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Exploring the state of ex situ organic fertilizer and soil amendment production: an innovation systems analysis across eleven African countries

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Introduction: Many farming systems across Africa suffer from insufficient recirculation and replenishment of nutrients and organic matter, contributing to soil degradation. At the same time the scant management of municipal organic waste, agro-processing residues, and human excreta creates substantial externalities. Valorizing organic waste and recycling it back to farmland could create a win-win situation. This exploratory, cross-sectional study investigated the current state and emerging trends in ex situ organic waste recycling toward organic fertilizers and soil amendments (OFSA) across eleven African countries. The topic is timely, as recent disruptions in inorganic fertilizer supply chains may have heightened interest in ex situ OFSA.

Methods: We triangulated 74 key informant interviews with document and literature review, using the Technological Innovation System framework as analytical lens.

Results and discussion: Our analysis shows that while all system functions have progressed beyond the "pre-development" phase, most still remain in an early formation stage. Core functions such as *entrepreneurial activities, knowledge development and diffusion, guidance of the search, market formation, resource mobilization, and legitimacy* are emerging, for instance through the introduction of subsidies, the implementation of quality standards, and initial efforts of cross-country coordination. South Africa stands out, with multiple functions institutionalizing and reinforcing one another, characterized by pronounced private sector R&D, established entrepreneur networks and professional associations as well as recycling targets and public support of knowledge brokers. Across all countries, disruptions in national and international value chains are acting as pull factors for increased experimentation, raising demand, and enhancing legitimacy. Certified organic farming and export oriented high value crops constitute important niches. Yet, ex situ volumes remain small relative to organic waste volumes and nutrient demand in agricultural production. Looking ahead, strengthening '*guidance of the search*' and '*resource mobilization*' could drive system development by enhancing resource recovery and recycling of organic waste and closing the loop to agriculture.

KEYWORDS
agroecology, circular bio-economy, organic fertilizer, organic waste recycling, resource recovery, soil amendments, sub-Saharan Africa, technological innovation systems

1 Introduction

1.1 Background and state of the art

Loss of soil fertility and nutrient depletion on agricultural land are widespread across Sub-Saharan Africa (Jones et al., 2013; Nkonya et al., 2016), contributing to overall low agricultural productivity (Bjornlund et al., 2020). The transfer of agricultural produce from rural production areas to urban consumption centers leads to significant shifts of nutrients and biomass (Drechsel et al., 2007). In urban areas, the scant management of municipal solid waste, agro-processing residues, and human excreta creates substantial externalities, including environmental and health hazards (Cao et al., 2025; Ferronato and Torretta, 2019; Friedrich and Trois, 2011; Rajoo et al., 2020; Tomita et al., 2020), along with associated monetary costs (Hoornweg and Bhada-Tata, 2012). Recycling organic waste back to agricultural land, particularly non-renewable resources such as phosphorus (Childers et al., 2011; Raniro et al., 2025), is thus a crucial step in building circular bio-economies (Feleke et al., 2021; Muscat et al., 2021).

Therefore, in this paper we focus on ex situ organic waste recycling, i.e., off-farm treatment pathways that convert urban and agro-industrial residues (e.g., municipal organics, agro-processing by-products, fecal sludge) into organic fertilizers and soil amendments (OFSA). By contrast, *in situ* denotes on-farm production or management (e.g., farmyard composting). For brevity, we use 'ex situ OFSA' to denote OFSA produced via off-farm (ex situ) treatment pathways.

Recycling and returning nutrients through ex situ OFSA[1] production can enhance nutrient and biomass recirculation back to agricultural systems (Ellssel et al., 2024a; Castro-Herrera et al., 2022; Freyer et al., 2023; Leitzinger, 2001; Meinzinger et al., 2009; Perez-Mercado et al., 2022), and thus support the remediation of soil degradation. Yet uptake remains limited, with recycling via ex situ pathways into OFSA such as compost, liquid formulas, or digestate still remaining in its infancy in Africa, or being limited to pilot projects (Kalina et al., 2022; Kaza et al., 2018; Sekabira et al., 2022; Yeo et al., 2020). Kaza et al. (2018) estimate that less than 1% of the organic municipal waste is composted in Sub-Saharan Africa. Systematic assessments of national-level agro-processing waste volumes and recycling potential are scarce; notable exceptions include FAO (2019) and Mugodo et al. (2017). For human excreta, recycling is seldom practiced (Cofie et al., 2016), although it has substantial potential as most households in Sub-Saharan Africa use onsite sanitation systems (Cofie et al., 2009; Greene et al., 2021). However, recent disruptions to inorganic fertilizer supply chains linked to COVID-19 and the Russo-Ukrainian war (Vos et al., 2025), along with increasing policy engagement for soil health (AUC, 2023), heighten the timeliness of examining innovation dynamics in ex situ organic waste recycling into OFSA.

1.2 Literature gaps and study contribution

Despite growing interest in organic waste valorization as part of a circular bioeconomy (Feleke et al., 2021), the evidence base for ex situ organic waste recycling into OFSA in sub-Saharan Africa remains fragmented. Most studies are city- or project-specific (Castro-Herrera et al., 2022; Danso and Drechsel, 2014; Ddiba et al., 2022; Leitzinger, 2001), with few cross-country studies (Cofie et al., 2009; Lenhart et al., 2022; Sekabira et al., 2022, 2023). Some work has been conducted on potential business models and financing for resource recovery from organic waste (Otoo and Drechsel, 2018; Lazurko et al., 2018; Taron et al., 2023), and on entrepreneurship and innovation in waste valorization, particularly in South Africa (Godfrey et al., 2022; Adewunmi, 2024). However, empirical work seldom analyzes innovation-system dynamics (e.g., market formation, legitimation, resource mobilization) alongside technology pilots, and quantitative information on production volumes/capacities is scattered and inconsistent. Hence, describing and understanding the dynamics of innovation in ex situ OFSA production becomes crucial.

Therefore, we investigated the current state and trends in the ex situ OFSA innovation systems across eleven African countries. We choose the Technological Innovation System (TIS) framework as our analytical lens. TIS is a systems approach that has been proposed to study transitions in socio-technical systems (Loorbach et al., 2017) and is defined as "a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product" (Markard and Truffer, 2008, p. 611). The framework has been applied to technological domains such as carbon capture and storage technologies in South Africa (Ko et al., 2021), wind and solar energy in South Africa, Brazil, and Ethiopia (Furtado and Perrot, 2015; Kebede and Mitsufuji, 2017), and biogas and improved cookstove development in Rwanda and Kenya (Tigabu et al., 2017; Tigabu et al., 2015a, 2015b).

To our knowledge, no prior study applied a TIS lens to ex situ OFSA production and innovation systems in Africa, nor adopts a cross-country perspective. The latter is particularly useful to inform decision makers (Bergek et al., 2008). We addressed this gap by providing the first cross-country TIS assessment of ex situ OFSA production across eleven African countries. Specifically, we (i) identified the current state and trends of the field; (ii) assessed the maturity and performance of core TIS functions (entrepreneurial experimentation, knowledge development/diffusion, guidance, market formation, resource mobilization, legitimation) alongside structural features; and (iii) combined descriptive production indicators (e.g., reported OFSA volumes/capacities) with a functional diagnosis to reveal emerging dynamics, country contrasts, and cross-cutting patterns. This integrated analysis provides insights for policy, practice, and priorities for future research.

1 As outlined in EU Regulation 2019/1009, we classify materials as organic fertilizers when their nitrogen, phosphorus, and potassium content each exceed 1%; if these nutrient levels are below 1%, they are considered soil amendments.

The remainder of the article is organized as follows. Section 2 outlines the analytical framework, describing the TIS framework, its relevance and adaptation to our study context. Furthermore, the section describes the methods including data sampling and collection, coding/analysis procedures of empirical data, and the triangulation across interviews, policy documents, and grey as well as scientific literature. Section 3 presents the combined results and discussion along the seven core functions of the TIS framework. Then, we offer a cross-sectional analysis spanning across the eleven countries and present limitations and our suggestion for future research. Section 4 briefly concludes with key takeaways.

2 Analytical framework

2.1 Technological innovation systems framework

Within sustainability transitions research, several complementary approaches—Multi-level Perspective, Strategic Niche Management, Transition Management, and Technological Innovation Systems (TIS)—offer distinct lenses on socio-technical change (Loorbach et al., 2017). We adopt TIS for its technology-field specificity and diagnostic system functions (Table 1) (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007), which also facilitates comparison across diverse institutional contexts. TIS is used to analyze the development of a technology, technology field, a product, or a combination thereof (Hekkert et al., 2007; Negro et al., 2007; Suurs and Hekkert, 2009). We treat ex situ OFSA as a technology field-level TIS that encompasses several sub-fields of recycling pathways (e.g., composting, anaerobic digestion, black soldier fly (BSF) frass, pyrolysis) and the resulting OFSA products (e.g., composts/blends, frass, biochar). These sub-fields differ in technology readiness, regulatory status, nutrient profiles, and actor constellations. However, they share (i) common upstream inputs, (ii) overlapping governance and standards, (iii) partially shared market channels and agronomy, and (iv) cross-cutting legitimacy narratives around safety, quality, and efficacy. This hybrid scope allows us to capture the full innovation chain from technical experimentation to market uptake of the resulting product (Markard and Truffer, 2008). Considering different waste sector particularities, raw materials and processes are key to final product quality and, consequently, user and market demand (Manipura et al., 2025; Pandyaswargo and Premakumara, 2014; Roy et al., 2021). By focusing on this integrated technology field, the analysis captures the systemic interdependencies between technological innovation and product utilization.

Further, we analyzed actors, networks, institutions, and functional dynamics. These elements are interdependent and drive the development of a technology field (Bergek et al., 2015). While we emphasized actors in TIS Function 1, networks in Function 3, and institutions in Function 4 and 5 for expositional clarity, consistent with TIS literature we treated actors, networks and institutions as cross-cutting dimensions that jointly shape all system functions (Hekkert et al., 2007; Bergek et al., 2008). According to Bergek et al. (2015), institutions within the TIS context include, e.g., laws, policies, and regulatory frameworks. Policies set the overarching goals, principles, and strategic direction. Laws establish the legal framework and enforceable rules, while regulations are derived from laws and provide specific guidelines, technical standards, and enforcement mechanisms.

Although TIS is often applied dynamically to map innovation system processes over time (Hekkert et al., 2007), we used it cross-sectionally to portray the current state (2023) across eleven countries. This broad, exploratory approach allowed us to identify the overall system features, enable comparisons across regions and countries, and delineate potential hotspots for further in-depth study (cf. Bergek et al., 2008). Hekkert et al. (2007) identified seven key system functions that typically underpin the emergence and diffusion of new technologies (Table 1). To increase context specificity

TABLE 1 Core functions in the Technological Innovation Systems (TIS) framework for organic fertilizer and soil amendment (OFSA) production (adapted from Bergek et al., 2008; Binz and Truffer, 2017; Edsand, 2019; Hekkert et al., 2007; Negro et al., 2007).

Core functions of TIS	Description
F1. Entrepreneurial activities	The extent to which entrepreneurs are actively engaged and experimenting with new products, processes, or business models for organic waste recycling toward OFSA production.
F2. Knowledge development	Determines how knowledge about the technology is developed, e.g., co-creation/collective experimentation and social learning; R&D investment and projects, increase of technological performance, and formal/codified knowledge development (e.g., research output).
F3. Knowledge diffusion	Describes how knowledge about the technology/product is shared and applied across actors and regions through networks, peer exchange, and advisory systems, e.g., informal learning networks.
F4. Guidance of the search	The clarity and strength of the direction for technology/product development, typically through policy, regulations, donor agendas or market signals, e.g., targets set by governments.
F5. Market formation	Emergence of markets for OFSA products, including demand and supporting infrastructure, supply chains, and pricing, such as introduced niche markets, tax regimes, environmental and/or other standards.
F6. Resource mobilization (Government/International loans and grants)	Availability of public support, e.g., financial, human, logistical, or institutional, and global partnerships for OFSA development and deployment.
F7. Creation of legitimacy/advocacy coalitions	The extent to which the technology gains societal and political legitimacy, e.g., acceptance and support from key stakeholders and society, growth and actions of interest groups.

