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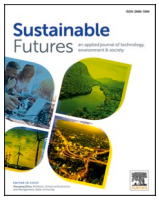

The practice of scaling landscape-based fertilizer advisory in Ethiopia: Drivers, pathways, and strategies for upstream-downstream integration for scaling

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ABSTRACT

Smallholder farming in Ethiopia faces challenges with poor nutrient use efficiency and low yields. Addressing these issues requires site-specific nutrient management strategies. Since 2020, a landscape-based fertilizer advisory has been developed, co-validated, and piloted to improve fertilizer use efficiency, lower costs for smallholder farmers, and promote environmental sustainability. This effort has been catalyzed by the CGIAR Excellence in Agronomy Initiative and driven by demand partners from the local to the national level. This paper systematically analyzes the process and practice of scaling up this innovation, using an agricultural innovation system (AIS) analysis. Using a contextualized innovation scaling framework, we examine the dissemination process and mechanisms, key drivers of scalability, the institutional collaboration and governance of the scaling process and practices. We emphasize the importance of a demand-driven, participatory, and collaborative scaling process that guides the analysis of scaling drivers, diffusion pathways, barriers, and strategies for responsible scaling from both local (horizontal scaling) and national (vertical scaling) perspectives. This scaling process has led to a localized, farmer-relevant nutrient management approach that delivers optimized and cost-effective advisory services. Consequently, farmers have demonstrated significant improvements in understanding (86–94 %) and implementing the landscape-based advisory (75–91 %), with usability scores ranging from 4.2 to 5.2 out of 7. This paper provides insights and guidance to facilitate the transition from delivery to scaling agricultural innovations on a large scale, emphasizing the importance of a contextualized science of scaling and pathways, customized strategies, successful partnerships, responsible scaling, and ongoing efforts to overcome emerging barriers to effective scaling.

1. Introduction

In Ethiopia, agricultural soils have degraded in quality due to years of continuous cultivation and severe soil erosion, resulting in the depletion of soil nutrients [1]. Soil treatment interventions, such as fertilizers, are widely recommended to restore soil health and increase agricultural productivity. However, smallholder farmers often apply fertilizers inefficiently [2–4] due to inadequate availability, limited access to fertilizers, and a lack of location-specific fertilizer recommendations. Additionally, smallholder farming is characterized by both spatial and temporal variability in production factors, which leads to variations in yield, nutrient use efficiency, and return on fertilizer investment [4]. Therefore, increasing agricultural productivity of smallholder farmers requires the application of targeted, site-specific, and demand-driven technologies complemented with systemic innovation packages.

Site-specific fertilizer agro-advisories can help improve nutrient use efficiency, reduce costs, enhance productivity, improve soil health, and promote sustainability of farming systems. Specifically, replacing current blanket fertilizer recommendations with site-specific fertilizer

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advisories together with complementary agronomic, soil health and land management practices is considered a key strategy to improve fertilizer use efficiency and its impact on productivity [4]. On the other hand, providing site-specific advice on agricultural innovations to millions of smallholder farmers presents formidable technical, logistical, and institutional challenges. As a result, landscape-based fertilizer recommendation solutions have recently garnered increasing interest as an entry point for localized nutrient management that meets local demands and requirements of diverse agricultural landscapes [2,3,5,6].

This paper aims to systematically analyze recent efforts to scale a locally validated and digitally enabled landscape-based nutrient management approach to enhance fertilizer use efficiency and reduce costs for smallholder farming systems in Ethiopia. A proof of concept for the landscape-based fertilizer application was developed from long-term experiments and translated into a decision guide over several years [6]. This innovative solution was based on on-farm experiments across four regional states representing low to high-rainfed systems and central highlands characterized by mixed cereal cropping systems. From 2021 to 2024, the landscape-based fertilizer advisory was co-validated and co-piloted for sorghum, teff, and wheat in various parts of Ethiopia, covering 120 kebeles (the smallest administrative units) from 23 districts across seven zone administrations in four regional states. This was achieved through the collaborative efforts of demand partners from local to national levels, including Agricultural Research Institutes, District Agriculture Offices, non-governmental organizations, universities, extension agents, and farmers. One of the key technical achievements that facilitated the scaling of landscape-based fertilizer recommendations was the demonstrated benefit of the advisory in optimizing profits and nutrient use efficiency based on landscape positions, which are the main drivers for localized nutrient management. Additionally, the relevance of the landscape approach to local farmers' good agronomic practices and integrated land and water management practices was highlighted [4]. Overall, these demonstrated benefits have generated significant interest in the advisory among Ethiopian farmers, agricultural stakeholders, and the government.

It is essential to note that innovating and bundling technologies with other technical solutions alone does not guarantee success [7]. The literature has highlighted that several non-technological, socio-political conditions limit the potential for these technologies to reach broader beneficiaries and hinder the institutionalization and scaling of successfully piloted technologies [8,7]. However, much of the current discussion about scaling and its processes remains theoretical (e.g., [9–11]). Overall, the questions of what innovative nutrient management solutions can be developed; how fertilizer use can be made more efficient, productive, and profitable at scale; and which context-specific scaling processes, drivers, pathways, and strategies can be leveraged to scale innovations and their relevance to the science of scaling, the usability of the innovation, scalability, and outcomes remain important areas for agricultural innovation research and policy enhancement. Employing a systemic innovation analysis framework, this case study addresses these questions by leveraging multi-stakeholder platforms that bring together perspectives of various demand and scaling partners and a regular feedback mechanism for adaptation.

