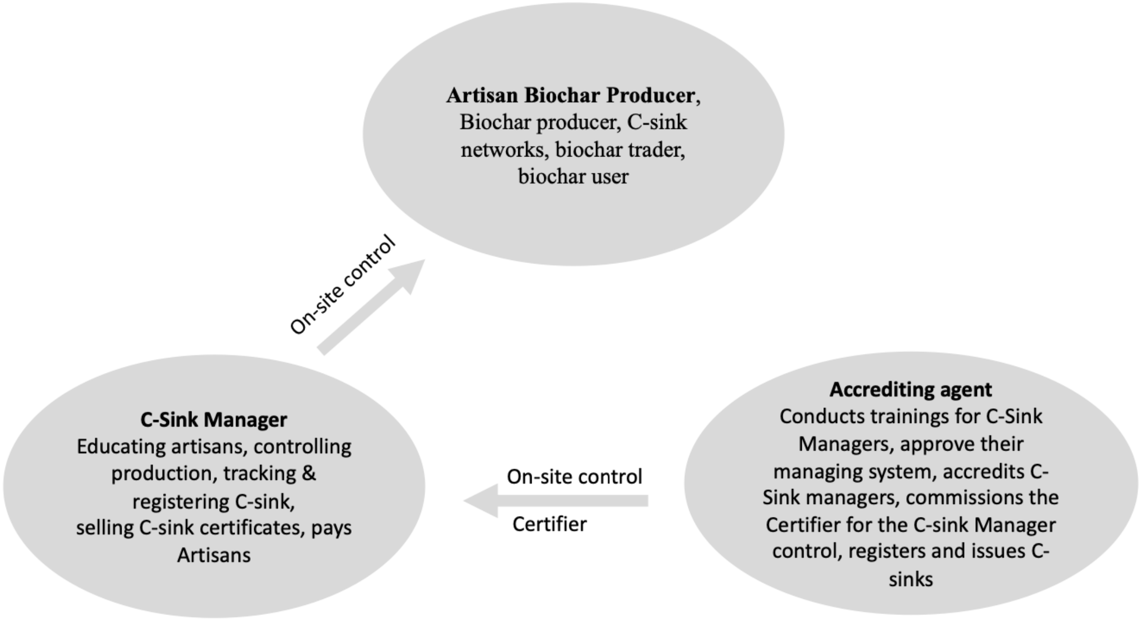
[21] *https://kwcakenya.com/wp-content/uploads/2023/08/Carbon-Credit-Trading-Bill-Eighth-draft.pdf*

Figure 18: Global Artisan C-Sink certification structure consists of interlinkage and controls between three entities. (Credit: Ithaka Institute for Carbon Strategies 2020).

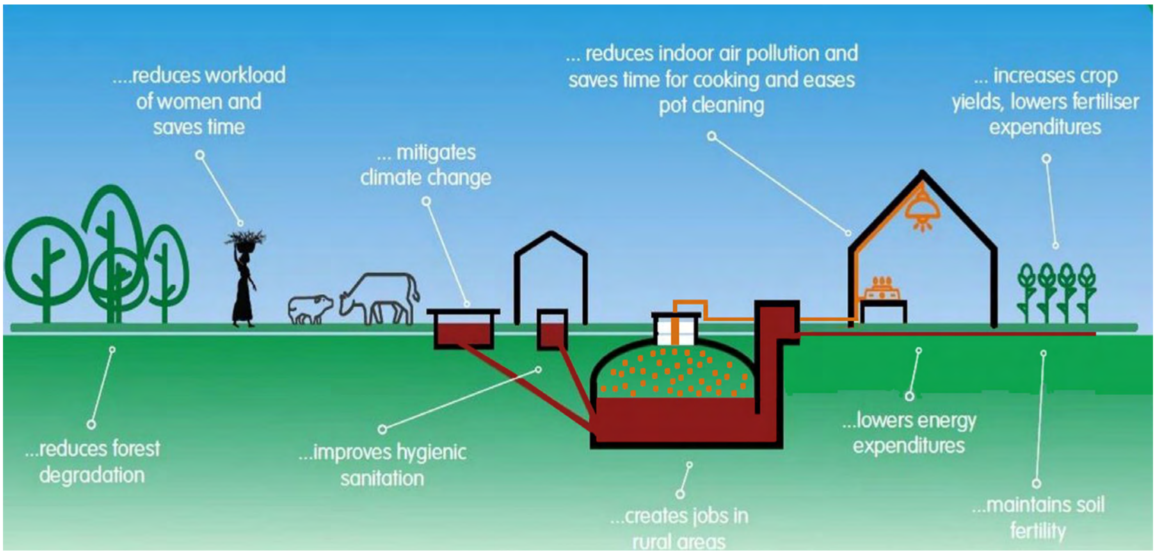


3.5 Biodigester slurry for nutrient inputs to crops

Main features

The slurry remaining from anaerobic digestion is a rich source of nutrients and bioactive compounds that promotes overall soil and plant health management and benefits microbial communities and nutrient use efficiency. Livestock manure and toilet waste, which contain up to 75% of all recyclable phosphorus in biomass, can be utilized to feed digesters as well as purpose-grown energy crops or wastewater sludge. Digestion has a dual purpose because it creates value from biomass waste through energy and results in organic inputs for sustainable agriculture while saving time on fuelwood collection and tree cover (Figure 19). Cow dung is one of the most common sources for biogas digesters, but also human faeces can be used along with biomass leftovers from crops, grass clippings or solid organic municipal waste. The fixed dome system is the most preferred plant design in rural settings, prefabricated digesters are entering the market that are primarily used for urban settings. Because of lower installation cost, some argue that flexible balloon models should be promoted.

Figure 19: Benefits from biodigester systems on agriculture, people and climate (Credit: SNV)



Use of slurry from digesters as agricultural input has some concerns such as bulkiness, low C/N ratio, nitrogen loss, and high pH value, it must be managed appropriately to avoid any environmental consequences. The bulkiness arises from a high water content (>90%) which complicates transport and utilization whereby it must be produced and applied locally. A large proportion of nitrogen in manure or waste can be lost during digestion and slurry storage which must be avoided to obtain a valuable nutrient input for agriculture. Overfertilization with slurry that has high nitrogen loads may increase the mineralization rate of organic carbon present in the soil. Leafy vegetables are known to be prone to higher uptake of heavy metal from slurry as compared to the root vegetables and grain crops. Hence, there is need for comprehensive testing and agronomic advisory on the efficient and safe use of slurry. Digesters must be operated at optimum retention time, pH level and temperature for pathogens to be killed in the process. Storage of slurry without bottom liners or impermeable surfaces causes nitrogen and potassium leaching into groundwater. Hence, regulations and monitoring for production and handling are critical so hazards to human health are avoided.