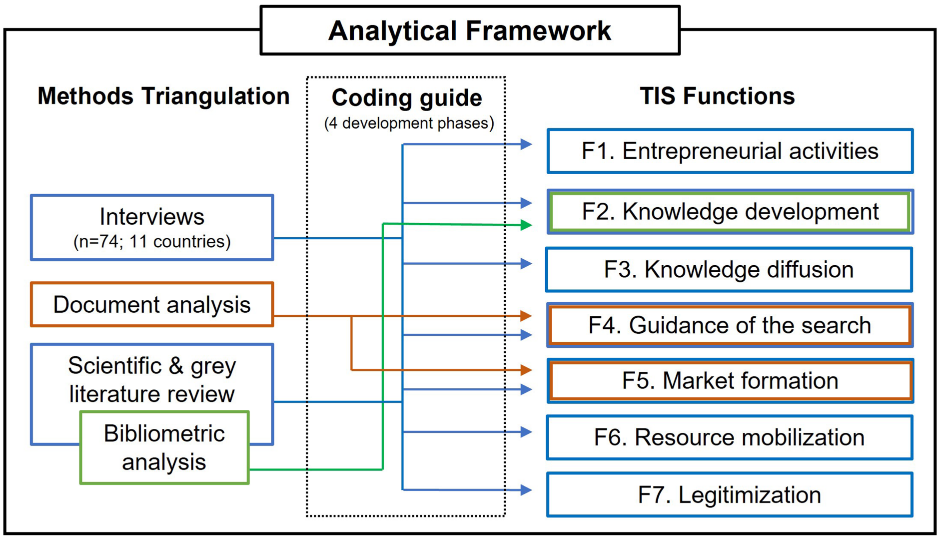

FIGURE 1
Analytical framework for the study, illustrating the triangulation of research methods and their mapping onto Technological Innovation System (TIS) functions via a four-phase coding guide.

of the TIS framework proposed by Hekkert et al. (2007), we followed Edsand (2019) by differentiating '*resource mobilization*' by national vs. international sources to reflect low- and middle-income realities (Table 1).

Recognizing that many TIS are transnational (Bergek et al., 2008), we adopted a global innovation systems perspective as knowledge, capital, and legitimacy flow across borders (Binz and Truffer, 2017). Accordingly, in '*knowledge development*' and '*knowledge diffusion*' functions we considered domestic and cross-border collaborations; in '*resource mobilization*', international loans and grants; and in '*legitimization*', international advocacy coalitions. This perspective further aids in understanding how innovation systems evolve in regions like Africa, where actors often rely on international collaborations, external funding, transnational policy frameworks and technology transfer mechanisms such as the Clean Development Mechanism to foster new technologies (Binz and Truffer, 2017).

2.2 Methods

2.2.1 Study design

We conducted an exploratory, qualitative multi-country study with a comparative approach and convergent multi-source triangulation to assess the current state and trends of ex situ OFSA production in Cameroon, Ethiopia, Ghana, Ivory Coast, Kenya, Malawi, Rwanda, Senegal, South Africa, Uganda, and Zimbabwe (Figure 1). Key informant interviews provided primary evidence, whereas documentary and scientific sources contextualized and corroborated findings. The three data streams were analyzed in parallel and integrated during interpretation: (i) semi-structured interviews; (ii) documentary evidence (policies, regulations, technical/implementation reports); and (iii) scientific literature relevant to TIS functions (e.g., technologies, markets). Countries served as comparative contexts. Quantitative figures from documents (e.g., production volumes/capacities) were used as descriptive indicators to contrast with interview accounts. Data sources were integrated via tables and narrative synthesis, assessing convergence, complementarity, and discrepancy across sources.

2.2.2 Geographical scope

We selected eleven countries balanced between African sub-regions (East, West, South)[2] and agro-ecological zones (semi-arid to humid). We also considered interviewer networks, ongoing research, and observable market developments to ensure feasibility and relevance.

2.2.3 Key informant interviews

Sampling

We combined purposive and snowball sampling to access stakeholders with relevant expertise across a wide geography (Palinkas et al., 2015; Noy, 2008). In total, we recruited 74 key informants, including OFSA entrepreneurs, scientists, policy makers, retailers, farmers, consultants, farmers' organizations, advisory services, civil society actors, inter- and non-governmental organizations. Interviewee abbreviations are used throughout (Table 2).

Data collection

We used semi-structured interviews, suitable for exploratory research, to cover core topics while allowing interviewees to introduce new perspectives and insights (Adams, 2015). Interview guides were tailored to stakeholder groups and addressed: (1) fertilizer markets (e.g., market demand, pricing), (2) OFSA production (e.g., technologies, business models), and (3) trends and policy needs (Supplementary file 1). We conducted online interviews from March–September 2023, recorded, and transcribed them. Interviews lasted 30–60 min; 65 were

2 Cameroon is typically considered part of Central Africa. To facilitate description and potentially highlight certain shared characteristics, we group Cameroon with the West African community in this study.

TABLE 2 Overview of countries, interviewee types and number of interviews.

Country (two-digit code)	Interviewee type (abbreviation)	Total
1. Cameroon (CM)	Entrepreneurs (CM-1; CM-6; CM-7), scientists (CM-4; CM-5), civil society (CM-3), NGO (CM-2)	7
2. Ethiopia (ET)	Entrepreneur (ET-2), Scientists (ET-5; ET-6), NGO (ET-1)	4
3. Ghana (GH)	Entrepreneurs (GH-6; GH-7; GH-10; GH-11), scientist (GH-5), policy maker (GH-3), retailer (GH-8), advisory service (GH-4), farmer organization (GH-2), NGO (GH-1)	10
4. Ivory Coast (CI)	Scientists (CI-1; CI-2)	2
5. Kenya (KE)	Entrepreneurs (KE-3; KE-4), scientists (KE-1; KE-2)	4
6. Malawi (MW)	Entrepreneurs (MW-2; MW-3; MW-5), scientists (MW-4), policy maker (MW-6), farmer organization (MW-1)	6
7. Rwanda (RW)	Entrepreneurs (RW-5; RW-6), scientists (RW-1), policy maker (RW-2), advisory service (RW-3), NGO (RW-4)	6
8. Senegal (SN)	Entrepreneurs (SN-6; SN-7), consultant (SN-3), NGO's (SN-1; SN-2; SN-4; SN-5)	7
9. South Africa (SA)	Entrepreneur (SA-6), scientists (SA-4; SA-7; SA-8), policy maker (SA-5), farmer (SA-1)	6
10. Uganda (UG)	Entrepreneurs (UG-3; UG-6; UG-10), scientists (UG-5; UG-8; UG-9), policy maker (UG-2), FO (2), NGO's (UG-1; UG-4; UG-7)	10
11. Zimbabwe (ZW)	Entrepreneurs (ZW-3; ZW-4), scientists (ZW-8; ZW-9), farmer organization (ZW-6), policy maker (ZW-7)	6
12. Cross-country (CC) experts	Entrepreneur (CC-3), scientists (CC-1; CC-2; CC-5; CC-6), inter-governmental organization (CC-4)	6

Interviewee abbreviations in brackets are used throughout the study for referencing purposes.

in English and 9 in French. French interviews were translated into English by a native French-speaking co-author with support from translation program DeepL.[3] We used Descript (v65.1.1) for transcription and manually corrected errors. All participants provided informed consent for recording and transcription.

Coding and analysis

We applied a deductive code scheme based on the seven TIS functions and used descriptive coding to assign short labels to text (Saldana, 2015). To compare countries and functions, we developed a phase rubric (four development phases) grounded in TIS. For each country and function, we compiled an indicator sheet (interview excerpts, document extracts, quantitative figures) and mapped evidence to the four phases using anchor criteria (Table 3 and Supplementary file 2). Two researchers independently assigned a phase using a majority-signal rule (≥ 2 concordant indicators). Tie-breaks were handled as follows: if evidence spanned adjacent phases, we selected the lower phase unless corroborated by two independent sources (e.g., interview + regulation). Disagreements, which only occurred in one case (South Africa; F2), were resolved by structured discussions among the author team.

For cross-country synthesis, we produced country summaries by function (1–2 pages each), and a country by function matrix then used pattern matching and explanation building to identify recurrent configurations (e.g., strong entrepreneurial activity but weak market formation) and linkages among functions. The phase classifications are interpretive summaries of triangulated indicators. Countries may display features of multiple phases simultaneously of which we report the prevailing pattern per country and function to aid comparison.

TABLE 3 Development phases of the Technological Innovation System (TIS) in organic fertilizer and soil amendment (OFSA) production, qualitatively assessed using a coding guide (Supplementary file 2), adapted from Bergek et al. (2008), Hekkert et al. (2007), and Suurs and Hekkert (2009).

Development phase	Interpretation
A). Pre-development	Function absent or extremely weak
B). Formation	Function emerging in an *ad hoc* or fragmented manner
C). Growth/expansion	Function institutionalizing and reinforcing others
D). Maturation	Function fully embedded, professionalized, and stable

For structuring, clustering, and analyzing the data, we used Microsoft Excel (Version 2021; 16.0.14332.20631).

2.2.4 Literature review and document analysis

We conducted a non-systematic search (Scopus, Web of Science Core Collection, Google Scholar; September 2023–September 2024) to contextualize and corroborate interview data. Search strings combined keywords such as "organic fertilizer," "soil amendment," "organic waste recycling," "organic waste valorization" and country names. We included peer-reviewed articles, FAO and AU reports, and relevant IGO/NGO publications. Grey literature was obtained via institutional websites and direct requests to key agencies (e.g., GIZ, TechnoServe). Policy documents were searched online or directly on government websites and triangulated selectively, particularly for TIS functions '*Guidance of the search*' and '*Market formation*' and were cited, respectively. Documents were screened for relevance to process technologies, market development, and policy and regulatory frameworks.

3 www.deepl.com

Consistent with TIS applications that treat publication activity as one indicator of codified knowledge (e.g., Aliahmad et al., 2022; Negro et al., 2007), we distinguished codified (publications) and practice-based knowledge (e.g., learning-by-doing, farmer trials). Given data constraints across eleven countries (e.g., R&D finances, patents), we used bibliometrics as a partial proxy for codified outputs and triangulate with practice-based evidence from interviews and grey literature. We assessed the Scopus database to indicate publication trends related to the current state of OFSA publications. We searched for articles in the time range 1980 to 2025 with the following keyword combinations: "organic fertil*" OR "soil amendment*" OR "soil conditioner" OR "compost*" OR "organic waste recycling" OR "organic waste valorization" OR "organic waste valorisation" OR biochar AND "country." We included peer-reviewed publications, conference proceedings and book chapters and removed any duplicates.

3 Results and discussion

We present the results and discussion along the seven core functions of the TIS framework. We place particular emphasis on actors in Function 1, networks in Function 3, and institutions in Functions 4 and 5. Then, we offer a cross-sectional analysis spanning across the eleven countries and present limitations and our suggestion for future research.

3.1 Structures and functions of the innovation system

3.1.1 Entrepreneurial activities and experimentation (F1)

Across the eleven countries, entrepreneurs are experimenting with and exploring new solutions and problem-solution combinations, a key feature of TIS (Hekkert et al., 2007).

A group of ten countries emerged, in which Function 1 remains in development phase B: "formation." It was characterized by multiple, isolated, small-scale, often donor funded projects that lack networks and self-reinforcing activity bundles. This is typical for TIS in the formation phase (Bergek et al., 2008). Production generally remains limited to batch-size artisanal production, under 500 t/a^{-1}, with some mechanized operations producing up to 10,000 t/a^{-1} (see Supplementary file 3 for an overview on production sizes). Among these ten countries, Ghana and Kenya show signs of phase C: "institutionalization" with ex situ OFSA entrepreneurs scaling production and expansion plans (KE-4; KE-3; GH-6; GH-7). Ghana has industrial scale entrepreneurs, such as Zoom Lion, ACARP, Safisana. While Kenya is characterized by a multiplicity of actors with new entrants and business models (Jumba et al., 2024; TechnoServe, 2023). Some of the entrepreneurs in both countries are backed by international parent companies with respective know-how or operate in public-private partnerships.

South Africa stood out from the other ten countries with entrepreneurial activity indicating development phase C: "growth." Its semi-industrialized niche comprises profitable, scaled entrepreneurs offering certified, diversified portfolios, coordinated by professional associations. As one of the interviewees underscored: *"Now with up to 15 products of which 14 are all hundred percent organic certified […], we export to Zimbabwe, Mozambique, Swaziland, Uganda and up to Unit Arab Emirates."* (SA-6: OFSA entrepreneur).

Entrepreneurial experimentation in South Africa has departed from ad hoc trials to sophisticated systems with mechanized composting, precision organo-mineral blending, and biodigesters from low-tech to industrial scale (Mutungwazi et al., 2018). However, as stated by an interviewee, municipal organic waste management, sanitation and agriculture integration remains limited, largely confined to research pilots (SA-8).

Technological experimentation

The interviews revealed that in most countries, technologies for OFSA production are generally low tech, such as composting. There are sporadic mid-tech pilots such as small biodigesters, modular biochar kilns and some more high-tech pilots that include containerized composting with sensor technology.

Conventional composting persists in low-tech settings, but mechanization yields higher quality and volumes (KE-4; CC-1; Tumuhairwe et al., 2009). An entrepreneur in Uganda (UG-10) experimented with containerized composting, a controlled process potentially reducing composting time (Smårs et al., 2002). Various interviewees experimented with vermicomposting and black soldier fly larvae, highlighting their nutrient-rich outputs (CC-5; KE-4; UG-6; ZW-4) as also shown by Beesigamukama et al. (2022) and Soobhany (2019). This experimentation is particularly prominent in Kenya and Uganda, valued for dual revenues of frass fertilizer and larvae, if consistent, uncontaminated waste is supplied (CC-5) (Isibika et al., 2023). As one Kenyan entrepreneur noted: *"Regarding the great variety of waste, it was really difficult for us to come up with a model with which we could expand [our production]. We have perfected that, now we have the technology to deal with the different types of wastes."* (KE-3: OFSA entrepreneur).