While co-developing and piloting the landscape-based fertilizer advisory innovation, we have recognized the importance of various aspects of scaling in practice within the systemic innovation analysis framework. These include scaling approaches, pathways, drivers, and strategies that must be contextually defined to support the scaling of the innovation at a large scale. By examining the demand driven scaling context, sociopolitical and institutional drivers and constraints, multidimensional scaling pathways and user segments, and synthesizing lessons learned, this paper provides insights and guidance for delivering and scaling agricultural innovations on a large scale. It also emphasizes the significance of tailored scaling principles, as well as the essential roles of responsible scaling and partnerships in the scaling process. Importantly, scaling is not a linear expansion of a single innovation in a specific context. Instead, it is a continuous and non-linear process that involves intentional learning from feedback from end users and partners and data analysis from monitoring and evaluation in the context of multi-stakeholders and changing development environment, while navigating system lock-ins and factors underpinning path-dependency in scaling.

2. Methodology

2.1. The study context

In Ethiopia, the adoption of nutrient management practices and fertilizers is low, with varying performance across agroecological systems due to farm and landscape heterogeneity. Challenges are related to a lack of location-specific practices and approaches for nutrient management and fertilizer use according to local requirements and preferred needs [4]. The current practice of blanket fertilizer application across varying agroecological systems, topographic, and climate regimes has led to low nutrient use efficiency, yield losses, and low income for farmers. In response, a proof of concept on landscape-based nutrient management and fertilizer use has been developed from the thorough analyses of demand from farmers and extension agents, farming contexts and long-term fertilizer response experiments under the auspices of various project support since 2011 [2,3,5,6,12].

Over several years, the innovation on landscape-based fertilizer recommendation was co-developed by integrating agronomy and landscape features and further translated into a decision guide over the years [6]. This innovation solution was drawn from on-farm fertilizer response experiments across four regional states representing low to high-rainfed systems and major highlands characterized by mixed cereal cropping systems. Through the Excellence in Agronomy (EiA) initiative of the CGIAR (2020–2024), the landscape-based site-specific fertilizer recommendation approach went through different validation stages before it matured and was technically validated and later translated into a decision support tool (LandWise: https://dst.icrisat.org/download) [4]. Between 2021 and 2024, the landscape based fertilizer advisory was co-validated on 260 farmer fields against blanket fertilizer recommendation and later co-piloted and scaled on more than 25,000 farmer fields in several parts of Ethiopia, covering 120 kebeles (the lowest administration units) from 23 districts across seven zones in four regional states (Fig. 1), through joint efforts of Agricultural Research Institutes, District Agriculture Offices, Non-Governmental Organizations (NGOs), extension agents, and farmers. The details of the validation and piloting of the landscape fertilizer advisory is presented in Desta et al. [4].

2.2. The landscape approach and sustainable transition

The landscape approach is a development strategy that encourages integrated management and governance of landscapes as a critical nexus for understanding and managing synergies and trade-offs among various objectives and functions of rural landscapes [13]. The rise of the landscape approach reflects a growing recognition of the interconnectedness of different land uses and the needs of all stakeholders across agriculture, conservation, policy, and economic development sectors. It offers an operational scale and sectoral boundary that promotes a holistic view, enabling deliberate work at the landscape level to improve inter-sectoral coordination of planning, policy, and management through the alignment of activities, policies, or investments at this scale [14]. The landscape approach is highly participatory, adaptive, and collaborative, involving multiple stakeholders within a social learning framework, helping them negotiate priorities among multiple goals and outcomes, and mediating trade-offs and synergies among these goals and outcomes [13,14].

The landscape-based fertilizer advisory is informed by insights from the landscape approach. While it is grounded in landscape configuration, its scope, extent, and stakeholder mapping are specific to the

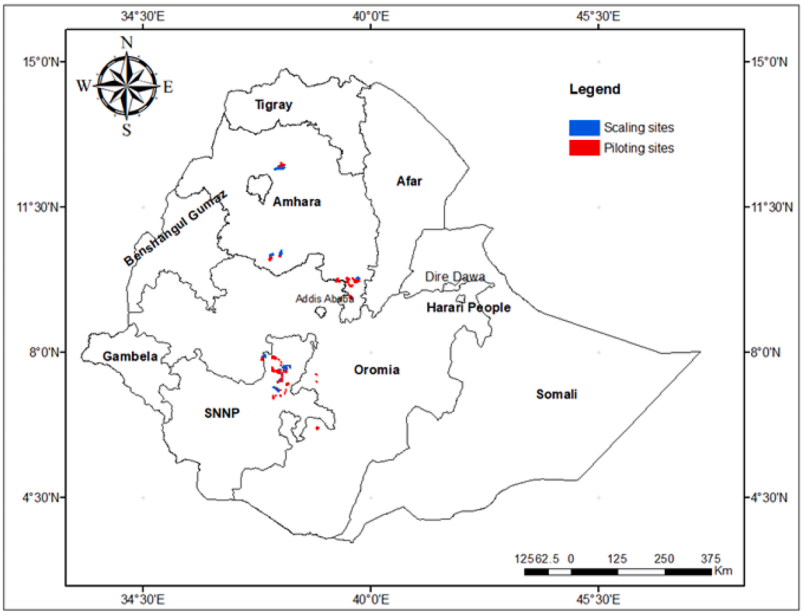

Fig. 1. Piloting and scaling sites in 2024 across 23 districts in 7 zonal administrations of Ethiopia.