Complementarity

Amending biogas slurry to farmland has substitutive and supplemental benefits on synthetic fertilizer and soil properties. If the feedstock input and biodigestion process are well managed the effluent slurry has high concentrations of readily available nitrogen, phosphorus, potassium, and organic matter which interact to enhance nutrient supply to crops and conservation. Residual slurry from digesters has a broader spectrum of micronutrients and trace elements than common fertilizer which are critical to address deficiencies and balanced input management. By enhancing microbial activity, increasing water retention capacity, and preventing soil erosion, the use of slurry promotes nutrient cycling and conservation that would not happen with synthetic fertilizers alone. Nutrients in bioslurry, especially nitrogen, are more readily available then in raw manure, leading to a greater short-term yield benefit. Field research on maize in Kenya found that combining slurry with mineral fertilizer gave the higher or equal grain yield and no drop in soil pH over two growing seasons as compared to inorganic fertilizer only (Rewe et al., 2022). Another study by these authors recorded similar responses in maize production to slurry from different digester systems but varying changes in soil properties. Experiments with teff in Ethiopia demonstrated that yield effects from increased application of slurry may be dependent on the rate of mineral N and P fertilizer input (Berihu, 2021). Effluent from biogas digesters may also offer a good substrate for multiplication of microorganisms for inoculants and production of bioactive compounds with anti-phytopathogenic activities. The nutrient content of biogas slurry varies depending on the feedstock used and the specific anaerobic digestion process, and farmers must know how much it would be to tailor its application for specific crop and soil needs. Risks are connected to the improper processing, storage and application of slurry that can lead to nutrient leaching, greenhouse gas emission and disease transmission. For instance, if bioslurry is not injected into the soil or applied under conditions of lower air temperatures and moist soil, a significant portion of the ammonia can volatilize and be lost to the atmosphere.

Availability/Scalability

The most opportune areas of deploying anaerobic digestion and slurry use are households and communities rearing cattle and camel for dairy and meat, as well as markets or factories for processing of vegetables, fruits, palm oil and other that generate a lot of nutrient-rich waste material. Based on livestock ownership, water availability, fuelwood scarcity, population density and climate it is estimated that biogas and slurry is technically feasible for 18.5 million households in 24 African countries (ter Heegde & Sonder, 2007). Human sanitation waste offers a suitable feedstock for slurry application since the biodigestion process can overcome health risks. For proper feeding and effective operation of digester a minimum volume of four cubic meter is recommended which requires four cattle or the equivalent in other livestock units. There is a strong relationship between households' cattle holdings and the feeding performance of digesters, and poorer families with small herds and limited housing for livestock often fail to meet the required flock size. Large biodigester systems with a volume of 800 m3 can discharge up to 15 tons of slurry per day which can treat three hectares of farmland at the minimal recommended rate. Smaller household-size biodigester of five cubic meters with daily feeding of 50 kg cattle dung, produced by five dairy cows, 20 pigs or 10 sheep, can annually produce of 11 tons of slurry that can fertilize 2 hectares of land.

Biogas slurry use by farmers in SSA is limited because of high investment cost, year-round access to manure and technical complexity. Low-quality design and construction of digesters, wrong operation and lack of maintenance by users have been found to hamper widespread adoption. Dysfunctional digester systems account for 17 to 27% across different geographies, and these rates are higher where livestock densities are lower. Effective capacity building and after sales support by the promoters of biodigester and local governments is key to achieving sufficient slurry production for displacing mineral fertilizer and soil health management in smallholder agriculture. Digesters at community level have the ability to draw manure and toilet waste from multiple sources ensuring reliable and cost-effective operation. Private equity and operation by specialized enterprises play a key role in making community-level digesters profitable and sustainable. By leveraging expertise and resources, these enterprises can optimize operations, ensure proper maintenance, and achieve economies of scale. This approach reduces financial burden on the community and will see more rapid implementation of best practices and innovative technologies.

Costs and benefits

The cost of a biodigester installation depends on factors such as size, type, site preparation, labor, and additional features like piping and concrete slabs for direct feed-in. Concrete tanks with a volume of four cubic meter cost around US $ 2,495. For most scaling programs in smallholder farming systems, adoption of systems has been achieved through subsidy from government and international cooperation agencies, up to half of the price. Besides that, purchasers utilized loans mostly from multi-purpose cooperatives and microfinance institutions. Many programs struggle with loan repayment for biodigester installations where in some cases only 13% of households complete the schedule within the set period, posing a risk for financing. For larger scale dairy and cattle farms with 50 heads of cow, the installation cost of a 48 cubic meter biodigester exceeds US $ 25,000. A comprehensive business plan is needed for large installations and community level programs, meticulously addressing risks of technical problems, operating costs, financial returns, and renewable energy credit (Figure 20).

Scaling programs in Kenya found that expenditure on chemical fertilizers reduced for 79-99% of households with a functioning biodigester. Surveys with farmers using bioslurry in Ethiopia demonstrated that substitution of mineral inputs saved between US $ 17 and $ 52 per year (Debebe & Soromessa, 2016). The profitability of slurry use depends on how farmers utilize it. Sole application is determined by factors such as availability, low cost, and soil fertility status. Combined application with mineral fertilizer is driven by the need to enhance nutrient balance and improve crop yields. Application of bioslurry from cow dung or poultry manure at 5 tons ha-1 and chemical fertilizer on maize crops has been reported to give 20-24% higher grain yield, 22-23% greater gross return and 52-53% higher gross margin compared with the traditional farmer practice (Ferdous et al., 2020).

Figure 20: Major business models for biodigesters and the institutional enablers (+) or barriers (-) critical for their survival or competitiveness (Adapted from: Valve et al., 2021)

Business model	On-farm manure processing	Waste management and energy generation
Value creation and capture	Focus on rural energy access/savings and slurry for increased crop yield and fertilizer substitution.	Focus on gate fees and energy outputs. Lower economic incentive for slurry due to need of advanced processing.
Institutional enablers (+) and barriers (-)	Equipment investment subsidies (+) Regulations on sale of excess energy (–)	Waste Act and Landfill restriction (+) Regulations on slurry from sewage sludge (-)

Climate mitigation and adaptation

By recycling nutrients and organic matter back to the soil, slurry application displaces synthetic fertilizer, whereby reducing the carbon footprint of agricultural practices. Studies on dairy farms with digestion systems found 12% to 27% less greenhouse gas emissions, 31% to 58% less terrestrial acidification, and 3% and 18% less freshwater eutrophication than those using manure directly on the farm for fertilization (Rivas-García et al., 2015). The stability of organic matter is increased through digestion, causing slurry to have longer carbon retention than raw manure when applied to agricultural soil. This has been empirically proven by lower CO_2 flux between digested slurry and untreated dung from cattle relative to organic matter input for maize production on sandy soils in South Africa (Mdlambuzi et al., 2021). Notwithstanding, less than 5% of carbon added through slurry is persistently stored which makes it less suitable for soil carbon sequestration and disqualifying it from credits for durable carbon removal. Significant contributions to climate mitigation and adaptation are made at the energy-side of the technology; a study in Ethiopia shows that 1.86 tons of fuelwood is saved per year by digesters of 6 to 8 m^3, equivalent to 2.75 tons CO_2 captured in forest (Kefalew et al., 2021). Biodigester systems, especially those with uncontrolled overflow, have risks of biogas formation outside the reactor, whereby CH_4 and N_2O are released into the atmosphere and reduce the net climate benefit of the technology.