In Ghana, South Africa, Uganda, and Zimbabwe, some entrepreneurs incorporate human excreta to raise nutrient density. Urine, rich in N and P (Rose et al., 2015), is either marketed directly or combined with biochar (CC-1; SA-8). Co-treatment of toilet sludge with market waste is common (SA-8; GH-9; Banamwana et al., 2022). One Ghanaian entrepreneur couples biodigestion for biogas with co-composting of the digestate and market waste (GH-6). Some entrepreneurs reduce pathogen levels to recommended safety thresholds (CC-1; SA-8), which is feasible if the co-composting process is properly managed (Manga et al., 2021; Werner et al., 2023).

Various entrepreneurs experimented with pyrolytic biochar potentially attributable to increasing research and popularity (Abdeljaoued et al., 2020; Qi et al., 2024). Some interviewees emphasized a lacking willingness of farmers to pay for sole biochar as it is not a fertilizer and its function needs explaining (CC-5; CC-6; KE-3). To address low nutrient content, entrepreneurs blended organic with inorganic fertilizers or combine different organic inputs to enhance product appeal to farmers, such as mixing biochar with compost, *Tithonia diversifolia*, or chicken manure (e.g., KE-3; KE-4; CM-1; UG-10).

In all countries, interviewees reported increased blending of organic and inorganic fertilizers following the price spikes due to Covid-19 and the Russo-Ukrainian war. Blending is considered promising in literature, but several challenges need to be addressed such as quality consistency and testing with long-term field trials (Bouhia et al., 2022; Sakrabani, 2024). Indeed, quality issues as well as the need for crop and soil specific fertilizer blends have been uttered by various interviewees (e.g., KE-4; CC-1). And in our study, only a few entrepreneurs actively experiment with crop specific nutrient formulations and conduct scientifically valid field trials, sometimes supported by donors and universities (CC-3; KE-4; SA-6; UG-10).

Business models and market experimentation

Beyond technology, entrepreneurs experiment with raw material sourcing and market access: *"It is not the technology that is usually the challenge. It's sourcing the input and getting the product out to the market. Those are the pieces, the demand and the supply side and what connects that."* (CC-2: Consultant). Some entrepreneurs collaborate with municipalities and agro-processors to restructure organic waste flows, which is identified as a key for advancing circularity (Desmond and Asamba, 2019). Private-public-partnerships can enhance waste management activities by improving efficiency and access to funding, among other benefits. While some highlight the success of such organizational models (Otoo and Drechsel, 2018), others remain critical, arguing that successful cases in sub-Saharan Africa are still limited (Kaza et al., 2018). Interviewees reported municipal support as a key lever. For example, in Ethiopia, municipal support enabled source-separated household waste collection (CC-1; ET-5), while in other countries municipalities allocated land near waste streams (KE-4). In South Africa, entrepreneurs partnered with the municipality in a private-public-partnership and co-located with a wastewater-treatment facility. Sewage sludge from the latter is co-composted with city-wide collected green waste and then marketed to commercial growers. This strategic siting minimized transport costs and capitalized on existing municipal infrastructure (CC-1; SA-8).

We show that go-to-market experiments are equally diverse, comprising bulk sales to farmer associations, marketing via community retailers, and farm demonstrations in the communities (GH-6; KE-4; RW-6), the latter considered a key success factor. Entrepreneurs also test farmer-driven campaigns and embedded extension to stimulate demand, while others focus on certified organic farms or export-oriented, high value crops (KE-4; SA-6; SE-6).

In Uganda, one entrepreneur works on an on-site business model with containerized composting units at food processing facilities, e.g., coffee, sugar, and juice processing. Fertilizers are distributed back to contract farmers, creating a closed-loop system that links waste management, fertilizer provision, and crop procurement. Processor's pre-finance fertilizer and recover costs post-harvest, thus addressing smallholder farmers' cash-flow constraints (UG-10). Such an input credit scheme, also referred to as asset-based financing or in-kind credit model, can enhance smallholder productivity as shown by Girma (2022). A similar model was reported in Senegal (SE-3), where biodigesters were provided without upfront payment, to reduce the initial investment. High initial costs have been previously identified as a key impediment of biodigester uptake (Diouf and Miezan, 2019); and in the studied Senegalese case (SE-3), households repay by providing a share of the biodigester's organic fertilizer (slurry). The business operator collects the slurry and integrates it into organic fertilizer production, thus generating higher profits over time compared to a one-time biodigester sale.

Increasing carbon prices and biochar integration are considered promising (Galgani et al., 2014; Ottani et al., 2024). Among interviewees, some report the integration of carbon credits into business models to increase and diversify revenue streams, although it was not a major part of the revenue in 2023 (CC-6; KE-3, 4).

Grassroots and community innovations

NGOs have been proven to serve as enablers of grassroots innovations (Christopher Go and Brummer, 2024; Dyck and Silvestre, 2019). In our study, we identified various NGOs experimenting with small scale, manual labor- and community-based approaches (ET-1; UG-7; RW-4; SE-4; CA-3). For instance, in Cameroon, local women's groups were organized around a tontine-style[4] model using locally available materials and community knowledge. Their model followed a systemic logic that blends social innovation, such as cooperation, inclusion with ecological and economic objectives (CA-3). Such bottom-up initiatives are associated with adaptive learning (e.g., iterative product adjustments, peer-to-peer learning) and thus sociotechnical change – patterns consistent with De Boni et al. (2022).

Key actors in entrepreneurial activity

The spectrum of actors involved in OFSA production ranges from private informal, e.g., community-based groups, and formal, e.g., small and medium sized enterprises, inter- and non-governmental organizations, public actors and policy makers, e.g., municipalities, and research organizations (see Supplementary file 3 for an overview of identified actors). Private informal initiatives are often small-scale and supported by NGOs that provide organizational support and knowledge input. We show that these initiatives are generally driven by the objective of improving agricultural production through organic inputs (CM-2, 3; UG-1, 4, 7; RW-4; SN-1, 4).

Municipalities play a key role in the public sector, as they are officially responsible for municipal waste management. However, due to lacking finances of municipalities, the informal waste sector is crucial in many African countries (Godfrey and Oelofse, 2017). The informal sector operates outside official regulation, where waste collection and recycling activities are unregistered and uncoordinated (Harfadli et al., 2024). Interviewees also highlighted that municipalities are usually mainly motivated by reducing the amount of waste that goes to landfills (CC-2, 6). Some public-private-partnerships were identified, where for example the municipality provides the waste to OFSA entrepreneurs (CC-1; ET-5; SA-8). Due to the amounts of waste available, e.g., from households, these operations generally produce higher OFSA volumes.

We show that private national companies are sometimes backed financially by international donors and technically by research partnerships and/or by their parent companies where they are subsidiaries (GH-6; KE-4; SE-6; UG-10). Particularly international companies play a crucial role by advancing technical expertise and innovation. Initiatives on municipal level are sometimes fostered by research projects or supported by research institutions (CC-1; ET-5; SA-8). Some of the small and medium sized enterprises cooperate with agricultural input dealers, extension agents, farmer cooperatives or large farms to market their products but also for experimental reasons (KE-4; GH-6). Manufacturers of production

4 A tontine system is a cooperative financial arrangement where a group of people regularly contributes money, goods, or labor into a collective pool, and the benefits are distributed to members based on an agreed schedule or criteria. It is commonly used in West and Central Africa as a form of mutual support, especially in rural and informal economies (e.g., Rozas and Gauthier, 2012).

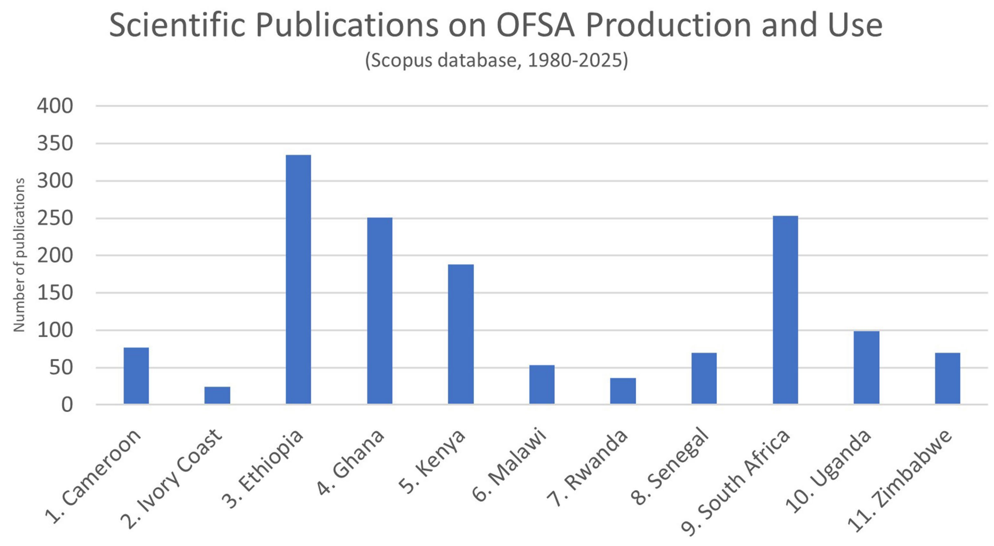

FIGURE 2
Bibliometric analysis of scientific publications. Total number of scientific publications related to OFSA production and use across 11 study countries, based on Scopus database records from 1980 to 2025.

equipment for OFSA production were only identified in South Africa. They are currently no key actors in the innovation system of most of the other 10 countries. Actors of importance, in countries where they exist, are national and ARSO[5] as a transnational standardization organization as they define quality standards for OFSA.

3.1.2 Knowledge development (F2)

Across the eleven countries, Function 2 '*knowledge development*' remains in phase B. It is largely *ad hoc* and fragmented. Practice-based learning is abundant with isolated R&D projects, informal trials, iterative product tweaks, and entrepreneur-led experiments, albeit with local variations in depth, institutional support, and international linkages. Formalized knowledge on the other hand, i.e., codification and institutionalization (peer-reviewed studies, standard methods, efficacy protocols, coordinated agendas) lag behind. This divergence explains why entrepreneurs report promising field effects yet face limited external validation and quality assurance, thus constraining diffusion (F3) and market formation (F5).

A targeted bibliometric scan indicates research activity across all countries. Most publications are found in Ethiopia, Ghana, Kenya, and South Africa with more than 150 publications compared to the other seven countries with less than 100 publications (Figure 2). Although various of the retrieved studies examine themes such as ex situ processing, product composition, or agronomic performance of ex situ OFSA, a substantial part of the retrieved studies rather addresses *in situ* OFSA, e.g., on-farm composting. Therefore, bibliometrics need to be interpreted only as a contextual signal, not as a stand-alone measure of Function 2.

South Africa demonstrates the most institutionalized R&D. Its national level Waste Research Development and Innovation Roadmap contains a 10-year program funded R&D that supports municipal waste valorization and circular-economy research (CSIR, 2024; Godfrey et al., 2021). Although this included research on crucial aspects such as organic waste separation at source (Nahman et al., 2018) and waste diversion from landfills (Schenck et al., 2022), there is a dearth of published research on themes such as ex situ OFSA production, product quality, and agronomic impacts. More particularly in our study, although some isolated research takes place at universities (SA-4, 8), there is no systematic approach to R&D of ex situ OFSA production, cross-sector integration and inclusion in mainstream agriculture. Private sector pioneers often have conducted all their own product development and field trials (SA-6; SA-4), indicating a growth phase dynamic where firms internalize R&D (Hekkert et al., 2007). Yet, the overall picture of ex situ organic waste valorization suggests fragmented knowledge development as indicative for the formation phase (Bergek et al., 2008).

Apart from South Africa, Ethiopia, Kenya, Malawi, Rwanda, and Uganda have established organic fertilizer standards, indicating signs of institutionalization in knowledge development. However, many standards have been only established recently, and public staff often still lack respective knowledge: *"They [public administration providing dealership certificates] are usually handling chemical fertilizer. And they have never seen any organic or biofertilizer before, so they have no knowledge about it."* (UG-10: OFSA entrepreneur).

Although no organic fertilizer standards have been established yet, Ghana shows early signs of institutionalization as the Ministry of Food and Agriculture created a National Technical Team to promote organic fertilizers (GH-3) and published guidelines on registration, sampling, and testing (PPRSD, 2022). Larger entrepreneurs have established in-house laboratories for OFSA analysis, while national labs perform quality control (GH-9).

Across all countries, except South Africa, one of the main features of knowledge development is, as characterized by Hekkert et al. (2007), learning-by-doing. Many of the interviewed entrepreneurs and NGOs experiment in a non-systematic and non-coordinated manner with different feedstocks to produce OFSA,

5 African Organisation for Standardisation (https://www.arso-oran.org/).

small-scale on-farm trials with anecdotal evidence as emphasized by some entrepreneurs: *"We do not have formalized research on the outcome as it is also a small-scale project."* (CA-3: Advisory service). *"We engage in own research and opinion of people who are knowledgeable in the fertilizer sector."* (GH-11: OFSA entrepreneur). *"We see some farmers who apply it appropriately, and it's totally anecdotal, up to a 30% increase."* (KE-4: OFSA entrepreneur). *"The data we have on the effects of fertilizers are only visual […] We need quantitative research on yield impact to provide real evidence."* (CA-2: NGO). The dominance of learning-by-doing aligns with Hekkert et al. (2007) classification in early TIS. The fragmented R&D and weak coordination is mirrored in Bergek et al. (2008) description of emerging TIS, while the multi-actor platforms (GreenCape, industry associations) in South Africa reflect the contextual embedding as described by Bergek et al. (2015).