spatial and temporal variations of soil fertility and production factors across the landscape. Focusing on balancing nutrients at the landscape scale, the landscape-based fertilizer advisory embeds principles of sustainability—a social development framework that balances economic growth, environmental protection, and social equity. More specifically, it contributes to the economic and environmental dimensions of sustainability from farms to entire landscapes. This advisory can significantly improve crop yields, nutrient use efficiency, and economic returns for farmers (see Section 3.5 for details). For example, validation trials have demonstrated a notable yield increase of 13 % to 29 % over conventional practices, along with improvements in nutrient use efficiency ranging from 32 % to 45 % [4]. The innovation also boosts the profitability of smallholder crop production, with average profit increases ranging from USD 159 to USD 526 per hectare per season, depending on the landscape position [4]. The findings highlight the potential of this approach to tackle persistent yield gaps, low nutrient use efficiency, and low profitability in smallholder agriculture in Ethiopia. Importantly, these results are closely linked to broader economic development outcomes, including improved food security, dietary diversity, and poverty reduction [15,16].

Similarly, the landscape-based fertilizer advisory can help contribute to environmental sustainability by mitigating the impacts of chemical fertilizers. While chemical fertilizers are crucial for improving agricultural productivity and food security[16,17], their excessive and inefficient use can have severe negative environmental impacts. For instance, overuse of fertilizers can lead to the buildup of heavy metals, alter soil pH, and disrupt the natural soil cycle, which results in the degradation of soil organic matter and decreased soil fertility over time [18]. Excess nutrients, such as nitrogen and phosphorus, from fertilizers can runoff into water bodies, harming aquatic ecosystems [19]. Chemical fertilizers also contribute to greenhouse gas emissions, causing air pollution and climate change. Additionally, some contaminants in fertilizers can pose risks to human and animal health, reducing biodiversity in terrestrial and aquatic environments [20]. The landscape-based fertilizer advisory can help address some of these environmental challenges by reducing excessive nutrient use and promoting good fertilizer management, such as optimizing application rates, timing, and methods. These practices can ensure proper fertilizer dosing and slow nutrient release, thereby increasing nutrient efficiency and decreasing the risks of nutrient runoff and leaching.

Furthermore, the landscape-based fertilizer advisory is not a standalone innovation; it is a systemic innovation that is integrated with complementary practices such as rainwater management, soil management, biodiversity conservation, and tailored production systems for specific landscapes. These good agricultural practices enhance soil organic matter, preserve natural soil structure, and improve soil fertility, thereby supporting the environmental sustainability and resilience of smallholder farming. Overall, the landscape-based fertilizer advisory can facilitate a transition toward sustainability by its long-term positive impacts on environmental health and economic well-being. In addition to technological advancements, achieving sustainability transitions demands a comprehensive strategy that includes policy support and shifts in the values and behaviors of smallholder communities towards prioritizing increasing agricultural productivity versus other social development goals.

2.3. *The fertilizer Ethiopia use case: a systemic innovation analysis*

To understand and frame the discussion on the scaling process of the landscape-based fertilizer advisory, we draw insights from the agricultural innovation system (AIS) analysis framework, which examines how agricultural innovations are created, diffused, and adopted within a specific context [21]. Since the AIS framework has been well developed and adapted with many tweaks to boundaries, actors, networks, and contexts of innovations[21–23], we choose not to reproduce it here but to use its insights to contextualize and conceptualize the scaling of the landscape-based fertilizer advisory in Ethiopia. The key insight from the AIS framework is moving beyond a linear view of research and development to include the complex interactions of various actors, institutions, and policies that drive agricultural innovation. Consequently, the overall performance of an innovation system depends on the interplay of multiple actors, networks, and processes within a specific innovation context.

The scaling approach of the EiA initiative was organized around demand-driven Use Cases in a defined target area, focusing on the development, validation, and scaling of an agronomic solution, formulated through a Minimum Viable Product (MVP). The MVPs are packages of innovations that generate agronomic gains for smallholder farmers in terms of (i) increased yield, profitability, and/or yield quality, (ii) climate change adaptation and reduced risk, (iii) increased resource use efficiencies, and (iv) improved soil health.

The Fertilizer Ethiopia Use Case, implemented by the International

Crops Research Institute for the Semi-Arid Tropics (ICRISAT), was one of these flagship Use Cases, which is the case study and the main source of empirical results for this study. This Use Case is a collaboration where partners with well-defined demands for science-based agricultural innovations are paired with research institutions leading the development of the innovation through multi-stakeholder innovation processes. The rigorous stage-gate evaluation process involves several steps, such as partnership development, co-designing, analytics, co-validation, piloting, and developing a scaling framework. Fig. 2 shows these main steps in the scaling practice of the innovation. These processes are drawn from the theory and practice of the systemic innovation analysis approach that emphasizes the integration of data driven bundle of innovations and complementary technologies, creating enabling policies and governance for a system change, and involving collaboration in innovation networks with multiple scaling partners [24,25].

This case study aims to systematically analyze the scaling process and the experience of horizontal and vertical scaling practices by applying a context and demand-led framework of innovation analysis for co-creation and testing, delivery process, and scaling pathways. We specifically explore scaling concepts, pathways, drivers, and strategies to scale the landscape-based fertilizer advisory supported by partnership, monitoring, learning, and evaluation tools. Additionally, we complement our analysis with insights and reflections from scaling partners obtained through three scaling partner workshops (involving 130 participants) that help provide a more structured idea of the scaling process. Finally, we relate our discussion to literature on the science of innovation scaling to inform scaling innovations and strategies.