Growth pathways

The Africa Biogas Partnership (ABP)[22] has been assisting national programs on the application of biogas for energy and slurry for food production. To date, the program has facilitated the construction of 18,534 plants in Ethiopia, 11,529 plants in Kenya, 6,441 plants in Tanzania, 7,628 plants in Uganda, and 10,310 plants in Burkina Faso. Production has progressively increased thanks to the establishment of construction companies, under the ABP programme, masons are registering companies and operate as business entities which contribute to a commercially viable and market-oriented biodigester sector. In Burkina Faso, a major impetus was provided to uptake from the government which made a subsidy that covers 30% of the initial cost of a 6 cubic meter digester under the ABP programme. Women lead in the uptake of biogas plants loans, in addition, the number of females trained in operation and maintenance and bioslurry utilization stood at 48%. Use of bioslurry for improved agricultural production has increased due to enhanced training and awareness among women users. Farmers are also selling excess slurry to other farmers creating revenue which recovers capital and operational expenses. In Ethiopia, the Biogas Dissemination Scale-Up Programme (NBPE+), a public-private partnership with technical backstopping from SNV that works at federal, regional, and district levels, installed more than 45,000 biodigester by 2024[23]. Under the program 20,000 hectares of land are cultivated using bioslurry annually, and more than 100,000 tons of fuelwood is saved annually, reducing the over-exploitation of tree cover. In Kenya, the Organic Fertilizer Valorization Implementer under the African Biodigester Component has trained 22,000 households with a biodigester on the use of slurry. Loan plans have been implemented for biodigesters by local micro-financing institutions in Ethiopia[24] through SNV supported projects. The loan size was US $120 with amortization over two years at 16% declining annual interest rate and 2% service charge. As of June 2016, the repayment rate of the company is about 95% which is the highest among those engaged in providing bio-digester loan in the country. To increase the size of loan to US $173, the microfinance company submitted a proposal to the DBE to access World Bank (WB) funded “market development for renewable energy and energy efficient product” line of credit.

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[22] *https://www.africabiogas.org/countries/*

[23] *https://www.snv.org/project/biogas-dissemination-scale-programme-nbp*

[24] *https://www.snv.org/update/pioneering-bio-digester-financing-ethiopia*

Support functions

- **Development:** Engineering on digester systems must be carried out to reduce the cost and increase the functionality and lifespan so to make it more accessible for farmers in SSA. Research on slurry formulation is critical to address limitations and risks of slurry like N leaching, bulkiness and contamination to make efficient and safe use in agriculture. Solutions have been investigated including enrichment with de-oiled press cake, cultured microflora, and specialty nanoparticle materials. In this way nutrient recovery can be enhanced and additional processing steps for slurry like dewatering, separation, and decontamination, be minimized or circumvented entirely.

- **Financing:** Assisting farmers' self-help groups to access cheap loans from for purposes of lending to their members is key for adopting biogas technology. Digester installations are often financed through credit facilities with saving cooperatives accounting for most of the lending and only a minor part of credit provided by banks. A competitive commercial market must be developed for construction materials, appliances, and labor to ensure these can be obtained at a reasonable cost. Since biodigestion construction companies offer systems on credit they must assess the creditworthiness of customers and adapt to profiles in new geographies.

- **Extension:** Quality management in construction of biogas plants is a key pillar of successful scaling where supervisors must be engaged to back up technicians to enhance control service and mason operations. Training and agronomic advisory to obtain more value from bio-slurry benefits is required to ensure expanded uptake and growth of the market. For outreach, partnerships with construction companies and NGOs are a cost-effective strategy to strengthen both the supply and demand sides of the technology and operation. Extension services that foster exchange and interaction between farmers are most successful towards increasing adoption of good manure management practices like biodigestion and slurry use.

Enabling policies

Legislation and regulation on manure management are governed by different ministries and their policies must be streamlined for coherent and concerted actions (Ndambi et al., 2019). Extension services must be broadened to inform farmers that plants must be connected to a bioslurry pit and disseminate the value for crop production through good agriculture practices. Providing farmers with recommendations on effective application rates and necessary complements of mineral fertilizers in line with specific resource endowment and production objectives is key for guaranteeing profitable use and expanded adoption. Governments at the national and local level also play an important role in subsidy incentive policies for digester installations, which can be facilitated by financing mechanisms from international cooperation. Coordinated efforts are needed to build supply, demand, and an enabling policy environment for biodigestion and agricultural use of slurry, which entails a feedback loop of service-quality, user satisfaction, promotion and sector development. Programs to support the adoption of biodigester and slurry in rural communities must have a multi-disciplinary delivery structure, this typically involves a fund manager, a technical advisor and implementing agency like a ministry.

Governments can intervene in the establishment of training centres at vocational schools where masons and other actors learn technical and entrepreneurial skills. In Uganda a centralized client service centre has been formed to ensure compliance with technical and business standards for the biogas sector. This independent agency ensures accountability to clients by the construction companies, implement plant coding for quality monitoring and customer service inquiries. Creation of trade unions for biogas contractors and sectoral associations with actors from the biogas value chain should be encouraged for advocating legislation and regulation that promotes uptake. The consolidation of local capacities is a pivotal point for interventions by the private sector and civil society. Another example for mainstreaming the use of bioslurry as high value organic fertilizer comes from Ethiopia where the Ministry of Agriculture and Natural Resources was made part on the National Biogas Steering Committee (in 2016) which elicited harmonized action between energy and farming. In Ghana's capital Accra, a project with the district assembly was set up to build capacity for the biogas technology to manage faecal sludge with the aim of producing inputs for peri-urban farms. The International Livestock Research Institute is conducting research in partnership with the Kenya Biogas Program to assess the environmental, agronomic and productivity effects of bioslurry as organic fertilizer for crops in smallholder systems comparing the nutritional value of common fodder species treated with and without bioslurry. In 2017 a conference was held with delegation from Burkina Faso and Kenya to chart a way for improving extension services on use of slurry in agriculture where knowledge of benefits and appropriate dissemination strategies were shared.

Several impact-based financing mechanisms can be leveraged for investments to promote use of biodigester and slurry in communities (Figure 21)[25].

Grant-based funding plays a major role at the initial development stage of the market but offer the long-term stability needed to drive scaling. Carbon-offsets is an emerging mechanism that has been growing rapidly, and major traders such as Gold Standard have recognized and marketed the impact of biogas. Crowd-based financing can fund multi-million credit sizes over a multi-year period but for larger deal sizes the interest rates are significant and can create currency mismatches on the balance sheets of biogas companies. Development impact bonds remain at a nascent stage, off balance-sheet securitization requires significant portfolio sizes to be cost-effective, and government subsidy programs depend on local political will and budget capacity. The most promising in the short-run whilst companies are still seeking to scale are carbon-offsets and crowd-based financing. Biogas companies with significant customer portfolios could also explore off balance-sheet securitization, whilst development impact bonds may develop as a more feasible funding option in the future.