International learning-by-searching (Hekkert et al., 2007) occurs in all eleven countries through international partnerships conducting research and other development activities, where deliberate R&D and knowledge-scouting activities take place with the aim of adapting external scientific knowledge and technical information (cf. Hekkert et al., 2007). These multi-scalar networks indicate a transnational innovation system (Binz and Truffer, 2017), which has also been highlighted by Tigabu et al. (2015a, 2015b) for biogas TIS in Rwanda and Kenya and by various interviewees: *"The company has enjoyed partnership from other organizations both local and international like from Germany and Ghana. These partnerships have helped the company both at the policy and research front."* (GH-10: OFSA entrepreneur). *"We received knowledge and technology from partners from Cornell University, MIT, Nairobi University, mostly in the research phase. They have been key in product development."* (KE-3: OFSA entrepreneur).

Our study indicates that international research partnerships with local research institutions, NGOs, and intergovernmental organizations foster knowledge development through social learning by methods such as farmer field schools, community demos, training-of-trainers schemes and collective experimentation (CC-1, 5; CA-3; ET-1; UG-1, 4, 7; RW-4). These partnerships along with international companies are currently the key knowledge creators, supporting pioneers, and niches, as also identified by Hauser and Lindtner (2017). However, there are no formalized national research agendas building systematic knowledge. Furthermore, we show that there is a lack of cross-sector coordination and knowledge development between waste management, sanitation and agriculture regarding the restructuring of feedstock flows and product development to ensure viable business cases (CC-2, 6). Across all countries, systematic knowledge on the impacts of different combinations of ex situ feedstocks and potential blending with inorganic inputs and respective impact on product quality and crop as well as soil specific usage is lacking: *"There is need for authentication of the products done through research and standardization to avoid selling with claims that are far from reality."* (GH-4: Consultant) *"Organic fertilizer companies should also come up with products that are specific to crops depending on individual crop nutrient requirement rather than selling a product that is said to have a blanket effect."* (MA-1: Farmers organization). However, there are exceptions with emerging institutional anchors such as government-initiated research trials on organo-mineral fertilizer blends like in Malawi (Mwafulirwa, 2023), or the testing of efficacy of ex situ OFSA in Ghana by the Ministry of Food and Agriculture (GH-3).

3.1.3 Knowledge diffusion (F3)

Function 3 '*knowledge diffusion*' through networks can be differentiated between pan-African and national or local networks (Table 4). Across the eleven countries, only South Africa indicates clear signs of institutionalization in the knowledge diffusion function, i.e., phase C, while Kenya, Rwanda and Ghana show only early signs. Each of these countries hosts at least one platform where public, private, and civil society actors exchange technical and other expertise. In the other countries efforts are fragmented and often led by NGOs or project consortia rather than permanent institutions, hence the function is emerging in a fragmented manner (Hekkert et al., 2007; Musiolik et al., 2012), corresponding to phase B. The absence of sustained, formal actor networks restricts cross-functional feedback loops that are essential for TIS consolidation (Bergek et al., 2008; Binz and Truffer, 2017). Nonetheless, in our study, even where formal networks are absent, informal networks occasionally coordinate standard development with national bureaus of standards (e.g., UG-10). Such informal networks play an important role in aligning policy decisions, on fertilizer and waste standards for example, with on-the-ground technological developments (Hekkert et al., 2007).

South Africa hosts multiple formal associations that facilitate advocacy, capacity building, and policy dialogue. FERTASA serves as an industry network for the inorganic and organic fertilizer industry, while ORASA and SABIA focus specifically on organic waste valorization (Table 4). These networks organize training workshops, lobby for regulatory frameworks, and disseminate best practices, thereby strengthening legitimacy and reducing information asymmetries (Furtado and Perrot, 2015; Ko et al., 2021). Government-backed intermediaries (GreenCape) further catalyze multi-stakeholder coordination by hosting forums that identify circular economy opportunities (GreenCape, 2019). The network initiatives along with government regulations are considered important support mechanisms for the development of the sector in South Africa (Godfrey et al., 2021). These formalized networks and policy initiatives create an enabling environment that supports scaling of OFSA technologies.

In Kenya, formal networks have formed in the waste recycling sector through associations and among inorganic and organic fertilizer entrepreneurs (Table 4). However, a lack of cooperation and knowledge sharing has been highlighted by an interviewee for example for Black Soldier Fly (BSF) technology: *"There are lots of BSF entrepreneurs in Kenya, […] often they're struggling with the same issues. And somehow some have found some solutions, but they don't talk to each other. They're in this mindset of competition. […] They're scared to share. And that just blocks, it's such a barrier."* (CC-5: Scientist). This reluctance highlights that formal networks alone do not guarantee effective diffusion. Trust building and shared governance must accompany institutional structures (Bergek et al., 2015).

Rwanda lacks formal industry associations dedicated to OFSA, but the CIRF program - a multi-stakeholder platform aligned with the Circular Economy Action Plan - facilitates dialogue between public, private and civil society players (MoE, 2022). Coordinated agendas across sectors are of importance for strategic TIS development (Hekkert et al., 2007). CIRF's strategic alignment with the Ministry of Environment's roadmap ensures that knowledge exchange channels incorporate and coordinate both policy and technical dimensions.

TABLE 4 Key national and transnational level networks and industry associations supporting organic waste recycling toward organic fertilizer and soil amendment (OFSA) production across eleven African countries.

Country	Network/association	Description	Source
1. Cameroon	n.a.	n.a.	n.a.
2. Ethiopia	n.a.	n.a.	n.a.
3. Ghana	Environmental Service Providers Association (ESPA)	Represent waste companies, provide networking, advocacy, coordination and capacity building.	www.espaghana.com
	Organic Fertilizer Entrepreneurs Association of Ghana (OFPAG)	Founded during the fertilizer shortages in 2022 with aim to coordinate production.	GH-3 (policy maker)
4. Ivory Coast	n.a.	n.a.	n.a.
5. Kenya	Kenya Association of Waste Recyclers (KAWR)	Umbrella body for private sector entities engaged in material recovery from waste.	www.kenyarecyclers.co.ke
	Fertilizer Association of Kenya (FA-K)	FA-K represents manufacturers, importers, formulators, blenders, and distributors of both inorganic and organic fertilizers in Kenya.	www.fa-k.or.ke
	Organic Fertilizers and Input Manufacturers Association of Kenya (OFIMAK)	Promotes sustainable agriculture. Platform for collaboration among organic input manufacturers.	www.ofimak.co.ke
6. Malawi	n.a.	n.a.	n.a.
7. Rwanda	Circular Food Systems for Rwanda (CIRF)	Multi-stakeholder platform to enable and encourage exchanges and dialogue between public, private and civil society players.	MoE (2022)
8. Senegal	n.a.	n.a.	n.a.
9. South Africa	Organics Recycling Association of South Africa (ORASA)	Promote and represent the organics recycling sector / anaerobic digestion and biogas from organic waste. Advocacy, lobbying for regulatory frameworks, provision of trainings and knowledge sharing.	www.orasa.org.za
	South African Biogas Industry Association (SABIA)		www.sabia.org.za
	GreenCape	Cross-stakeholder mediator and information service (market reports).	www.greencape.co.za
	Fertilizer Association of Southern Africa (Fertasa)	Serves as the primary industry body for the inorganic and organic fertilizer sector (entrepreneurs, traders, blenders, and distributors).	www.fertasa.co.za; SA-6 (OFSA entrepreneur)
10. Uganda	n.a.	n.a.	n.a.
11. Zimbabwe	n.a.	n.a.	n.a.
12. Transnational	African Circular Economy Alliance (ACEA)	Government-led coalition and policy platform consisting of 15 countries.	www.aceaafrica.org; ACEA (2021)
	African Circular Economy Network (ACEN)	Multi-stakeholder network platform for entrepreneurs and new business models.	www.acen.africa
	Africa Circular Economy Facility (ACEF)	Facility for funding and technical assistance for scaling of CE initiatives in African countries.	AfDB (n.d.)
	Africa Organization for Standardization (ARSO)	Harmonize standards across Africa.	www.arso-oran.org

In Ghana, the ESPA association organizes waste management firms, and the Organic Fertilizer Producer Association emerged as a response to the 2022 inorganic fertilizer shortages (GH-3). These associations represent an early step toward institutionalizing knowledge diffusion in Ghana's OFSA sector, particularly by coordinating production targets and sharing processing protocols.

On a Pan-African level, we found several coalitions and initiatives that foster cross-border learning and harmonization of standards. The African Circular Economy Alliance and Africa Circular Economy Facility support policy advocacy and technical assistance that directly benefits OFSA innovation. The African Circular Economy Network convenes grassroots stakeholders, while the Africa Organization for Standardization works to harmonize organic fertilizer standards across member states (Table 4). These transnational networks contribute to legitimacy building (Function 7), funding flows (Function 6), and training programs (Function 2 and 3), which aligns with Binz and Truffer (2012, 2017), who argue that global innovation systems can supply resources and norms which local TIS actors subsequently adapt to their contexts.

3.1.4 Guidance of the search (F4)

Function 4 '*guidance of the search*' remains largely in phase B: "formation" across ten out of eleven countries, characterized by non-binding, fragmented policy signals and weak enforcement, which is characteristic for an emerging, *ad hoc* governance phase (Bergek et al., 2008). Only South Africa has advanced this function to phase C: "growth," due to coherent targets, financing mechanisms, and dedicated R&D support. Our focus here is on institutions - specifically laws, policies, and regulatory frameworks - related to organic waste management, which are central aspects in innovation systems (Bergek et al., 2015). In OFSA production, these institutions can include policy targets such as organic waste recycling quota, laws and regulations such as recycling laws. They all provide directional signals that shape actor expectations and steer innovation trajectories (Hekkert et al., 2007). We created three policy-guidance clusters - advanced, emerging, and nascent - using a qualitative rubric we developed. Countries were grouped based on: (i) the presence of a dedicated solid waste management law; (ii) explicit references to recycling/resource recovery within that law; and (iii) explicit organic-waste recycling targets (see Table 5). Countries were rated advanced if all three criteria were met, emerging if waste management was at least included in broader environmental laws, and nascent if none of the criteria was fulfilled.

Advanced cluster

South Africa, Kenya, and Rwanda are considered advanced among the eleven countries as they have defined solid waste management laws. In addition, these laws reference recycling and resource recovery (Table 5). Further, they are the only countries with explicit organic waste recycling targets.

Based on our investigation, South Africa has the most mature regulatory framework and institutional capacity across all countries. The country established a Waste Act (2008), formulated a National Organic Waste Composting Strategy[6] in 2013 (DEA, 2013), and set organic waste recycling targets (DEFF, 2020). South Africa has a coherent and integrated legislative framework, with clear responsibilities, financing and enforcement mechanisms (Shi et al., 2021). However, Godfrey and Oelofse (2017) consider inefficiencies due to overregulation. Furthermore, Oelofse and Muswema (2020) criticize that the scarcity of accurate organic waste recycling data introduces difficulties in assessing the success of the recycling targets. Godfrey et al. (2021) find that the low costs of landfilling have been inhibitive for organic waste treatment and viable business models, but the government is increasing restrictions.

We find that Kenya has established a progressive Sustainable Waste Management Act (2022) and set an ambitious municipal waste recycling rate by 2030 (NEMA, 2015). Nevertheless, the implementation of solid waste management policies has been historically faced with practical obstacles such as poor implementation and enforcement, corruption and inadequate public cooperation (Amugsi et al., 2022). One of the market leaders in OFSA production stated: *"From a regulatory environment, there's not much creating headwinds, but there's also nothing creating tailwinds."* (KE-4: OFSA entrepreneur).

Finally, we find that Rwanda's circular economy legislation and ambitious targets is advanced compared to other countries in Sub-Saharan Africa (Surchat et al., 2023). Rwanda's 2022 Integrated Solid Waste Management Strategy mandates source separation and recovery targets, yet implementation remains faced with challenges due to limited institutional capacity and budgetary constraints (Mulindwa et al., 2024).

6 Strategies in public policy are high-level plans that guide policy development, funding, and program implementation but they are non-binding (e.g., Zorpas, 2020), however, they can be a legislative requirement as demanded by law (e.g., National Waste Management Strategy in South Africa is demanded by the Waste Act, 2008).

Emerging cluster

Based on our grouping, Ghana, Uganda, Ethiopia, Malawi, and Zimbabwe belong to the emerging cluster. In these cases, we show that solid waste management is included within broader environmental laws, but explicit recycling and resource recovery targets are generally absent (Table 5).