2.4. The concept of scaling

The definition of scaling varies in the agricultural innovation literature. Sartas et al. [7] define scaling as expanding the use and impact of innovations beyond their initial testing locations, emphasizing the importance of readiness assessment and system-wide considerations. In contrast, Wigboldus et al. [26] view scaling as a complex process involving interventions, mechanisms, and outcomes, arguing for a distinction between scale as a noun (outcome) and scaling as a verb. According to Frake and Messina [27] and Cooley and Linn [28], scaling is defined as "expanding, replicating, adapting, and sustaining successful innovations in geographic space and over time to reach out to a greater number of users." These diverse definitions highlight the multifaceted nature of scaling, encompassing both quantitative expansion and systemic changes, as well as context-specific adaptations in pursuing broader impact and sustainable development. In this paper, we use a broad definition of scaling in which the landscape-based fertilizer advisory solutions are used and benefited by many users that go beyond their initial users in the piloting stage and the adopted version of innovation development stages [28,29].

Scaling has often been conceptualized as scaling out and scaling up. Scaling out, also known as horizontal scaling, involves increasing the number of innovation users through awareness creation and capacity building of extension agents and farmers within the same sphere. It involves expanding activities to reach more people and communities, can be achieved through replication (dissemination) by geographically expanding to cover more people within the same stakeholder group [30] or spreading (adaptation) where core activities are dispersed more independently from the central point. On the other hand, scaling up, or vertical scaling, refers to creating conducive conditions and policies for scaling at higher hierarchies to mainstream and institutionalize successful innovations and technologies at policy level [10,21]. Scaling up is achieved by growing along hierarchies at local, regional, and state levels or involving other institutions towards institutional innovation and system change [8,31–33]. Scaling up is generally externally driven and requires a multi-partner approach involving national governments, donor agencies, non-governmental organizations, the private sector, research institutions, community organizations, and extension workers, among others [34]. This approach involves balancing upstream and downstream strategies and managing interests at multiple levels [33, 34]. Additionally, scaling deep involves impacting cultural roots by influencing relationships, cultural values, beliefs, and mindsets to create conditions conducive to scaling successful innovations [35]. Different types of scaling processes are achieved through various mechanisms [9, 36]. Scaling can be led by the private sector, public sector, or a hybrid of both sectors to enhance innovation delivery capacity or enable policy. Overall, the scaling practice for the case study combines both scaling out and scaling up at multiple governance levels.

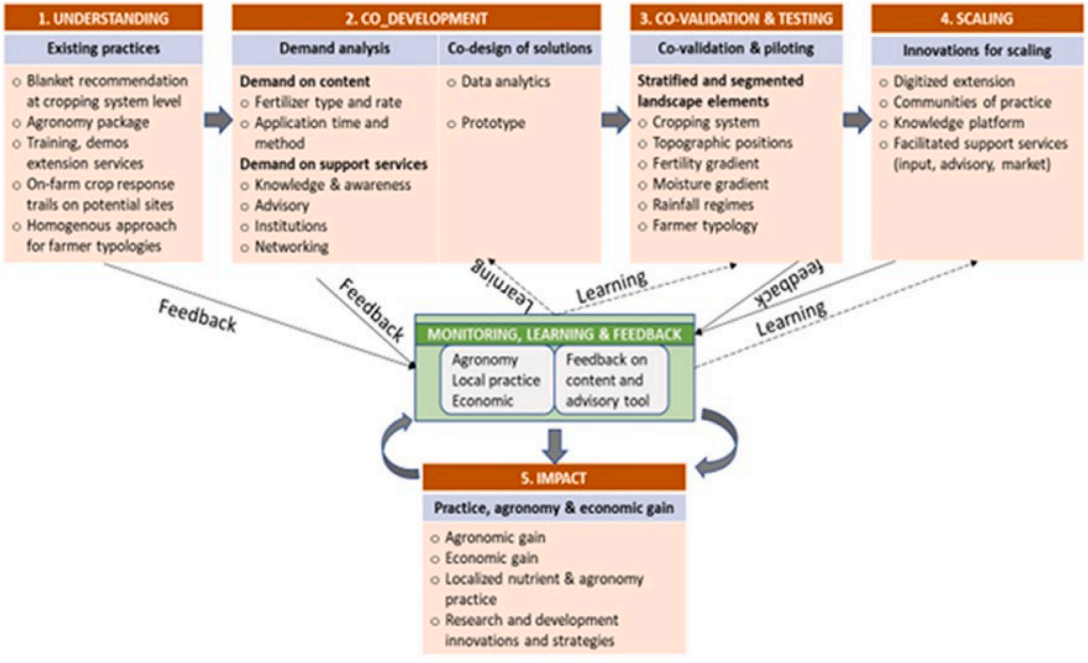

Fig. 2. The framework of the innovation design, development, testing, validation, delivery, and scaling process, illustrating the scaling practice of the landscape-based fertilizer advisory (adopted [4]).

2.5. Empirical approach

This study relies on a qualitative research approach to provide an in-depth understanding of the implementation process and scaling experiences of the landscape-based fertilizer advisory. This approach particularly allows us to reflect on the complex perspectives and science of scaling in practice within the context of the innovation, while highlighting contextualized insights that may help guide the scaling of agricultural innovations. Building on this unique real-world experience and the process of scaling the landscape-based fertilizer advisory increases the relevance, credibility, transferability, dependability, and validity of our study, all of which are key standards in a qualitative research approach [37,38].