Public support should be based on digester outputs such as electricity and utilization of slurry in agriculture for nutrient recycling. Impact-based monetization requires clear and rigorous results measurement, to demonstrate and persuade stakeholders that this is worth financing. This means developing systems to measure, track, understand, and communicate the impact of biogas to external stakeholders. Indicator frameworks based on two methodological tools, 'outcome harvesting' and 'most significant change', have been designed that can be adapted and contextualized for specific projects.[25]

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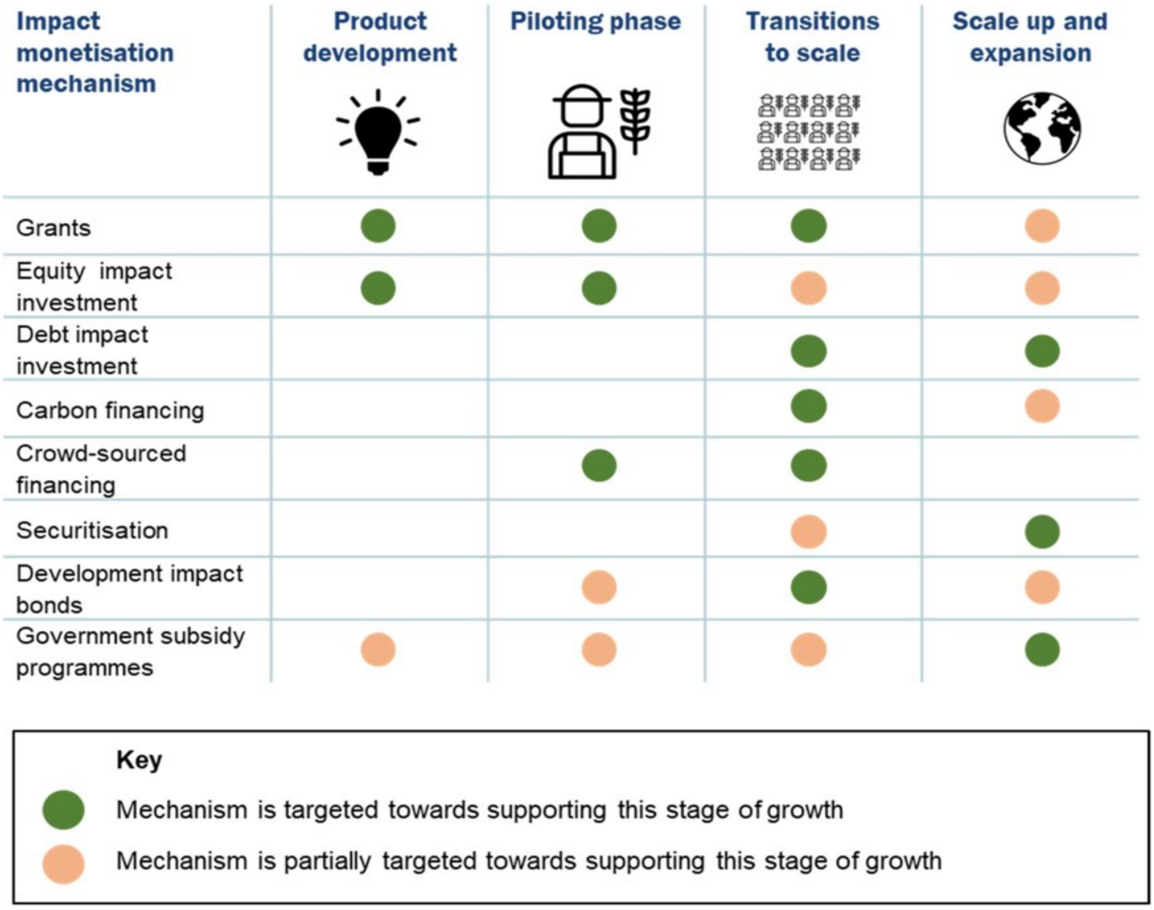
[25] *https://shellfoundation.org/learning/demonstrating-the-potential-of-biogas-to-contribute-to-the-sdgs/*

Figure 21: Matrix for identifying appropriate mechanisms to finance the scaling of bio-slurry (Source: IPE Triple Line)



Impact monetisation mechanism	Product development	Piloting phase	Transitions to scale	Scale up and expansion
Grants	🟢	🟢	🟢	🟠
Equity impact investment	🟢	🟢	🟠	🟠
Debt impact investment			🟢	🟢
Carbon financing			🟢	🟠
Crowd-sourced financing		🟢	🟢	
Securitisation			🟠	🟢
Development impact bonds		🟠	🟢	🟠
Government subsidy programmes	🟠	🟠	🟠	🟢

Key

🟢 Mechanism is targeted towards supporting this stage of growth

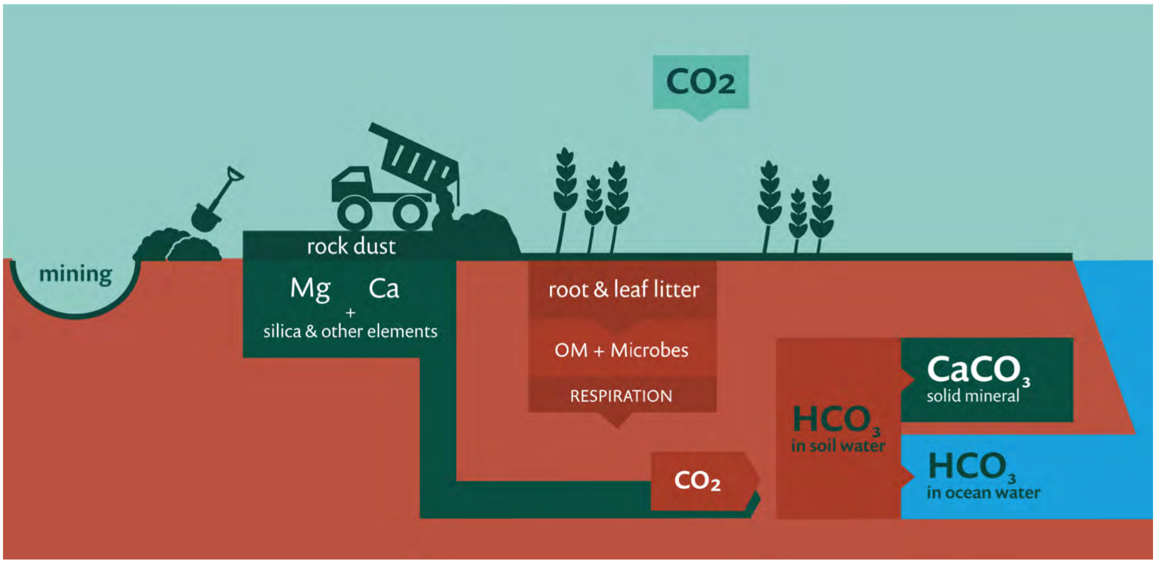
🟠 Mechanism is partially targeted towards supporting this stage of growth

3.6. Enhanced rock weathering as fertilizer and lime substitute

Main features

The decomposition of stone – known as weathering – is one of the key natural processes that sustains life on earth, it is the origin of soil formation and liberates nutrients that drive production on land and ocean. When rocks react with water mineral carbonation occurs, whereby carbon dioxide from the atmosphere gets locked into a stable form of carbonates that help regulate the climate over thousands to millions of years. Enhanced rock weathering (ERW) involves the application of small fragments of crushed rock, measuring 0.2 to 5mm, on land which speeds up the release of nutrients, creation of sand, silt and clay and capture of CO_2 (Figure 22). ERW utilizes wastes from mining and industrial processes such as fines from ballast grinding, overburden material that is removed to access ore, and slags tailing remaining after ore extraction. These resources have limited or no other purpose and pile up on mining sites, hence their use in a value-added agricultural manner supports a circular economy. When commercial ERW value chains are established, companies may intentionally extract rock minerals for selling into farming.