Ghana has attempted to increase organic waste recycling with their National Solid Waste Management Strategy for Ghana (2020). The strategy provides a structured approach to tackling waste management challenges, with a particular emphasis on waste minimization, organic waste recycling, and private sector involvement (MSWR, 2020). Nevertheless, a lack in the effectiveness of governance structures, particularly disconnections between national and local stakeholders, institutional collaboration and coordination, is hindering effective steering (Volsuuri et al., 2022; Williams et al., 2023). Further, the insufficient emphasis on waste segregation at source, as in most other countries, remains a key issue: *"Waste collection has been privatized but the biggest challenge is that the waste is not separated […] the quality [of raw material] is questionable."* (GH-7: OFSA entrepreneur).

Uganda released its National Environment Regulations in 2020, including a section that foresees waste separation at source for sorting recyclables. Currently, a Sector Strategy for Organic Waste Management (SOWU) is under development. It aims to align organic waste management with national policies and strengthen institutional capacity to promote waste separation and the recycling of organic waste (Sanabria and Okello, 2024).

Countries like Ethiopia, Zimbabwe, and Malawi have made comparatively early efforts in organic waste management and recycling (Table 5). Ethiopia released Solid Waste Management Proclamation No. 513 in 2007, which aimed to encourage organic waste recycling and composting. In particular, article 11.1. of the Proclamation mandates waste segregation at the household level, but this has not been achieved in practice (Lenhart et al., 2022). In 2017, the National Integrated Urban Sanitation and Hygiene Strategy began promoting the 3Rs (Reduce, Reuse, Recycle) and the integration of informal waste collectors. Yet, the majority of organic waste is still disposed of through open dumping and uncontrolled incineration (Lenhart et al., 2022). Despite these policy initiatives, there remains a lack of responsibility and clarity about financing mechanisms: *"It needs to be defined who is responsible for it. Because there is currently not really a responsibility. Of course, in cities like Addis there are companies who get a contract by the city for waste, but it is not actually enshrined in law that the city is responsible for this waste, so of course it feels responsible for keeping the streets clean. But there is always the question of who pays the bill"*. (ET-6: Scientist).

In Zimbabwe, the Zimbabwe National Integrated Solid Waste Management Plan was released in 2010. It aimed to develop a decentralized waste management, improve stakeholder integration, waste reduction, source separation and recycling. However, many of the proposed actions have not been implemented (Nhubu et al., 2021).

Malawi released the Environment Management (Waste Management and Sanitation) Regulations in 2008. These regulations provide detailed guidelines for waste management practices, including organic waste separation at source and recycling. Malawi also established a EAD (2019), which prioritizes recycling. However, effective implementation remains limited due to low public participation,

TABLE 5 Solid waste management and recycling laws, policies, and legal frameworks in eleven African countries (adapted from Freyer et al., 2024a).

Country	Solid waste management and recycling laws, policies and legal frameworks	Comments	Source
1. Cameroon	Law No. 96/12 Environmental Management (1996)	Lays out waste management practices.	Albrecht et al. (2022)
	Urban Development and Housing signed Order No. 00072/MINAT/MINVILL (2000)	Defines hygiene/sanitation, collection and/or treatment of household waste.	
	Decree no. 2012/2809/PM (2012)	Lays down the conditions for the sorting, collection, storage, recycling, treatment and final disposal of waste.	UN Habitat (2018)
	Decree no. 001/MINEPDED (2012)	Sets out the conditions for obtaining an environmental permit for waste management.	
2. Ethiopia	Ethiopian Environmental Policy (1997), Public Health Protection Proclamation No 200/2000, Environmental Impact Assessment Proclamation No 299/2002, Environmental Pollution Control Proclamation 300/2002.	Well-developed set of policies and regulations on environmental management that include SWM, but no measures for enforcement, effectiveness unknown.	Singh and Singh (2022), Xie and Mito (2021)
	National Solid Waste Management Proclamation (No. 513/2007)	Waste segregation at households' level is foreseen by it in Article 11.1.	Lenhart et al. (2022)
	National Integrated Urban Sanitation and Hygiene Strategy (2017)	Strategy to improve urban sanitation and hygiene, including (organic) SWM. It promotes 3R (reduce, reuse, recycle) and the integration of informal waste collectors.	FDRE (2017)
3. Ghana	Local Governance Act (1993)	Lays the foundation for the formulation of by-laws for MSWM.	Singh and Singh (2022)
	Environmental Sanitation Policy (ESP), 2010	Comprehensive guidelines for environmental sanitation, incl. SWM. Reference to waste reduction, reuse, recycling, recovery. Emphasis on composting for the management of organic waste, promoting its conversion for agricultural use.	GoG (2010a)
	National Environmental Sanitation Strategy and Action Plan (NESSAP), (2010)	Aims at, e.g., Awareness creation—change in sanitation behavior.	GoG (2010b)
	Local Governance Act, 2016 (Act 936)	Mandates Metropolitan, Municipal, and District Assemblies (MMDAs) to manage solid waste directly or through private sector partnerships. MMDAs are responsible for developing sub-national plans based on national strategies and are empowered to enact by-laws on sanitation to regulate local environmental conditions, including MSWM.	GoG (2016)
	National Solid Waste Management Strategy (NSWMS), (2020)	Aims to enable effective waste reduction, recovery, reuse and recycling.	MSWR (2020)
4. Ivory Coast	Government with World Bank elaborated the Urban Resilience and Solid Waste Management Project (USWMP) (2019–2020).	Aim is to improve SWM and services—among others. There is no legislation specific to SWM; no specifics regarding recycling or composting are provided in the USWMP.	MoS (2020), UN Habitat (2018)
	Hygiene and Health Law Code (2023–899)	Intends to regulate waste management incl. Increased circular practices and recycling (the law is currently under review).	Republique-de-Cote-D'Ivoire (2023)
5. Kenya	National Solid Waste Management Strategy (2015)	Platform for action between stakeholders, objectives are to reduce waste, waste segregation at source, resource recovery etc.	Singh and Singh (2022)
	Sustainable Waste Management Act, no. 31 of 2022.	The act includes the promotion of a circular economy, including recycling and reuse. It covers organic and non-organic wastes.	The Republic of Kenya (2022)

(Continued)

TABLE 5 (Continued)

Country	Solid waste management and recycling laws, policies and legal frameworks	Comments	Source
6. Malawi	Environment Management Act (1996)	Broadly framed, can be applied to MSW management.	GoM (2018), GoM (2014)
	National Environmental Policy (2004)	Provides policy guidance incl. Waste management.	
	Environment Management (Waste Management and Sanitation) Regulations (2008)	Detailed guidelines for waste management practices, including waste separation at source and recycling (incl. Organic materials).	
	National Waste Management Strategy (2019–2023)	It guides actions of regulatory bodies, the public, and stakeholders in areas such as policy formulation, promotion of waste segregation (at source), resource recovery, and the establishment of sound infrastructure for waste management.	EAD (2019)
7. Rwanda	Organic Law No 04/2005	Foundational law, provides the basis for all waste management activities.	Singh and Singh (2022)
	Regulations No 002/EWASTAN/ SW/RURA (2015)	Governs solid waste recycling, establishing standards and procedures for recycling activities.	
	National Sanitation Policy (2016)	Aims to ensure sustainable, equitable, and affordable access to safe sanitation and waste management services. It emphasizes the importance of integrated waste management strategies, including waste reduction, reuse, recycling.	MoI (2016)
	Law No. 48/2018 of 13/08/2018 on Environment	Revises and supplements the Organic Law on Environmental Protection and Management, incl. Waste management.	GoR (2018)
	Regulation No. 007/R/SAN-EWS/ RURA/2021	Provides a licensing framework for solid waste collection/ transportation services.	RURA (2021)
	Rwanda Integrated Solid Waste Management Strategy (2022)	The strategy includes the promotion of a circular economy, including recycling and reuse (e.g., organic wastes).	MoI (2022)
	Ministry of Agriculture Strategic Plan 2018–2024	Promotes an "integrated approach to soil fertility/nutrient management, which employs agro-ecology, resource recovery and reuse, and fertilizer enriched composts."	MoAAR (2018)
8. Senegal	The Environment Code on Waste Management and Recycling (Law No. 2001–01).	Foundational law that states that disposal or recycling shall be environmentally sound.	RVO (2022), World Bank (2019c)
	National Solid Waste Management Program (PNGD) (2014)	This program aimed to achieve a "Zero Waste" vision for Senegal through integrated waste management strategies with specific emphasis on the roles of local authorities.	
	Integrated and Sustainable Solid Waste Management Strategy (2015)	Emerged as a continuation from the The National Solid Waste Management Program (PNGD - Programme National de Gestion des Déchets) (2014). The key components include decentralization and private sector engagement, establishment of waste management agglomerations.	
	Law No. 2022–18, enacted on May 23, 2022	Authorizes the creation of the National Integrated Waste Management Company (Sonaged S. A.), a state-owned enterprise responsible for implementing integrated waste management strategies nationwide.	RoS (2022a, 2022b)
	Law No. 2023–15 of August 2, 2023, enacting the Environmental Code	The update to Law No. 2001–01 addresses various environmental issues, including strengthening waste management.	RoS (2023)

(Continued)

TABLE 5 (Continued)

Country	Solid waste management and recycling laws, policies and legal frameworks	Comments	Source
9. South Africa	National Environmental Management Act (NEMA), 1998 (Act No. 107 of 1998)	Foundational law, provides the overarching principles for environmental management.	RoSA (2008)
	National Environmental Management: Waste Act, 2008	Promotes integrated waste management based on the waste management, waste avoidance, reduction, reuse, recycling, and recovery. Treatment and safe disposal are considered as a last resort. Integrated Waste Management Plans (IWMPs) have to be developed by all government spheres.	
	National Waste Management Strategy (NWMS)	Aligned with the Waste Act, the NWMS outlines the government's approach to waste management (waste avoidance and reduction, development of a recycling economy).	DEA (2013), DEFF (2020), Ricci-Jürgensen et al. (2020)
	Municipal By-Laws	Local municipalities in South Africa have the authority to develop by-laws that address waste management within their jurisdictions.	De Villiers et al. (2020)
10. Uganda	National Environment Act, 2019	This act constitutes the principal environmental legislation, providing guidelines for environmental management, including waste management practices.	GoU (2019)
	National Environment (Waste Management) Regulations (2020)	Detailed guidance on waste management. Section 18 foresees waste separation at source for sorting of recyclable, hazardous and/or nonbiodegradable waste.	NEMA (2020)
	Sector Strategy for Organic Waste Management (SOWU)	Current development of a strategy aimed at aligning organic waste management with national policies and enhancing the capacity of institutions to promote waste separation and recycling of organic waste.	Sanabria and Okello (2024)
11. Zimbabwe	The Public Health Act (1996)	Deals with solid waste.	Shabani and Jerie (2023)
	The Environmental Management Act (2002)	Addresses SWM; Comprehensive legislation exists, but implementation and enforcement are lacking.	
	Environmental Management (Effluents and Solid Waste Disposal) Regulations, 2007 (SI 6 of 2007)	These regulations govern the disposal of effluents and solid waste, including provisions for licensing waste disposal sites and standards for waste management practices. Local authorities are required to develop waste management plans.	GoZ (2007)
	The Zimbabwe National Integrated Solid Waste Management Plan (ZNISWMP), (2010)	To address shortcomings, the Plan aimed to develop a decentralized MSWM, better stakeholder integration, waste reduction, source separation and recycling. However, many of proposed actions are not implemented.	Nhubu et al. (2021)

budgetary constraints, and inadequate infrastructure (Chikukula et al., 2024; Kamanga et al., 2024).

Nascent cluster

Senegal, Cameroon and Ivory Coast belong to the nascent cluster of countries, where organic waste recycling is less explicitly prioritized. Therefore, in these countries none of the three grouping parameters studied is present (Table 5). Senegal has recently strengthened its legal base regarding waste management (Law No. 2022–18 and Law No. 2023–15); however, the explicit prioritization of organic waste recycling is not distinctly emphasized.

Cameroon has enacted several legislative instruments to regulate waste management, but organic waste recycling is not prioritized. Furthermore, Cameroon faces poor implementation of existing laws and regulation, along with a lack of infrastructure, limited public awareness of laws and regulations, and insufficient source separation (Albrecht et al., 2022).

In Ivory Coast, general regulation regarding solid waste management has historically been weak (UN Habitat, 2018). The potentially forthcoming Hygiene and Health Law Code (2023–899), currently under review, intends to regulate waste management and promote circular practices and recycling (Republique-de-Cote-D'Ivoire, 2023).

Across all countries, solid waste management and recycling face similar challenges in being effective. Lacking enforcement of regulatory frameworks, budgetary constraints, corruption, insufficient infrastructure, insufficient integration of informal waste pickers, and public participation are among key challenges in many Sub-Saharan countries (Muheirwe et al., 2022; Shi et al., 2021). Additionally, inconsistency and ambiguity in regulations and a lack of clear incentives can discourage recycling such as the payment based on the weight of waste delivered to landfills (Lenhart et al., 2022). The gap between policy and implementation has been identified as a major barrier to innovation system growth in other emerging economies (Intarakumnerd and Chaminade, 2007; Schiller et al., 2020). Regarding the recycling of human excreta, regulations are either ambiguous, absent or highly bureaucratic, as expressed by some interviewees: *"Currently, most of the technological options in the ecological sanitation sector face bureaucratic limitations concerning reuse of human excreta."* (SA-8: Scientist). *"There needs to be clear policies that say you can use fecal sludge in agriculture production, and these are the guidelines for its use."* (CC-2: Consultant).