Relying on our experiences, interpretations, and interactions with partners, we systematically synthesize the scaling implementation process and practices experienced during the design, development, validation and piloting stages of the landscape-based fertilizer advisory, including drivers of the scaling process, innovation diffusion pathways, elements of responsible scaling, the usability of the innovation as assessed by farmers' feedback, constraints affecting the scaling process, and the scaling outcomes in terms of agronomic and economic gains and environmental benefits. We also draw lessons and offer insights on contextualized scaling processes about the science of scaling, the diffusion of innovations, and the disparity of digital services among different farmer types, as well as public-private partnerships and the scalability conditions for sustainable scaling of agricultural innovations.

3. Results

3.1. Framing the innovation and the scaling approach

3.1.1. The scaling approach and practice

The scaling approach adopted by the Use Case is primarily driven by local demand for localized agronomic solutions and existing institutional arrangements for delivering extension and advisory services. It involved a bottom-up scaling process, working with farmers to reach out to more farmers and cover wide geographic locations. Drawing from the experiences of our Use Case, scaling should be demand-driven from various perspectives categorized into four demand groups: 1) demand for data and scientific knowledge on innovation scaling; 2) demand for cost-effective, productive, and adaptable bundled innovation contents that align with functional extension services; 3) demand for last-mile innovation solutions with a viable delivery model; and 4) demand for scalable innovations and enabling frameworks that support policy buy-in to impact policy targets and create an enabling environment for system change for large-scale implementation.

Government partners at zonal and district levels demand the best innovations that are easily implementable and scalable to reach more farmers, increase productivity at scale, and contribute to national agriculture sector targets. Since these public sectors have a coordination responsibility to drive the scaling of agricultural innovations in their jurisdiction, they also aim to convene and influence institutions and stakeholders to implement the expansion and adaptation of the innovations. Smallholder farmers demand cost-effective, productive, and environmentally sustainable innovations to meet their food security and income needs. Non-governmental organizations (NGOs) and other partners of the Use Case demand the best last-mile innovations to bundle and mainstream them with their program portfolios. The demand of NGOs and civil society scaling partners is not limited to adaptable innovations at the project scale, but also innovations that contribute to the outcomes of their program portfolios and the sustainable development goals across their different operating geographies, regionally and globally. Private sectors, such as farmer-producer cooperatives and digital service providers, strive to have innovations with viable digital service delivery business models through last-mile market-based approaches, such as the end-user pay model. They often demand farmer-friendly digital content and dynamic, customizable services for farmers. Academic and research partners are interested in engaging with innovation and action-oriented research to test and validate innovations at an experimental level.

Overall, nationally, there is a demand for digitalized innovations to institutionalize digital agriculture and digitalized extension advisory services that ensure the reach of technologies to all types of farmers, unlike the current model or champion farmer-based extension service approach [4,39]. This is supported by the development of the national Digital Agriculture Roadmap (DAR 2032) and pluralistic extension advisory services. However, the ICT infrastructure, institutional mechanisms for high-quality data management systems, support for user-driven digital technology innovations, agricultural extension to proactively accommodate digital products and services, and public-private partnerships to catalyze agricultural digitalization remain persistent challenges for scaling agricultural innovations in Ethiopia [39]. Thus, the scaling framework of this study aimed to scale out and scale up the core innovation by implementing the innovation development and scaling processes while considering the scaling innovation components across various demand perspectives using a public-private partnership and adaptive learning approach.

Close collaboration with district agriculture offices and extension agents at the kebele level was the main mechanism for operating the scaling network. Over the years, the scaling approach further considered integrating diverse scaling partners to collaborate with and integrate hierarchical/vertical and horizontal scaling efforts. The implementation has become more process-oriented and diverse in the innovation development and piloting of the landscape-based fertilizer advisory. It is diverse because it includes spatial innovation (landscape segmentation) and cropping systems (sorghum, teff, wheat) associated with context-specific socioeconomic settings of production systems and farmer types.

The innovation piloting and scaling are process-oriented as they involve engagements with demand and scaling partners, as well as innovation users at different levels. Partners played specific roles along the value chain, underscoring interdisciplinary contributions and sectoral mandates to create a collaborative agricultural innovation system (AIS) framework. Overall, the scaling implementation has been framed through the systemic innovation analysis framework and guided by adaptive implementation protocols [40] and engagement of scaling partners around scaling innovation components to address scaling constraints. The scaling implementation involves implementing innovation use or diffusion of the innovation to different farmer types, learning, and feedback mechanisms that underline the scaling process (Fig. 2). These activities range from understanding current practices to devising diffusion pathways and scaling strategies, while also integrating key lessons from monitoring and evaluation and feedback from end-users and stakeholders. The process also involves the facilitation of stakeholder consultation workshops and scaling partners' network on upstream and downstream integration and inclusive partnership to ensure responsible scaling towards inclusive engagements and environmental sustainability.

3.1.2. Framing the innovation package

The landscape-based fertilizer advisory as a core innovation aims to provide localized fertilizer recommendations to address the challenges of blanket N and P fertilizer recommendations and minimize yield gaps resulting from unoptimized nutrient management along the landscape segments of Ethiopia's diverse geomorphologic features. This will improve nutrient use efficiency and increase returns on investments in fertilizers. The landscape-based fertilizer advisory optimizes fertilizer application for nutrient use and economic efficiency across the landscape segments in response to localized and varying nutrient balance and yield gaps (Fig. 3).