Figure 22: Main aspects from the implementation, processes, and benefits of ERW (Source: Boudinot et al., 2023)



The use of rock dust products has demonstrated short-term benefits on a variety of crops, including on soybean, common bean, maize, alfalfa, sorghum, rice, potato, and sugarcane. In various parts of the world such as Brazil, Australia and India, rapid expansion of ERW markets is taking place to address import dependence of conventional phosphorus and potassium fertilizers and mitigating rising prices and volatility. African regions have great opportunity for ERW due to the presence of suitable rock in shallow deposits, the high acidity of soils, and tropical temperature and moisture conditions. Through ERW applications, mining companies can augment the value of processing wastes and diversify their business models. ERW requires transport and spreading of material which attracts costs and emissions that must be factored in. Rocks may contain high levels of heavy metals (e.g., nickel, chromium) that can be harmful to soil and crop health with accumulation over time. There is little to no published research on the suitability of rock characteristics for ERW nor about the benefits and risks of application on farmland in Africa. Because of this, uncertainties remain around the feasibility of ERW, and value chain development and investment are hindered. Cross-sectoral efforts are needed to formulate legal and regulatory frameworks and agronomic recommendations that tie in soil health benefits with climate and environmental impacts of ERW technology.

Complementarity

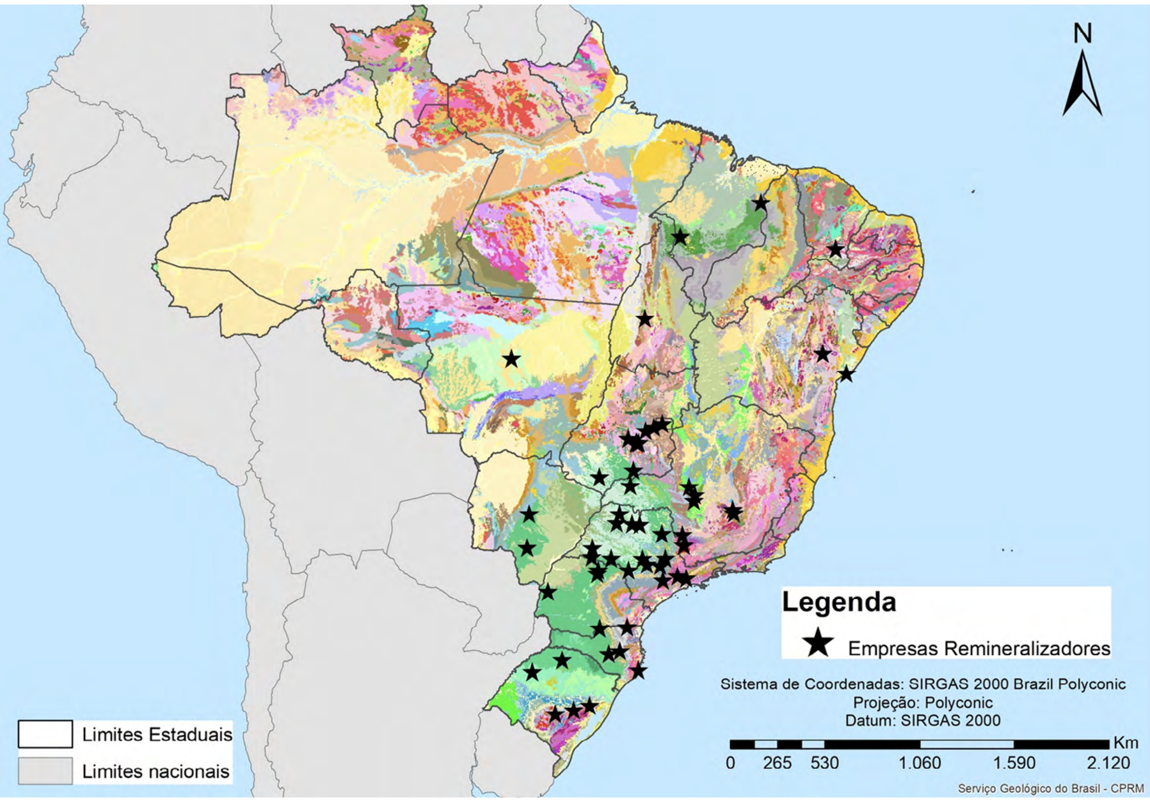
A range of nutrients is released from rocks, including potassium, phosphorus, calcium, magnesium, boron, amongst others, that contribute to soil fertility and crop growth. The phosphorus (P) and potassium (K) content of rock dust depends on the type of rock from which it is derived. Basalt, granite, and other rock dusts generally contain lower amounts of phosphorus, often less than 1%. Basalt dust may contain around 1% to 2% potassium, whereas granite dust often contains about 3% to 5% potassium.

This displaces and complements the use of synthetic fertilizers both in the short and longer term. Calcium and magnesium react with soil acidity and reduce the need for fast-acting lime. ERW can significantly increase uptake efficiency of nitrogen by crops and thereby decrease fertilizer-derived nitrogen oxide emissions, a potent greenhouse gas. Rock dust increases the availability of silicon which is deficient in most African soils and serves a key role in plant defence against pests and diseases. Benefits extend beyond the farming system, as carbonates and cations are washed out to sea where they deacidify the oceans and reducing coral reef destruction. Unwanted yield reductions may occur at high application rates and after repeated input of ERW if fine particles are compacted and form a dense layer which impede water infiltration, reduce air exchange, and hinder root penetration. Rocks contain heavy metals like arsenic, mercury, and lead which can accumulate in the soil and potentially reach levels that are harmful to plants, animals, or humans. A wide range of factors, including rock composition, soil properties, crop nutrition, local environmental conditions and accompanying practices, must be considered to ensure maximal benefits as well as no drawbacks of ERW technology for farmers over the longer term.

Availability/Scalability

Displacing substantial amounts of fertilizer and lime requires higher input of rock dust at more than 5 tons per hectare with common rates of 20 – 100 tons per hectare, and thus sufficient volumes must be supplied for widespread adoption of ERW. Basalt offers large potential because it is an abundant by-product of mining and has a high weathering rate and micronutrient content. Other minerals offering good ERW candidates include diabases, gabbros, amphibolites, phonolites, syenites, dunites, pyroxenites, and serpentinites. ERW inputs for agriculture can be derived from different mining waste fractions such as fines from ballast and ornamental stone, as well as overburden covering ore deposits, or slag remaining after earth metal extraction. Crushing of rocks for production of gravel and larger aggregate inherently yields about 20% of fine-grained material that cannot be used in construction. An industrial quarry may collect 60–70 tons rock dust each month which is disposed in piles (Kautzmann, 2011). Estimates indicate that several hundred thousand cubic meters of waste have accumulated near mines across SSA, and as exploration activities expand, the disposal of rock debris is increasing (Lowdes & Jeffrey, 2009). Strict due diligence frameworks must be obeyed for rational and safe application of ERW in farming systems, else ineffective or hazardous inputs may flood the market and trounce testing capacities. The availability and suitability of rock dust must be determined through agroecological surveys, combining information on lithology, geochemistry, topography, soil properties, crop nutrient requirements and climatic factors (Figure 23). Demographic and economic data must further be considered to assert the economic viability of rock dust supply and use. Transporting the crushed rock to the spreading site is the most expensive part of the process, depending on the distance and method of transport. Logistics are an important factor as it affects the availability and cost of the materials. Assessing the nutrient supply, net carbon footprint and operating costs from a life cycle and business performance viewpoint is critical to earmark areas with high technical potential for ERW deployment.