3.1.5 Market formation (F5) for organic fertilizers and soil amendments

Across ten countries, Function 5 '*market formation*' is in phase B, emerging in a fragmented manner. Only South Africa achieves a more institutionalized level and reached phase C, characterized by standardized quality classes, diverse market segments, and formal procurement channels.

Current market size

There is a dearth of systematic, quantitative data on OFSA production volumes or capacities. IFDC (2023) provides statistics on inorganic fertilizer and, to some extent, on organic fertilizer plants, production quantities, and/or capacities. The current gaps in reliable market data reflect weak development of Function 2 '*knowledge development*' and 7 '*resource mobilization*'. Without reliable market data, policy makers and investors cannot assess the scaling potential or system growth (Hekkert et al., 2007). Qualitative estimates from interviews on the current market size of ex situ OFSA production vary widely across the studied countries, reflecting differences in waste sources and production approaches (Table 6).

According to official statistics, South Africa stands out as having one of the most advanced ex situ OFSA production systems in Sub-Saharan Africa, with an organic waste recycling rate of 49%, equivalent to approximately 10 million t a^{-1} (DEFF, 2020). However, these figures are in conflict with other reported numbers by DEFF (2020). Oelofse and Muswema (2020) note that recycling rates for organic waste in South Africa cannot be accurately determined due to data limitations. Consistent with this uncertainty, interviewees emphasized that reliable national figures are not visible on the ground (SA-1, 4, 6, 8).

Across most countries, except South Africa, supply chains for OFSA remain fragmented and informal. Production and distribution typically rely on artisanal units or small firms producing less than 50 t a^{-1}. Medium-sized enterprises produce up to 3,000 t a^{-1} and larger production units more than 3,000 t a^{-1}. The latter two are professionalizing with mechanized operations and structured waste acquisition. Larger entrepreneurs sometimes sell in bulk to farmer cooperatives, as reported by one interviewee (GH-6), or through government programs, as in Ghana (GH-7). However, our interviews show that their overall geographic coverage and production volumes remain limited compared to the total agricultural area, especially in rural areas: *"To get it to the farmers, to semi-urban farmers is fairly easy, but to get it to the rural areas, transportation becomes the challenge."* (CC-2: Consultant). Current estimated OFSA production amounts range from less than 5,000 t a^{-1} in Cameroon, Malawi, and Rwanda, to over 100,000 t a^{-1} in Ghana (Table 6), which has several well-established OFSA entrepreneurs. In Ethiopia, recently installed production capacities achieve approximately 270,000 t a^{-1} (Mutukaa and Ermias, 2021). Notably, more than 100 million people inhabit Ethiopia and there are significantly higher amounts of organic waste compared to the other 10 countries (Kaza et al., 2018).

Many of the smaller entrepreneurs among the interviewees use relatively clean waste streams from agro-processing units, markets, or hotels, as household waste is usually not source separated. Some larger and mechanized entrepreneurs do use household waste. However, interviewees report that this negatively affects both the cost and the quality of the final products (CC-2, 5; GH-7). A few entrepreneurs we interviewed experiment with or are actively using human waste, such as fecal sludge (CC-1; GH-6; SA-8), though it is currently of minor relevance. Still, some interviewees emphasized its potential: *"[…] there's lots of the fecal sludge. And in the countries where we work, 95% of all the fecal sludge comes from onsite sanitation systems, it's not in sewage systems. So, we speak about onsite sanitation, about septage tanks and the septage is rather clean. It has microbial risk, but we can eliminate those. And co-composting nitrogen rich fecal sludge with carbon rich municipal organic waste, can produce quite a good product."* (CC-6: Scientist).

The wide variation in ex situ OFSA market size reflects the heterogeneity of TIS maturity across countries. Most remain in niche experimentation, while Ghana indicates signs of institutionalizing with, for example, larger scale entrepreneurs. Only South Africa indicates a development phase C: "growth," with professionalized, large scale industrial operations and associated industry associations although concise numbers on recycling rates are lacking.

Nonetheless, considering overall volumes of potentially available municipal organic waste and human excreta, as well as nutrient needs in agriculture, the current market size across all eleven countries can be considered niche (cf. Ellssel et al., 2024a; Freyer et al., 2024a).

Market demand

In all countries, interviewees reported increasing inorganic fertilizer prices due to the value chain disruptions caused by COVID-19 and the Russo-Ukrainian war. This is in coherence with literature (cf. Assefa et al., 2025; Vos et al., 2025). Consequently, most interviewees observed a crisis induced demand for fertilizer alternatives: *"In Ethiopia there are more and more companies that do composting and that sell compost for good prices. […] But it's interesting to see that there is a market as such a market was so far not existent."* (ET-6; Scientist) *"In South Africa, the [inorganic] fertilizer market was growing rapidly, but fertilizer has become so expensive that most farmers are cutting down on the amount of fertilizer they use, and therefore they're more open to alternatives."* (SA-4: Scientist). However, interviewees fear a short-lived signal compared to the impact of stable policy frameworks, as one entrepreneur pointed out: *"[…] I think this is the window of opportunity we have, […] until the traditional fertilizers will get in the same position as they were before the conflict [Russo-Ukrainian war] and the Covid-19 pandemic."* (CC-3: OFSA entrepreneur). Yet, success stories have been shown in literature to create momentum for change in a specific direction (Hekkert et al., 2007). In our study, we also note that due

TABLE 6 Ex situ organic fertilizer and soil amendment (OFSA) production or production capacities by country (t a^{-1}) according to information collected from interviews in contrast to literature and/or web sources (status quo 2023).

Country	Ex situ organic fertilizer production or production capacity*				
	Estimations from interviews (2023) (t/a^{-1})	Description (organic waste source)	Literature and web sources (t/a^{-1})	Description (organic waste source)	Source
1. Cameroon	< 5,000	Households, plant collection	n.a.	-	-
2. Ethiopia	< 250,000	Households	270,000*	Compost produced from municipal solid waste	Mutukaa and Ermias (2021)
3. Ghana	≈ 130,000	Households, markets, human excreta, abbatoirs, agro-processing	12,500*	n.a.	IFDC (2023)
			87,000	Household waste	www.acarpghana.com
4. Ivory Coast	≈ 60,000	Households, animal manure, palm oil production residues	50,000*	n.a.	IFDC (2023)
5. Kenya	≈ 20,000	Households, hotels, markets, abbatoirs, agro-processing	20,000	Households, hotels, markets, human excreta, abbatoirs, agro-processing	TechnoServe (2023)
6. Malawi	< 5,000	Households	n.a.	-	-
7. Rwanda	< 5,000	Households, agro-processing	n.a.	-	-
8. Senegal	≈ 70,000	Households, agro-processing, animal manure	5,000	n.a.	IFDC (2023)
9. South Africa	> 70,000	Households, green waste from municipalities, markets, human excreta, abbatoirs, agro-processing	**	Household municipal organic waste	DEA (2013), DEFF (2020)
10. Uganda	< 10,000	Households, agro-processing, animal manure, plant collection, human excreta	n.a.	-	-
11. Zimbabwe	≈ 50,000	Households, markets, human excreta, agro-processing	n.a.	-	-

All numbers are rounded; t = metric tons; *Yearly production capacity, own calculation with data from IFDC (2023). Daily production (calculated with 8 h of operation) multiplied by 220 estimated working days per year. ** The reported figures are contradictory.

to inorganic fertilizer shortages, both institutional actors and farmers have become open for alternatives: *"If the crisis had not happened […] MOFA [Ministry of Agriculture] would not be talking about encouraging farmers to use chicken manure and things like that."* (GH-1: NGO). *"We have seen a lot of farmers moving to organic fertilizers […] due to the shortage in inorganic fertilizer and the increase in price."* (GH-9: OFSA entrepreneur). *"The war has made importation of chemical fertilizer into Malawi difficult […] This shortage has driven demand of Bionitrate fertilizer by Malawi farmers."* (MW-2: OFSA entrepreneur).

Market stimulation by policy

The long-standing emphasis on inorganic fertilizer, particularly in subsidy schemes, in extension and education can discourage OFSA use (Cai et al., 2019) and could be addressed through targeted policy reforms. Currently, none of the countries comprehensively combine price incentives, e.g., subsidies, credits, with quality assurance, e.g., fast-track standards, and ancillary support, e.g., tax waivers, PPP logistics, which would be most effective for broad market stimulation (Bergek et al., 2008, 2015). In the case of inorganic fertilizers, subsidies alone have generally not guaranteed increased fertilizer use (Wang et al., 2018), or as one interviewee stated: *"The skewed public funds allocated to [inorganic] fertilizer subsidy programs alone has not helped […] a blended approach is needed."* (KE-2: Scientist). Presently, policies are not aligned in most countries. All countries subsidize inorganic fertilizers, while only Senegal und Ghana have introduced fiscal incentives for organic fertilizers (Table 7). However, broad subsidies for all fertilizers may unintentionally reinforce incumbent inorganic fertilizers, as farmers may default to higher nutrient products. Instead, one interviewee proposed subsidies for blends or combo-packages of inorganic and OFSA (CC-5).

TABLE 7 Inorganic and organic fertilizer subsidies in eleven African countries (adapted from Freyer et al., 2024a).

Country	Subsidies (2023)		Comment	Source
	Inorganic fertilizer (yes/no)	Organic fertilizer (yes/no)		
1. Cameroon	yes	n/a	-	AfDB (2022)
2. Ethiopia	yes	no	-	ENA (2023)
3. Ghana	yes	yes	Fixed prices for organic fertilizers from specific companies	GH-3; PPRSD (2022); MoF (2023)
4. Ivory Coast	yes	no	For specific crops only (cotton)	Gouvernement-de-Côte-d'Ivoire (2022)
5. Kenya	yes	no	-	Traore et al. (2024); Waweru (2025)
6. Malawi	yes	no	Through the Agricultural Input Program (AIP)	ActionAid (2025); Benson et al. (2024)
7. Rwanda	yes	n/a	-	IFDC (2023); Spielman et al. (2025)
8. Senegal	yes	yes	OF subsidies since 2022; 10% of fertilizer subsidies for organic fertilizers	SE-3; Ricome et al. (2024)
9. South Africa	yes	no	Provision of production inputs (seeds, fertilizer)	RoSA (2024)
10. Uganda	yes	no	-	UG-2
11. Zimbabwe	yes	n/a	-	World Bank (2020)

Niche markets

The majority of the interviewed entrepreneurs were already active before the 2020–2022 market disruptions. They focused part or whole of their product range on niche markets, such as certified organic production or other high value crops for export (KE-4; SA-6; GH-10; RW-2, 5, 6; ZW-3). Niches often emerge around specific user needs, e.g., certified organic production, where knowledge, networks, institutional linkages, and legitimacy building processes take shape (Bergek et al., 2008; Hekkert et al., 2007). The area under certified organic farming has grown steadily and significantly over the past decade in all 11 countries (Willer et al., 2025), indicating a potential indirect driver of demand for certified OFSA products: *"But South Africa's unique in that we've got a very good export and a very good domestic market. There's a big demand for organically produced food. So, definitely at the moment there's a huge demand for organic fertilizers, especially ones that are approved for use in certified organic crops."* (SA-5: Policy maker).

Pricing

Price differences can be explained by various factors, but a wide variation creates confusion over the "fair" value, thus undermining transparent price signals that market formation needs for efficient selection (e.g., Hekkert et al., 2007), which in turn, can negatively affect market uptake (Aggarwal et al., 2024). We show that prices for OFSA products display pronounced heterogeneity both across and within countries, whereas inorganic fertilizer prices tend to vary less (Table 8). The variation in inorganic fertilizer prices can generally be explained by geographical location (Bonilla Cedrez et al., 2020). Price differences in OFSA are influenced by various factors, such as the nutrient content and the resulting value proposition. Some of the interviewed entrepreneurs blend their products with materials, i.e., inorganic fertilizers, minerals, nitrogen rich plant materials, or use more labor intensive or otherwise costly production methods. Entrepreneurs who have mechanized operations and secure access to larger quantities of organic waste benefit from economies of scale and thereby reduced unit costs (KE-4; ET-5; CC-1).

We find that regions with well-developed infrastructure such as roads and reliable access to waste streams, as well as collaborations with municipalities through land provision or logistical support, can help reduce operational costs. Logistics and distribution overheads are major cost drivers in operations and can affect pricing: *"One of our big learnings is the importance of being as close as possible to the waste streams (<60 km) to reduce transportation costs to a site, especially given the inefficiency of freight on the continent […]."* (KE-4: OFSA entrepreneur).