The landscape-based fertilizer advisory has been piloted for the last three years through public extension services and a collaborative public-private partnership network targeting extension agents and lead

farmers. It has been delivered using mobile apps, SMS, chatbot, and published formats. Over the last three years, the innovation has spread to wider localities and reached more than 25,000 teff, sorghum, and wheat producer farmers. However, a challenge in the scaling process is that these solutions do not respond linearly to specific constraints. Other agronomic practices and socioeconomic factors influence the success of scaling efforts for innovative solutions.

The co-creation processes and deliberations during scaling partners' workshops have highlighted many such factors and barriers, including digital literacy problems, technical capacity limitations of extension agents and farmers in implementing digital innovations, inadequate bundled agronomic technologies, gaps in data availability on farmer profiles and geolocation of localities, lack of locally structured digital hubs for dissemination of digital advisories, and lack of collaboration along the value chain for scaling the fertilizer advisory. Other limiting factors include a lack of standardized digital extension service approaches, the dominance of public extension service pathways that do not fit all farming systems and farmer types, less emphasis on private extension services, lack of a coordinated approach among scaling partners, and a weak input supply chain - access to seed, fertilizer, lime, credit, and farm machinery.

3.2. Scaling readiness

The scaling readiness can be ensured by assessing key innovation requirements along the value chains of the core innovation and developing innovation package addressing each of the barriers for scaling. For a ready to scale package of innovations, in addition to the core innovation, all scaling constraints need to be managed through public-private partnership networks along the value chain approach. Furthermore, integrated and complementary socioeconomic and institutional innovations are required to ensure scalable digital advisory solutions and enable system changes. Efforts must be made to embrace both the development of innovations and the process of scaling them. Scaling successful innovations and technologies requires a deliberate, rigorous, and integrated analysis of the technology development process, constraints to technology diffusion, and behavioral factors of technology users [32,41].

The core innovation mainly involves landscape-based fertilizer application, along with soil and agronomic advice for major cereals like wheat, teff, maize, and sorghum. It combines existing advisory experiences to support decision-making by development practitioners, policymakers, extension workers, and smallholder farmers through site- and context-specific advisory services. The framework follows a seven-stage workflow (see Fig. 4) that includes collecting agronomic and geospatial data, processing and analyzing these data, creating and validating advisory prototypes, and collecting feedback to continuously improve the advice. The readiness of the advisory for scaling is assessed based on its level of integration and innovation to ensure each step functions harmoniously. Besides the integration within the workflow, the landscape-based fertilizer advisory's readiness also depends on the progress of other innovation packages.

The data curation part of the workflow (steps 1 and 2) involves collecting and integrating relevant agronomic and spatial data at the landscape level to collate information on crop type, yield, fertilizer use, soil fertility status, crop management practices, and farmer socio-economic characteristics. The outputs of the data curation phase include datasets with farmer-level field variables, spatial layers, and stacked geospatial predictors that explain landscape variations in soils, climate grids, and crop conditions necessary to inform models estimating nutrient needs and yield responses for specific advisory packages. The data processing and analytics (steps 3 and 4) focus on exploratory data analysis (EDA), modeling, and prediction. The goal is to create spatial maps of yield responses, nutrient deficiencies, and expected responses to fertilizer with landscape layers that improve the accuracy of the advisory system. The final outputs of the data processing and analytics phase are landscape-specific, context-relevant advisory prototypes of fertilizer advisories bundled with appropriate agronomic practices.

The advisory and validation steps (steps 5 and 6) focus on packaging and delivering tailored recommendations to diverse end-users using various methods..÷direct outreach to individual smallholder farmers and their organizations, digital and analog platforms, and existing public and private extension systems. The advisory converts model outputs and predictions into farmer-friendly, actionable fertilizer recommendations that are tailored by crops and landscapes. The validation confirms the technical integrity and performance of the advisories through field trials across representative landscapes and statistical validation to continuously refine the advisories, while engaging partners for participatory validation. During the validation stage, the technical validation of the prototype advisory was compared with the blanket fertilizer recommendation. Lastly, the feedback step creates a continuous learning loop through iterative input from both end-users and national partners regarding usability, accessibility, and effectiveness of the advisory. The feedback mechanism also ensures the integration of policy and market insights (such as fertilizer availability, prices, and regulations) to enhance the relevance of the advisory in response to new developments.

Finally, the framework considers the heterogeneity of end-users in their preferences for outcomes and factors conditioning the optimal application of the advisory by farmers, such as their resource-endowment, subsistence-orientation, and market-orientation. It specifically provides a tailored and objective decision-support tool to users, considering the preferences of users to objectives of either increasing yield, maximizing return profit, or an optimized outcome for both yield and profit.

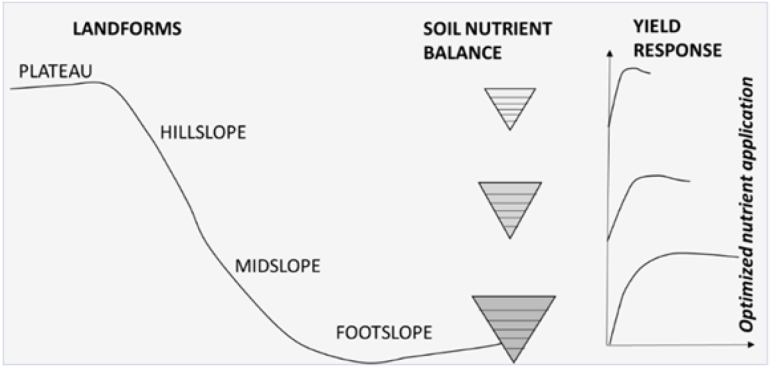

Fig. 3. An illustration of concept of developing landscape-based nutrient management that provides an optimized nutrient management along landscape segments in the perspectives of gradients of soil nutrient balance and yield response capability along landscape positions.