Figure 23: Map of candidate rock dust sources from mining sites in Brazil based on geochemistry and soil properties (Source: Brazilian Agricultural Research Cooperation)



Costs and benefits

The primary cost is sourcing and transporting the rock to the site, crushing it, and then applying it to the target area, on average cost of applying one metric ton of silicate rock is around US $ 12.5, including both processing and application costs. In Kenya, quarry fines are currently sold as substitute for sand in concrete and mortar at US $ 10 per ton. Supply of ERW does not require large new capital investments since most resources, machinery and physical infrastructure is part of day-to-day mining, logistics and agronomic operations. Project costs will vary based on other factors such as land acquisition cost, transportation costs, and labor costs. Therefore, it's essential to assess the total expenses accurately. If the extraction site is close to the processing site, these costs can be reduced. Also, the technology used to do the processing of the material can impact the overall cost of the ERW project, as well as efficiency of the technique. To spread costs and optimize profitability, farmers can apply 5 tons every three years and gradually build up soil fertility. Credits for carbon removal through the ERW process are already traded on voluntary markets at prices of US $ 230 to $ 300 per ton CO_2, higher than biochar for instance due to its persistence. Several pioneering projects by climate-tech companies around the world that offer ERW application as a service have illustrated that all costs of purchase, application and monitoring can be recouped at current market value of the carbon credit.

Climate mitigation and adaptation

When silicate rocks react with water and CO_2 through weathering processes, they form bicarbonate, which washes out to oceans. There, it is turned into carbonate and sinks to the ocean floor, storing carbon for millions of years. Simulations for African cropland estimate that at a rate of 10 tons of basalt dust per hectare a carbon capture of 1.2 to 1.6 tons CO_2 ha^{-1} $year^{-1}$, the highest together with Asian tropical regions (Baek et al., 2023). Because this coincides with low household income and pervasive soil fertility degradation the technology allows for just climate action. Different types of minerals and rocks sequester varying amounts of CO_2, so the choice of material affects the contribution to climate mitigation. The above-referenced assessment confirms that ERW is resilient to global climate change and becomes more effective with global warming and does not compete for arable land which allows for large scale deployment. Release of P, K and micronutrients from locally sourced ERW inputs can displace synthetic fertilizers which are manufactured with high energy and emission intensity and transported overseas. This contributes to lower climate footprint from agri-food systems and makes them less vulnerable to supply chain shocks.

Certification guidelines and a framework for MRV, the “Global Rock C-Sink”, have been recently developed by Ithaka Institute for Carbon Strategies.[26] This methodology considers the specific nutrient and trace-element content of the deployed rock dust, as well as the field’s soil characteristics, to ensure application rates that are safe and beneficial for the agricultural system and in accordance with all relevant European regulations. It is imperative that cropland based ERW applications are carried out in such a framework, so they have positive effects to the agronomic system and do not put burden on farmers and the food system. Process emissions occurring during rock powder production and transport/spreading are considered in the life cycle analysis of the complete carbon budget.

Growth pathways

Brazil is a global leader of ERW use in agriculture and has built a full-commercial industry for the soil input. In 2021, rock dust was applied on approximately 3 million hectares across the country, and 30 mines were certified to produce rock dust in 2022. The latest national plan on agrominerals for ERW includes a goal to certify 1,000 mines by 2050, potentially supplying all farmers nationally with rock dust and replacing 50% of imported phosphorus and potassium fertilizer. Brazil’s government took a proactive approach in developing rock dust supply chains from mining industry, putting in place agile market regulations and blended concessional loan programs. Through the association, ABREFEN, incentives and legislation for Brazilian mines are developed to produce remineralizers, supports quality management, and monitoring, and enables legislative processes to accelerate the transition from conventional to sustainable agricultural inputs. Alongside with infrastructure and finance, service provision for mining companies and farmers has been developed, such as Reminera[27] which offers analytical, certification and go-to-market-consultancy. Brazilian farmers can buy one ton of rock dust at US $ 20 to $ 200 depending on the quality and the supply distance is by law capped at 200-400 km so a net neutral carbon footprint is achieved. In Africa there are no industrial-scale supplier of ERW products, but several companies are starting up like UNDO.[28] They are at the stage of identifying and securing rock dust with high carbon removal potential and low levels of trace metals, evaluating agronomic benefits and recommendations through field trials, and developing models for monitoring, reporting and verification. Business models of these companies are pegged on the

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[26] *https://www.european-biochar.org/media/doc/139/rock-c-guidelines_0_9.pdf*

[27] *https://remineralbrasil.com.br*

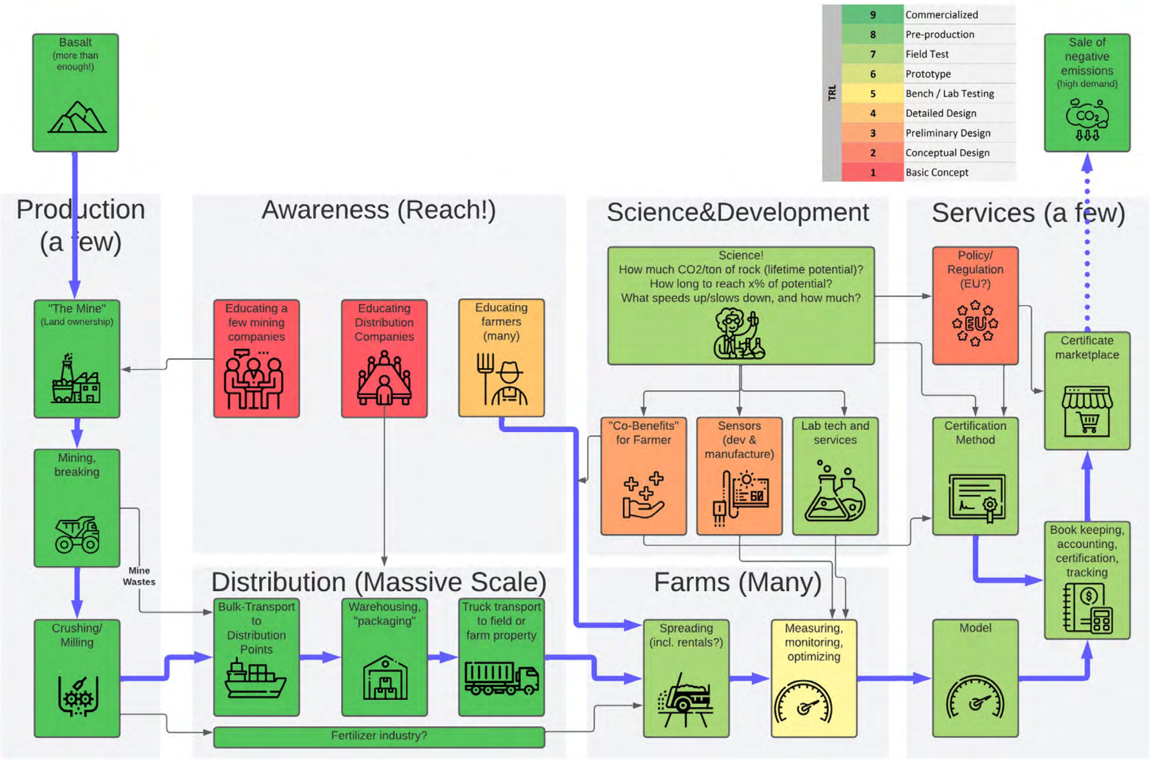
[28] *https://un-do.com/enhanced-rock-weathering/*

carbon credit value where costs for sourcing and distribution are recouped from this revenue, enabling supply to farmers at very low cost. A challenge of this approach is the large investment needed to build knowledge and purchase equipment for quantifying actual CO_2 removal, and because of methodological procedures are not ratified by international climate offset schemes there is no clarity if, when and how pay-outs for ERW will take place.