Certified organic growers producing for export are willing to pay premium prices for traceability and third-party quality assurance, while bulk buyers such as smallholder farmer cooperatives are highly price sensitive: *"Our product is not easily affordable for farmers […] we recommend at least 2 t ha^{-1} and farmers struggle to pay."* (RW-5: OFSA entrepreneur). However, other entrepreneurs emphasize the increased yield and higher income for farmers, particularly where soils are affected by degradation: *"Farmers see an average of 30% yield increase when applying the compost in addition to mineral fertilizer applications."* (KE-4: OFSA entrepreneur).

TABLE 8 Inorganic and organic fertilizer and soil amendment prices in eleven African countries, as reported by interviewees (2023).

Country	Inorganic fertilizer prices (2023)	Organic fertilizer prices (2023) (*certified organic)		
	EUR (50 kg)	Type (N:P:K)	Unit	EUR
1. Cameroon	53–69 (DAP; Urea)	Compost (biofertilizer fortified)	50 kg	20.00
		Compost	50 kg	7.60 3.80
		Liquid OF	1 L	17.50
2. Ethiopia	60–100 (NPK; NPS)	Liquid fertilizer (<1:<1:<1)	1 l	0.94
		Compost	100 kg	5.00
3. Ghana	25–37 (Urea; AS)	Co-compost (sewage sludge)	50 kg	7.00
4. Ivory Coast	39–47 (n/a)	Compost	50 kg	15.00
		Poultry manure (not composted)	50 kg	0.76
5. Kenya	40–65 (DAP; NPK)	Compost (fortified) (1–3:>1:>1)	50 kg	15–25.00
		Fortified biochar-compost (5:3:3), fortified compost (3:5:3)	50 kg	21.00
		BSF Frass (3:1:3)	50 kg	9–16.00
6. Malawi	54–67 (NPK)	Urine-based liquid fertilizer	1 l	1.00
		Liquid OF	1 l	1.60
7. Rwanda	54–59 (DAP)	Compost	50 kg	3.80
		Compost (2:8:3,3)	50 kg	3.80
8. Senegal	46–54 (DAP; Urea)	Fortified compost (4:3:3)	1 t	300.00
		Compost (1:1:1)	1 t	213.00
9. South Africa	426 (t) (n/a)	Compost Compost	50 kg 50 kg	1.75 0.72
		Co-Compost (sewage sludge) (1.6:0.3:0.4)	1 t	28.00
		Fortified compost* (2:3:2; 3:1:5; 5:1:5; 6:3:4; 8:1:1; 4:10:0)	1 t	580–782.00
		Soil conditioner (vermi-compost)*	35 kg	10.00
		Liquid OF* (4:1:6; 5:1:4; 7:1:2)	5 L	14.70–17.60
10. Uganda	46–55 (Urea; DAP; NPK)	Fortified (4:7:2; 7:3:3; 2.4:3:9)	50 kg	38.00
		Liquid (vermi tea)	1 l	3.30
		Vermi-compost	50 kg	65.00
11. Zimbabwe	42–56 (n/a)	Fortified vermi-compost: (7:7:7; 6:15:12; 25%N)	50 kg	23.00-31.00
		Vermi-compost (4:3:2)	50 kg	12.20
		Vermi-foliar top dressing	20 kg	15.00
		Vermi-tea	1 l	9.30

Standards and certification

Slow, opaque, or inconsistent certification processes undermine trust and weaken the selection environment that the '*market formation*' function seeks to strengthen (Hekkert et al., 2007). In turn, the complete absence of any standard is inhibitive for markets to evolve (Bergek et al., 2008). The current wide variation in product performance we observe across studied countries is indicative for the "formation" phase (Bergek et al., 2008). Six of the eleven countries have introduced standards for organic fertilizers, and three have standards for soil amendments (Table 9). The establishment of standards indicates progress toward institutionalization of TIS development, corresponding to phase C. However, several countries such as Malawi, Rwanda, Uganda have only implemented them in recent years. Therefore, an immediate effect on market formation may yet not be visible. But even where standards exist, interviewees partly reported weak enforcement, long processes, and limited quality control, which undermine trust and hinder market formation: *"It took us 1 and a half years to get products registered. In this regard policies need to improve."* (KE-3: OFSA entrepreneur). "*We send samples to the lab and sometimes get no feedback for six months, so our product sits unsold."* (GH-7: OFSA entrepreneur). *"Even certified compost sometimes shows wildly different nutrient levels when retested, how can farmers trust the label?"* (ET-1: NGO). Other interviewees pointed to the absence of robust regulatory frameworks: *"There is need for a regulatory framework to guide production and packaging with clear labelling and no ambiguity, and standards in place so that farmers will get value for their money, with proven efficacy."* (GH-4: Consultant).

TABLE 9 Organic fertilizer and soil amendment (OFSA) standards and responsible institutions in eleven countries (adapted from Freyer et al., 2024a).

Country	Responsible institutions	Standards		Comment	Source
		Organic fertilizer (yes/no), (year)	Soil amendments		
1. Cameroon	Agence des Normes et de la Qualité—Standards and Quality Agency (ANOR)	No	No	General fertilizer regulation. Products need to be tested on, e.g., nutrient contents if marketed as organic fertilizer.	CM-1; RoC (2003)
2. Ethiopia	Ethiopian Standards Agency (ESA)	Yes (2008, 2018)	Yes (2018)	CES 69–1:2018 for Biochar/soil conditioners; CES 69–2:2018 for Compost/soil conditioner.	ESA (2022)
3. Ghana	Plant Protection and Regulatory Services Directorate (PPRSD)	No	No	Guidelines for OF developed in 2022, precursor for standards.	PPRSD (2022)
4. Ivory Coast	Ministry of Agriculture and Rural Development (MINADER) & Plant Protection Directorate (DPCQ)	No	No	General fertilizer standards derived from ECOWAS regional regulations.	PWIC (n.d.)
5. Kenya	Kenya Bureau of Standards (KEBS)	Yes (2011, 2023)	No	KS 2290:2011; KS 2290:2023—Organic Fertilizer; Standard for organo-mineral fertilizers currently in development.	KEBS (2011, 2023)
6. Malawi	Malawi Bureau of Standards (MBS)	Yes (2024)	No	DMS 2020:2023, liquid organic fertilizer; MS 1084:2023, solid organic fertilizer.	MBS (2024)
7. Rwanda	Rwanda Standards Board (RSB)	Yes (2021, 2024)	Yes (2024)	RS 279:2021, organic fertilizers; DRS 582:2024, organic fertilizers and soil amendments.	RSB (2024)
8. Senegal	Association Sénégalaise de Normalisation (ASN)	No	No	General fertilizer standards derived from ECOWAS regional regulations.	World Bank (2019a)
9. South Africa	Department of Agriculture, Forestry and Fisheries	Yes (2017)	Yes (2008, 2021)	Products need to be registered according to Act n. 36 of 1947; National Norms and Standards for Organic Waste Composting (GN 561).	RoSA (2017), RoSA (2021)
10. Uganda	Uganda National Bureau of Standards (UNBS)	Yes (2023)	No	US 1584:2023; US 1584:2024, Organic fertilizer	UNBS (2023)
11. Zimbabwe	Standards Association of Zimbabwe	No	No	Organic fertilizer must be registered before being sold*	World Bank (2019b)

*Compost, manure, and night soil do not require registration if sold under their original name (i.e., not labeled as fertilizers) (GoZ, 2016).

3.1.6 Resource mobilization (F6)

Once again across the same group of ten countries, Function 5 '*resource mobilization*' for OFSA production remains in phase B. The mobilization of resources is fragmented and largely dependent on short-term grants and donor support, with some exceptions involving direct investment. Once more, South Africa stands out, where sustained multi-institutional funding matured into an "institutionalized" phase C.

Financial capital

In most countries, public budgets for OFSA production, such as for R&D, are negligible. South Africa is an exception, with a multi-institutional funding architecture. The 10-Year Waste Roadmap committed substantial investment for waste valorization R&D (Godfrey et al., 2021), combined with additional funding opportunities and incentives (GreenCape, 2019).

Across countries, subsidies remain focused on inorganic fertilizers, with some exceptions (Section 3.1.5). Internationally sourced and donor-driven grants are a major source of finance for pilots and R&D. However, such support can collapse (e.g., USAID; Offord et al., 2025). Donor and pilot driven projects must transition to sustained government and/or private-sector finance, otherwise, they may remain time bound and fail to scale (e.g., Bergek et al., 2008; Tigabu et al., 2015a, 2015b). Nonetheless, we observe that initial donor engagement can catalyze local entrepreneurship, as for example in

Kenya (KE-3; KE-4). Foreign direct investments by parent companies such as in Ghana (GH-6), Senegal (SE-6), Uganda (UG-10), and Kenya (CC-3; KE-4), represent long-term and strategic commitments. Interviewed entrepreneurs across all countries reported difficulty in accessing credit on acceptable terms, a well-documented phenomenon (Williams et al., 2025). Green finance mechanisms currently play a minor role, though carbon credit sales have been reported (KE-2; KE-3; KE-4) and future potential has been highlighted (CC-6; Jawadi et al., 2025).

Human capital

Across countries, we document that donor- and project-driven university partnerships play an important role in knowledge creation and diffusion, e.g., formulation of crop specific formulations (CC-1; KE-4; CD-1; SA-8). Yet, local universities operate on limited domestic R&D budgets. South Africa has the most robust academic capacity, with dedicated curricula (SA-4, 8) and specially funded research chairs in circular bioeconomy (Godfrey et al., 2021). Interviewees across all countries emphasized a lock-in of agricultural education and extension on inorganic fertilization, leaving OFSA training under-resourced. The general availability of labor has been identified as a strength for OFSA production (CC-5).

Complementary assets

South Africa stands out with ISO-accredited laboratories, local manufacturers for recycling equipment, formalized memorandums of understanding with licensed organic waste recyclers (CSIR, 2024), and government supported knowledge brokers (GreenCape, 2019). Rwanda is mentioned in our interviews for its progressive lab protocols (CC-1), and both Rwanda and Kenya have been highlighted by an international company for its business support structures (CC-3). However, the lack of qualitative lab infrastructure, limited access to appropriate equipment, and high import taxes are important resource constraints across countries: *"Lack of adequate technological equipment for waste sorting and delivery […] adequate storage facility is another challenge."* (RW-5: OFSA entrepreneur). *"There isn't high quality enough equipment that matches what we need domestically, so we import it. The same for spare parts. And then you pay at least a 30% import tax."* (KE-4: OFSA entrepreneur).

In some cases, interviewees underlined that municipalities provide land, transportation, or other support (KE-4; CC-1; ET-5; SA-8): *"The municipality [Arba Minch, Ethiopia] has been very supportive in terms of helping us restructure the solid waste management. They've done a really good job of being able to separate waste streams at the household level."* (CC-1: Scientist). Interviewees consistently pointed out public support as a key lever for lowering the price-structure barrier for waste-to-soil ventures.

3.1.7 Creation of legitimacy (F7)

Across ten countries, Function 7 '*creation of legitimacy*' remains in phase B, with again only South Africa achieving phase C. Most initiatives are highly fragmented initiatives although some countries show early signs of institutionalization. Fragmented efforts correspond to development phase B, whereas coherent coalitions and enforceable standards indicate a shift toward phase C (Bergek et al., 2008; Hekkert et al., 2007).

In South Africa, formal industry associations (FERTASA, ORASA, SABIA) and government funded knowledge brokers (GreenCape, 2019) support the organic waste recycling sector, indicating policy legitimacy. Intermediaries like GreenCape facilitate knowledge flows and strengthen TIS functions (Binz and Truffer, 2017). The existence of formal organic fertilizer standards and enforcement through annual provincial inspections indicate also that South Africa has entered phase C.

In Kenya, OFIMAK, an organic fertilizer industry association established in 2024, supports entrepreneurs and advocates in the policy domain. Recently updated standards indicate increasing legislative legitimacy. Entrepreneurs and OFIMAK foster social acceptance through demo trials, although extension integration is found to be minimal in our study (KE-2; KE-3). Despite increasing OFSA production, overall volumes remain at niche level.

Rwanda has circular economy action plans, is a founding member of pan-African circular economy networks (ACEA), and has set ambitious recycling targets alongside fertilizer standards. Farmers are reportedly familiar with OFSA, indicating social acceptance: *"[…] they [farmers] often tell me that they would never plant crops without the application of organic fertilizers [imborera]. "*(RW-1: Scientist). Although political legitimacy and social acceptance are increasing, recycling rates and production volumes remain low overall.

We show that Ethiopia, Malawi, and Uganda have established formal standards but lack cohesive industry associations. Advocacy coalitions for ex situ organic waste valorization are weak and consist of uncoordinated efforts of pioneering private firms, NGOs, researchers, and research partnerships. Insufficient or inappropriate lab infrastructure hampers quality control: *"Good national laboratories are needed […] certification builds trust."* (ET-5: Scientist); as well as concerns regarding fake products (ET-2; ET-3). In Uganda, high demand indicates social acceptance: *"Solid sludge is overbooked [from treatment plants]."* (UG-9: Scientist).

In Malawi, urine-based fertilizers faced initial opposition, but uptake increased via demo plots and crisis-driven demand (MA-2). Nevertheless, extension staff and regulatory agents lack familiarity with ex situ OFSA in all countries, which undermines formal legitimacy.