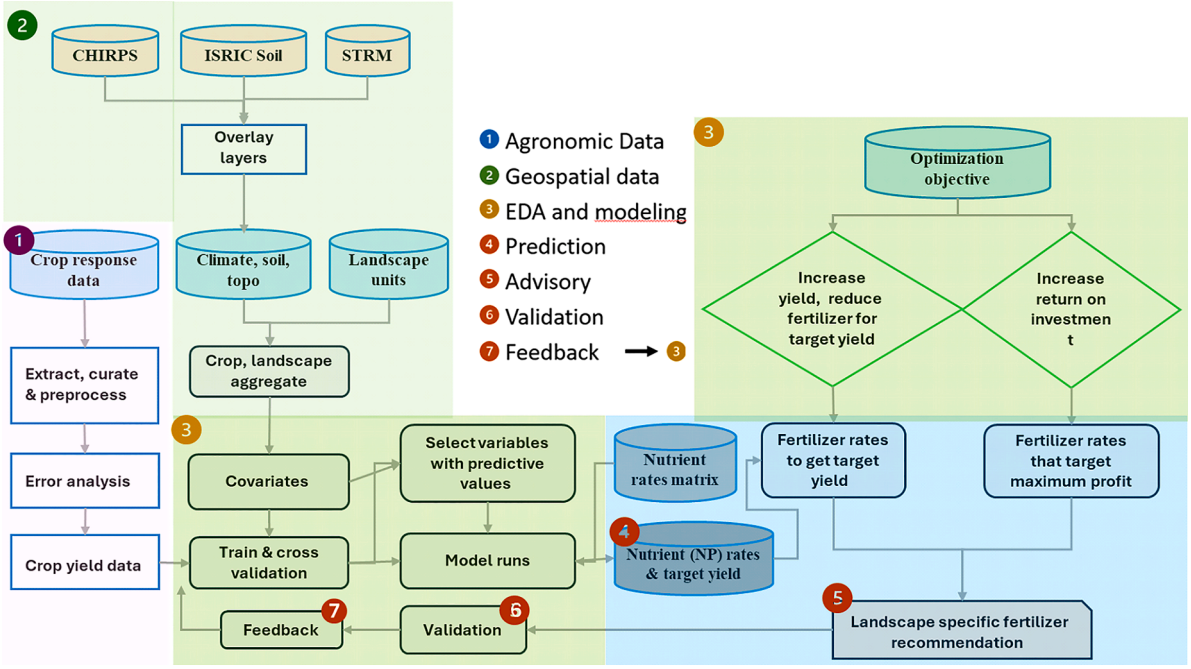

Fig. 4. The workflow of the development of the landscape-based fertilizer advisory. EDA (Exploratory Data Analysis); CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data); ISRIC (International Soil Reference and Information Centre); and SRTM (Shuttle Radar Topography Mission).

3.3. *The scaling process*

3.3.1. *Scaling drivers*

Given the background on the agricultural innovation system (AIS) analysis framework for scaling and the perspectives of demand, successful scaling activities require specific enablers and mechanisms to ensure responsible scaling. As interest in digital agricultural innovations increases, it is essential to thoroughly understand the drivers of both upstream and downstream scaling aspects. This understanding provides a foundation for scaling efforts and guides practitioners in identifying the most effective strategies for scaling digital fertilizer advisory. In the context of developing and scaling agricultural innovations in Ethiopia, several drivers influence scaling at both local and systemic levels. While most drivers can be managed within the scaling network, some threshold drivers have dynamic, systemic impacts and global repercussions on innovation scaling. Various influential drivers were identified during workshops with scaling partners and throughout the scaling process. Here, we present the major drivers of scaling that emerged from the scaling experiences and discussions with partners.

1. *The availability of finance* is the most critical factor for successfully scaling of innovations. Currently, scaling often relies on a top-down approach from the public sector, sometimes through campaigns, but it frequently lacks sufficient financial mechanisms to enable continued scaling. There are capability limitations and an unfavorable environment for implementing market-based scaling. Several studies have identified financing as a key driver for the success of scaling innovations [42,43]. These studies emphasize the need for increased investments in agricultural innovations [44], network building [45], and developing information technologies [46]. To respond to the financial constraints, the innovation scaling strategy recommended financial sustainability measures and business models [47].
2. *Access to and availability of agricultural inputs*, such as fertilizers, chemicals, and organic materials, are key factors that influence the success of the scaling process. This aspect not only affects the adoption of innovations but also determines the viability of those innovations and their impact on productivity and food security. Without a reliable supply chain and effective value chains, this factor can hinder the successful scaling of innovations. Therefore, it is crucial to strengthen the capabilities of the scaling network to ensure equitable access and to provide essential inputs at an affordable price and at the right time. The private sector is primarily responsible for supplying fertilizer and delivering the advisory tools, often working in conjunction with government agencies, and distributing them to users through cooperatives. The private sector's viability depends on farmers being able to purchase inputs at market-determined prices [48]. More efficient fertilizer use and higher returns for farmers can drive further commercialization of the fertilizer industry, involving the private sector deeply. The advisory tool provided by the private sector can also benefit them by helping ensure the correct amounts of fertilizer are delivered to the right place, which likely increases the willingness of farmers to pay for the services.
3. *Inherent attributes and market demand for the innovation*: There is a growing demand for innovations tailored to local needs, especially as farmers face the threat of rising fertilizer prices and changing climate. Thus, innovations that can lower farmers' production costs gain wider adoption. However, overall market demand for such innovations is often uncertain due to climate change and variability, market fluctuations, and changes in policies and institutions. Thus, climate and risk mitigation strategies need to be integrated as part of the innovation package tailored to different farmer types with various risk aversion capacity.
4. *Innovations often encounter challenges related to low adoption and inclusivity*. This is partly due to a lack of technical expertise in aligning the design and scaling of these innovations with user needs, as well as inadequate co-design of dissemination channels as per the socio-economic disparities of farmers. In the context of landscape-based fertilizer advisory, which targets extension agents and farmers, the adoption and scaling of this innovation greatly depend on extension agents' technical knowledge, facilitation skills, and communication abilities. Therefore, it is essential to evaluate extension agents' knowledge, skill sets, perceptions, and attitudes regarding the innovation and scaling process. Furthermore, delivery services should be customized to incorporate usability levels of the