Support functions

- **Development:** Mapping the readiness of existing actors from the mining and agriculture sectors is a crucial step for establishing ERW value chains (Figure 24)[29]. This process offers insights into strengths and opportunities that can be exploited as well as critical gaps that must be addressed. From a technical perspective, there is need for specific studies on materials from mining, and spatial integration of prevalent mineral deposits and crop production through agro-geological surveys to help make informed decisions. Agronomic recommendations that consider interactions with fertilizer, organic matter, rainfall, and irrigation must be designed to scale the technology. Research should gather understanding of yield benefits, soil health improvement, potential risks, and environmental impacts for low rates with repeated application and high rates with single application. MRV procedures for carbon removal by ERW must be further developed and linked to agronomic and socio-economic indicators.

Figure 24: Flow chart detailing actors involved with ERW on croplands, and technological and commercial readiness of each (Source: Carbon Drawdown Initiative)



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[29] *https://www.carbon-drawdown.de/blog/2022-12-14*

- **Financing:** To be viable and scalable, business models for ERW must be built that are tailored to local conditions and farmer needs, and that realize affordable prices of rock dust. Access to carbon finance must be leveraged to make ERW financially solvent. Given the innovation and development needs for this novel value chain, it is key to establish partnerships and shared financing programs between governments and mining companies to attenuate the initial costs and first losses. International cooperation agencies, climate funding institutions and philanthropic donors play a key role in supporting basic and applied research that will guide investment and policy. Venture capitalists and impact investors can be attracted for ERW projects since there is a high probability for short-term returns.

- **Extension:** Public awareness must be raised about the benefits of ERW for agriculture and climate through media campaigns and grassroot organizations. Profiling individual farmers as well as civil society programs based on literacy level and willingness to adopt ERW can help prioritize and improve messaging and skill building approaches. Training programs of extension agents provide the basis of widespread practical advisory to farmers on application rates and complementary practices. Digital support tools can reduce the cost of outreach and increase the number of people adopting the technology. Such support must be tailored to local contexts, address specific needs, and promote sustainable farming more broadly. In-person consultation from experts and artificial intelligence chatbot should be provided for mining industry and retailers that seek to enter into rock dust supply.

Enabling policies

The implementation of ERW projects on a large scale depends on product regulations and fiscal incentives that promote investment by mining sector and purchase by farmers. Given the cross-cutting nature of ERW ministries of mining, agriculture and environments must coordinate and harmonize efforts. This involves identifying the key barriers and gaps that may hinder ERW adoption and value chain development upon which advocacy for policy changes or financial support mechanisms can be designed. At the same time, national fertilizer, soil management plans and mining acts must define rock powders for agricultural use and chart roadmaps for the design of clear and predictable regulatory frameworks. In Brazil a decree from the Ministry of Agriculture, Livestock and Food Supply regulates the use of basalt rock powder. This describes ERW products as mineral material that underwent comminution and sorting, and provide plants with macronutrients and micronutrients, and improve physical, chemical, and biological properties of soil. Through this law and technical norms, the exact parameters that rock dust must fulfil in terms of elemental composition and granulometry are outlined for certification and labelling. Different oversight bodies have the responsibility to streamline the permitting for exploitation, quality standards of rock dust and environmental impact assessments for easy entry of mining companies.

Another key role from government is to implement agro-geological surveys to map out the suitable and viable sources of rock dust, which can be supported through grant-based finance. Through regulations and survey information, investors can better decide on engagement with mines that produce legally certified rock powder and sell a hazard-free sustainable input for agriculture. Ministries and development cooperation agencies are responsible for public education, extension training, and expert consultation services. Dedicated innovation funds and challenge grants for research, development, and implementation of novel ERW technologies and practices are an effective approach to enable scientists and industry with critical knowledge gathering. Financial support for mining companies would come through low-interest loan programs and other forms of credit enhancement like first-loss guarantee can encourage funder to enter novel ERW projects that bear greater risk. To promote sales, tiered pricing rules and subsidies can be put in place that are proportionate to application rates and farm size, ensuring different customer segments have equitable access to ERW inputs. Broader international collaboration plays a key role in facilitating technology transfer to mining companies and knowledge exchange to innovation centres from regions with established ERW value chains to shorten the learning curve, reduce funding needs, and avoid common pitfalls for adopting the technology. This may be through sharing legislative and practical experience around supportive policies and financing mechanisms which can help other governments navigate hurdles.

4. Conclusion

This toolkit provides a comprehensive review of the latest evidence from research and commercial applications for organic and auxiliary inputs that align with the complete principles of ISFM. Necessarily, it emphasizes solutions that can be sourced inside or nearby farming systems wherein they specifically pertain to use of beneficial microorganisms, reducing nutrient losses, displacing inorganic fertilizers, sequestering carbon, and strengthening resilience. This includes technologies that have been available for some time but did not achieve widespread uptake owing to persistent agronomic, financial and regulatory factors. Novel technologies that are being introduced in SSA or have been applied successfully elsewhere in the world are also covered to raise awareness and accelerate their adoption in program formulations. What sets the toolkit apart most, is its succinct discussion of innovative scalable enterprise models and revenue streams that can support investments. It is key to note the technologies in the toolkit alone do not warrant the system transformation as needed for boosting food security and incomes. For instance, it does not feature landscape-level practices for production of organic resources or water and soil conservation, nor technologies for processing and marketing that create strong incentives for adoption of sustainable practices. Interventions to promote the use of farm inputs described in the toolkit must be considered in complement with those areas since coordinated efforts are imperative to realize catalytic change.

This catalogue was prepared with a variety of users in mind whether they be producers, agents of agricultural development, extension supervisors or private sector investors. Those from the public sector can utilize the toolkit to design projects for modernizing technologies. Members of the private sector, including producers, manufacturers, processors and investors also benefit from its contents of this catalogue. Direct use for this toolkit is the formulation of 10-year Action Plans for Fertilizer and Soil Health, the CGIAR Mega Programs and grant cycles from international development agencies. To this end, IITA offers services like technical backstopping of investment programs, strategic research, participatory evaluation, and capacity building. As part of the ISFM principle, this involves the bundling of technologies through co-design processes where improved germplasm and judicious use of inorganic fertilizer are co-applied with organic and other amendments to realize quick wins. This starts from a recognition that ISFM must be placed and operated within geographic and socio-economic contexts, and pathways for green growth in Africa. Beyond this, collaboration at the global, national and community level plays a key role to leverage expertise and achieve desired outcomes.