Cameroon, Ivory Coast, Senegal, Zimbabwe, and Ghana lack formal standards, although Ghana recently introduced organic fertilizer guidelines and a Technical Working Group, indicating growing policy recognition. In contrast, the other four countries have weak policy environments in which organic waste recycling is low priority. We observe that Senegal stands out from this group for pronounced civil society activities in Agroecology advocating waste recycling and first attempts to increase OFSA uptake through subsidies (SE-1, 2, 4, 5).

Across all contexts, political advocacy of ex situ OFSA is increasing (AUC, 2023). However, variable quality, lack of trust in certification, high price heterogeneity and longstanding emphasis on inorganic fertilizers in education and extension services are inhibitive.

Alternative fertilizers are sometimes perceived as a market threat, a view echoed in Zimbabwe's Fertilizer Value Chain Report (NCC, 2022). Confirmed by interviewees who noted incumbent resistance: *"Many of those who import chemical fertiliser are involved in politics and benefit from the trade."* (CM-4; Scientist). Resistance to change is typical in socio-technical transitions (Bergek et al., 2008; Hekkert et al., 2007), and can lead to lock-in situations (Hassink, 2010). Shifts in social practices are therefore needed to enable adoption (Freyer et al., 2024b). In our findings, advocacy coalitions remain fragmented; intersectoral coalitions across agriculture, waste management, and sanitation sectors are needed to legitimize OFSA initiatives as solutions to broader environmental and public-health challenges (CC-1, 2, 5, 6). Policy alignment across sectors is still in its infancy. However, the growing organic farming sector in most countries may enhance legitimacy, influence expectations, and generate positive feedback, especially for the TIS function *'guidance of the search'* (Bergek et al., 2008).

3.2 Cross-functional synthesis across 11 African countries

Our TIS assessment shows uneven maturity across countries. All have moved beyond A: pre-development, most remain in B: formation, none has reached D: maturation (Figure 3). According to literature, the concentration in formation indicates structural and functional barriers that inhibit co-evolution of functions (cf. Bergek et al., 2008; Hekkert et al., 2007).

Our findings show that the OFSA Technological Innovation System is embedded in transnational ties (donors, NGOs, universities, firms) that circulate know-how more readily than bulk products. Given OFSAs' low value-to-weight, long distance shipping is rarely economical, especially for smallholders. The most realistic regionalization is standards harmonization (e.g., ARSO) and selective near-border trade. Diffusion should prioritize shared protocols (quality assurance, standard operating procedures), ring-tested labs, and practitioner forums.

3.2.1 Structural components (actors, networks, institutions)

Across countries, we find that the entrepreneurial base is thin but diversifying. Small and medium-sized enterprises, NGOs, and some municipally linked ventures dominate F1, with widespread donor dependence outside South Africa. Private firms often internalize R&D. Public research contributes episodic projects (F2). Demand is often lead by export-oriented and certified organic farms, with limited penetration into staple crops (F5). Intermediaries (standards bodies, regulators, extension) are present but unevenly capacitated, constraining legitimation (F7) and market formation (F5). Overall, actor constellations are consistent with formation-phase dynamics.

Knowledge flows are mediated by fragmented networks, informal ties, short-lived consortia, and transnational partnerships. Where associations or meso-level intermediaries operate, most visibly in South Africa, brokerage and collective problem-solving strengthen diffusion, legitimation, and policy feedback (F3, F4, F7). Elsewhere, peer-learning platforms are sporadic, thus learning-by-doing stay localized and difficult to scale (F2, F3). The absence of stable network infrastructures (regular fora, working groups, buyer–supplier linkages) weakens the handoff from experimentation (F1/F2) to market formation (F5).

We find that cross-sector coordination between waste, sanitation, and agriculture operates in silos, despite clear potential for feedstock and waste-to-resource linkages, which is consistent with literature (Hanjra et al., 2018; Otoo and Drechsel, 2018). In the studied countries, policy and regulatory frameworks are often underspecified or weakly enforced, generating uncertainty that undermines entrepreneurial experimentation (F1), R&D investment (F2/F6), and market formation (F5). However, many countries are now introducing or refining relevant laws and standards. Their effectiveness requires monitoring and evaluation. The long-standing emphasis on mineral fertilizers in training and extension heightens the need for legitimation of OFSA alternatives.

3.2.2 Cross-country synthesis

In this study, South Africa stands out overall, as six of seven functions indicate C: growth. Nonetheless, knowledge development (F2) remains in phase B: formation, due to no coherent national R&D agenda for ex situ OFSA. Policy signals (F4) and knowledge brokers supported R&D (F2) and market formation (F5), while associations (F1/F3) aid legitimation. Organic waste streams remain underutilized, and

Country	TIS Functions						
	F1	F2	F3	F4	F5	F6	F7
1. Cameroon	B	B	B	B	B	B	B
2. Côte d'Ivoire	B	B	B	B	B	B	B
3. Ethiopia	B	B	B	B	B	B	B
4. Ghana	B	B	B	B	B	B	B
5. Kenya	B	B	B	B	B	B	B
6. Malawi	B	B	B	B	B	B	B
7. Rwanda	B	B	B	B	B	B	B
8. Senegal	B	B	B	B	B	B	B
9. South Africa	C	B	C	C	C	C	C
10. Uganda	B	B	B	B	B	B	B
11. Zimbabwe	B	B	B	B	B	B	B

Legend

A Pre-development
B Formation
C Growth
D Maturation

F1 = Entrepreneurial activities
F2 = Knowledge development
F3 = Knowledge diffusion
F4 = Guidance of the search
F5 = Market formation
F6 = Resource mobilization
F7 = Creation of legitimacy

FIGURE 3
Qualitative assessment of TIS functional maturity. Summary of the current state of development phases (A: Pre-development to D: Maturation) for each TIS function (F1–F7) within the 11 study countries.

mainstream agriculture still rely mainly on mineral fertilizers. The niche is robust but not yet regime-shifting.

In Ghana and Kenya, F1 show growth signs, as entrepreneurs engage in a range of technology and go-to-market experiments, yet volumes remain niche, largely serving export oriented and certified organic farms. Recent crisis driven demand increases still need to manifest into broader market growth. Other functions are in formation (Figure 3). R&D is fragmented and often internationally partnered, policy guidance is aspirational but thin on enforcement and quality control, finance is often donor-led, and legitimacy efforts are sporadic. Ghana is notable for OFSA inclusion in input subsidies. Without concurrent strengthening of R&D (F2), guidance (F4), finance (F6), and legitimation (F7), scaling is uncertain as observed by Tigabu et al. (2017) on cookstove entrepreneurs in Rwanda.

The remaining eight countries - Cameroon, Ethiopia, Ivory Coast, Malawi, Rwanda, Senegal, Uganda and Zimbabwe - cluster in formation (B), characterized by scattered pilots, champion entrepreneurs, and NGO-led trials that rarely scale into self-reinforcing ventures, similar to findings for solar PV and bio-digestion innovation systems (Kebede and Mitsufuji, 2017; Tigabu et al., 2015a, 2015b). R&D is project-bound, formal diffusion via networks and extension is limited. Notable outliers include international OFSA firms in Ivory Coast and Senegal, subsidies in Senegal, and standards in Ethiopia, Malawi, and Rwanda. Still, no single functions consistently catalyze others. Policies are ambiguous, markets thin, and resource mobilization short-term.

Present OFSA innovation systems are unlikely to reduce soil degradation at scale. Produced volumes are small, intermittent, and niche-oriented with prices and distribution models that potentially limit smallholder uptake. Yet the technical potential embedded in municipal organic waste, agro-processing residues, and sanitation by-products is substantial (Ellssel et al., 2024a; Freyer et al., 2024a). Effective valorization could close nutrient and organic matter loops and reduce urban externalities (landfill diversion, public health risks). Realizing this requires systemic shifts. This includes (i) codifying practice into quality assurance and efficacy protocols (F2 to F5/F7), (ii) standards and clear registration pathways to build trust (F4/F5), (iii) demand anchors such as public procurement and targeted inclusion in input programs to move beyond niches (F5/F&), and (iv) extension and agronomy packages that tailor products to crop and soil contexts. Without these changes, existing lock-ins such as mineral fertilizer subsidies, weak enforcement, patchy lab capacity, and siloed waste-sanitation-agriculture governance, will continue to stall diffusion and confine OFSA to thin market segments.

3.3 Limitations and future research directions

This study provides a snapshot of the current state of OFSA production systems within a defined timeframe and across diverse country contexts. While the exploratory approach enables a broad comparative perspective, it may not capture all country- or context-specific nuances, which would require in depth country-specific studies. In particular, South Africa's comparatively strong showing could be partially influenced by the greater availability and specificity of government and policy documents. Such sources can overstate program coherence and effectiveness. We, therefore, interpreted South Africa's documentary signals alongside interview evidence and noted divergences where entrepreneurs reported gaps [e.g., current recycling rates in DEFF (2020)]. Future work should systematically map documentary claims against independent performance indicators to minimize confirmation bias. Nonetheless, the insights gained offer a valuable foundation for understanding the current dynamics and trends in OFSA innovation systems.

Treating OFSA as a single technology field-level TIS inevitably masks heterogeneity among sub-fields (composting, digestate, BSF frass, biochar, organo-mineral blends). Our country-level phase ratings represent the dominant or most visible sub-system and may under- or overstate progress in others. Future work should apply nested or comparative sub-field analyses (multiple, coupled TISs) to capture differences in technology readiness levels, actor networks, and market uptake.

Our triangulation was function-specific rather than uniform, with interviews as the core source across functions, while policy documents mainly informed Function 4 and 5, and scientific literature provided context. Thus, some functions lack corroboration from all three streams. In addition, the interview panel may be skewed toward accessible stakeholders, and responses subject to recall (Coughlin, 1990) and social desirability bias (Grimm, 2010).

Building on our TIS assessment, future research could delve deeper into country-level studies to assess historical pathways (e.g., Tigabu et al., 2015b), path dependencies, and the influence of policy on OFSA system evolution. In-depth analyses of different value chain stages or individual TIS functions, such as '*resource mobilization*' or '*legitimization*', could help identify specific barriers and enablers, allowing more targeted interventions. Priority should be given to identifying and testing actionable levers with regard to policy, finances, organization and technologies. Longitudinal research is needed to capture how entrepreneurial experimentation, market formation, and knowledge diffusion evolve over time. Additionally, to strengthen the evidence for policy-making and reduce potential biases, future studies would benefit from applying systematic literature review protocols (Ellssel et al., 2024b).

Further research should examine the effects of recent policy measures, such as the organic fertilizer subsidies in Senegal and Ghana, and assess how such instruments support or constrain TIS maturation. Finally, targeted case studies on raw material availability, distribution systems, power relations, and multi-actor networks would deepen our understanding of how OFSA production systems can be technologically robust and socially inclusive.

4 Conclusion

This exploratory study provides a snapshot of the current state and trends in ex situ OFSA production across eleven Sub-Saharan countries. This inquiry was of particular interest regarding recent supply chain disruptions for inorganic fertilizers and its potential pull factor on innovation systems in OFSA production. Our analysis shows that, in all cases, no TIS function remains at the "pre-development" phase, each has at least emerged in an *ad hoc* or fragmented form. However, most functions (*entrepreneurial activities, knowledge development and diffusion, guidance of the search, market formation, resource mobilization,* and *legitimacy*) remain at the "formation" stage. In these countries, no single function has matured enough to catalyze others. Entrepreneurial efforts are typically uncoordinated, R&D and knowledge sharing are sporadic, policies and regulations are incomplete, ambiguous or unenforced. Formal markets have yet to develop, and funding is mostly short-term. Nevertheless, isolated signs of institutionalization appear such as emerging OFSA subsidies, increasing OFSA standard implementation and cross-country coordination. South Africa stands out with most functions institutionalizing and reinforcing one another. Entrepreneur associations and fertilizer quality standards support professionalized entrepreneurship. Policy signals ('*guidance of the search*') and dedicated funding actively foster R&D and build legitimacy in South Africa. Across all countries, disruptions in both national and international value chains are acting as pull factors for increased experimentation, raising demand, and enhancing legitimacy. Certified organic farming and export oriented high value crops constitute important niches. Yet, ex situ volumes remain small relative to organic waste volumes and nutrient demand in agricultural production. Looking ahead, strengthening '*guidance of the search*' and '*resource mobilization*' could drive system development by enhancing resource recovery and recycling of organic waste and closing the loop to agriculture.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans because no personal data was collected for research purposes. The authors affirm that the study was conducted in accordance with the principles of the Declaration of Helsinki. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

PE: Formal analysis, Writing – review & editing, Methodology, Writing – original draft, Data curation, Investigation, Visualization, Funding acquisition, Validation. BF: Funding acquisition, Writing – review & editing, Conceptualization, Methodology, Supervision, Investigation. HP: Methodology, Conceptualization, Writing – review & editing. MH: Writing – review & editing, Visualization, Data curation. FN: Data curation, Investigation, Writing – review & editing. NA: Writing – review & editing, Investigation. FA: Investigation, Writing – review & editing. SS: Investigation, Validation, Supervision, Data curation, Writing – review & editing.

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Supplementary material

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