Snapshot of content in technology profiles as related to potential for sustainable intensification, enhanced profitability, emission reduction, and policy mechanisms to promote access and use.

Microbial inoculants to manage nutrients and pests

- Advanced legume integration in maize and wheat crop rotations / intercropping systems, and harnessing biological nitrogen fixation processes, can save up to 10% of synthetic fertilizer input.

- Biopesticides for protection of cotton achieve return rates of 0.9 to 1.7 but would be higher than chemical products if environmental costs are accounted.

- The energy demand for the manufacture of an inoculant/biopesticide is 1% of that for a synthetic product whereby emission footprints can be substantially reduced.

- Selling of biofertilizer together with improved seed through farmer networks has increased the distribution-to-production ratio by 12%, and the sales-to-distribution by 34%.

- Certification schemes through industry control bodies with independent testing and labeling of inoculant products can ease quality control.

Composting for nutrient recovery and value addition

- Food and green waste from households in urban centers from Sub Sahara Africa (SSA) countries has the potential to produce 50,000 to 500,000 tons of compost per year.

- Service delivery models and automation systems are needed to increase the volume of organic waste that is composted in rural and urban landscapes.

- Through replacement of synthetic fertilizer, liquid compost can save 5.3 kg CO2 per ton, whereas solid and vermiculture compost save 17 kg CO2 per ton.

- A radio show with tips on compost has increased adoption from 25% to more than 89 %, proven that extension is key.

- Savings in disposal fees at landfills can measure US $24 to $113 per ton of organic waste, which can be used as financial support to enterprise development and capacity building.

Liming products to counteract soil acidity

- In SSA, cereal crops suffer yield losses of 10 to 80% resulting from reduced phosphorus and micronutrient uptake, and aluminum toxicity in acid soils.
- The use of agricultural lime across SSA is very low; for example, in Kenya the expected demand would be 187,000 ton based on soil data, but sales are less than 50,000 ton.
- Applying lime at rates of 2 to 5 tons per hectare on wheat and barley in conjunction with ISFM provides net added value of US $1,320 to $1,420.
- Yield increases and higher fertilizer use efficiency due to use of lime are lowering the emissions per food quantity and compensate for emissions from the transport.
- The Ethiopian government is exploring the option of a revolving fund to achieve its target of treating 4 million hectares of land with lime without relying on taxes or foreign investment.

Biochar as structural organic amendment

- Realistic input rates of biochar at 1 to 10 tons ha-1 can increase the agronomic efficiency of an inorganic fertilizer application by 50 to 70%.
- Yield increase and soil health benefits last for more than 15 years, with 60% sequestration of carbon under intensive cultivation.
- Its high permanence, lower cost of production and ease of verification favor biochar for climate offsets, delivering 93% of all durable carbon removals in 2023.
- Purchase agreements for over 30,000 tons C credits have been issued using the Global Artisan Standard that is designated to on-farm production.
- Legislation for carbon credit trading and benefit sharing is fast emerging but standards for biochar as farm input have not been prescribed.

Biodigester slurry for nutrient inputs to crops

- A tank of five cubic meter with daily feeding of 50 kg can annually produce of 11 tons slurry that allows to fertilize 2 hectares of land.
- Based on livestock ownership, water availability, fuelwood scarcity, population density and climate technology are feasible for 18.5 million households in SSA.
- Farmers using bio-slurry, e.g., in Ethiopia, were found to save US $17 and $52 per year through substitution of mineral fertilizer inputs.
- Use of digestion and slurry can lower greenhouse gas emissions, terrestrial acidification, and freshwater eutrophication compared to direct field application of manure.
- Result-based financing mechanisms are ideally placed to leverage investments for the promotion of biodigester and slurry in communities.

Enhanced rock weathering as fertilizer and lime substitute

- As rocks react with water, they release phosphorus, potassium and micronutrients that stimulate plant growth and improve soil structure.
- Several 100 thousand cubic meters of quarry fines and overburden waste has accumulated near mines in SSA, and as exploration activities expand the disposal of rock debris is increasing.
- An application rate of 10 tons of basalt dust per hectare removes between 1.2 and 1.6 tons CO2 per year, with carbon credits going for US $230 per ton.
- In Brazil, rock dust is applied on more than 3 million hectares of cropland, and 30 mines are certified to produce soil remineralizer products.
- Tiered pricing and subsidies proportionate to application rates and farm size can ensure different customer segments have equitable access.

Rate card

Table 3

			Technology					
Level	**Component**	**Metrics**	**Inoculants**	**Compost**	**Lime**	**Biochar**	**Slurry**	**Rock dust**
Manufacture	Raw material	Availability labor preparation logistics	🟢	🟨	🟩	🟩	🟨	🟩
	Production system	Skills equipment operation output	🟨	🟧	🟧	🟨	🟨	🟩
	Business model	Demand competitive profitable	🟩	🟨	🟩	🟢	🟨	🟢
Distribution	Stock keeping	Infrastructure quality loss bulk volume	🟨	🟧	🟩	🟩	🟧	🟩
	Supply chain	Logistics trading	🟢	🟨	🟥	🟨	🟨	🟥
Application	Input practice	Suitability labor frequency extension	🟩	🟩	🟨	🟩	🟩	🟨
	Agronomic benefit	Dosage responses legacy effect	🟩	🟩	🟢	🟢	🟩	🟩
Governance	Regulatory oversight	Standards procedures	🟩	🟨	🟩	🟨	🟨	🟩
	Incentive structure	Feasibility leverage potential	🟨	🟩	🟩	🟨	🟩	🟩

🟥 **Very difficult** 🟧 **Difficult** 🟨 **Average** 🟩 **Easy** 🟢 **Very easy**

5. Glossary

Aglime	Finely powdered limestone that is intended for application to farmlands capable of reducing harmful effects of an acid soil.
Auxiliary amendment	Substance added to soil or growing media that, while not providing direct nutrients to plants, improves soil conditions and support plant health.
Beneficial microorganisms	Microbes that positively impact plant growth, soil health, and ecosystem functioning.
Biochar	Carbon-rich material produced through the thermal decomposition of biomass in (near-) absence of oxygen, a process known as pyrolysis or gasification.
Biocontrol agent	Natural organisms, such as insects, bacteria, fungi or viruses, that suppress the population of a pest or disease, reducing their impact on crops.
Biofertilizer	Substance containing microorganisms like bacteria, fungi, and algae that, when applied to seeds, plants, or soil, increases the availability of nutrients.
Bioslurry	Mix of solid and liquid organic material left over after microorganisms break down biomass during anaerobic digestion processes.
Compost	Organic material created through the decomposition of organic waste by bacteria, fungi, and worms in the presence of oxygen.
Inorganic fertilizer	Fertilizer that is industrially manufactured, either synthetized or derived from rock and minerals through physical and chemical processes.
Organic fertilizer	Any farm input that is derived from natural sources, such as plant and animal materials, and is minimally processed to retain its organic content.
Organo-mineral fertilizer	Blended formulation combining organic materials and inorganic nutrients, obtained through mixture or reaction of one or more base matrices.
Rock dust	By-product from the crushing or grinding of rocks, typically basalt, granite, or other minerals, also known as rock powder and rock flour.

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