innovations by farmers and their feedback, effectively supporting the scaling process.

5. *Enabling digital infrastructure and promoting digital literacy* among users are essential for effectively delivering and disseminating digital solutions. In digital transformation, shifting from traditional extension services to a digital platform that digitizes content and delivery methods is crucial. However, inadequate digital infrastructure and low literacy levels often hinder access to these digital solutions for extension agents and organizations that work directly with farmers [39]. Therefore, creating a supportive policy environment for digital extension advisory services is vital for successful scaling, making it a critical factor in enhancing landscape fertilizer advisory services.
6. *Partnerships and networks involving diverse stakeholders* are vital for driving change across sectors. Formal public-private partnerships can enhance institutions' capacity for innovative solutions. Collaboration among public, private, and non-governmental entities can broaden the impact of initiatives and promote farmer-to-farmer knowledge sharing through lead farmers and network platforms.

3.3.2. *Scaling pathways*

To achieve system-level change and sustainable impact, we share pathways highlighting lessons from ongoing innovation pilots across various contexts. Systems change requires disrupting the status quo, a complex process involving key shifts [32]. Kohl [31] defines innovation diffusion pathways as a series of innovations, scaling processes, and sustainable implementation in a specific context. These pathways consist of steps beginning with innovations, scaling, and achieving large-scale sustainability. For significant impact, innovations must foster sustainable change by integrating technological and institutional innovations to reach a wider audience [32].

Effective diffusion and scaling approaches should be participatory and inclusive, addressing local needs, securing support and local ownership, establishing partnerships, and generating positive impact [8, 31]. Various agricultural innovation pathways can be utilized, including participatory delivery strategies, partnership, and advocacy for government support [31,34]. The scaling pathways we discuss in this section represent the practices experienced from the landscape-based fertilizer advisory delivery process, addressing 'what to scale,' 'how to scale,' and 'to whom to scale' by adjusting contextualized mechanisms for effective implementation.

1. Participatory mechanisms for innovation development, validation, and piloting

During the demand analysis, co-validation, and co-piloting stages, the participation of users and partners followed a bottom-up co-designing process involving farmers, public sector experts, and researchers [12,4]. This approach ensured that innovations were relevant to local needs, with farmers sharing their local knowledge on nutrient management and cropping systems [49]. Farmers provided feedback during field day events and participated in evaluation sessions to enhance the usability of advisory solutions. A farmer-to-farmer diffusion approach further increased farmers' awareness to the innovation and promoted its adoption. Extension agents who are the center for the diffusion and scaling network were vital, reaching 400–600 farmers each, facilitating capacity building, knowledge exchange, and communication. District agriculture office heads and senior extension experts coordinated implementation, logistics, and capacity-building efforts. Local leadership was crucial for determining scaling strategies and partners mobilizing support. Ultimately, scaling through participation effectively disseminates innovations to adapt them to specific contexts.

2. Bundling of technological innovations

The bundling of innovations serves as a diffusion and scaling pathway to meet the diverse needs of target users by offering a comprehensive package of innovations, services, and technologies. As the core innovation progresses and enters further piloting stages, there is a need for complementary technological innovations to create effective multifunctional innovation portfolios. This pathway involves a partnership between CGIAR and NARES to generate a big data ecosystem, validate prototypes of advisory services, and facilitate large-scale bundled innovation. The goal is to institutionalize these bundled digital agriculture innovations at a national digital platform, enabling all R&D partners to showcase their efforts. Apart from bundled innovation development, the pathway aims to enhance national digital agriculture delivery capacity in soil and agronomy innovations and provide advisory services through public extension services or public-private partnerships.

3. Mobilizing policy support

Scaling through policy support involves securing government and political backing at all levels (vertical scaling) and obtaining the support of policymakers by establishing multi-stakeholder partnership platforms for policy assistance. This support can foster a positive environment for adopting information and digital technologies. To be effective, national digital advisory coordination platforms have been created that facilitate resource mobilization and partner coordination throughout the value chain. Moreover, the policy support pathway for innovation scaling acknowledges the complex and multi-sectoral nature of scaling innovations and integrates the scaling delivery agenda, which are aligned with the national digital agriculture roadmap and pluralistic extension strategy [47]. Additionally, as illustrated in [50] and Digital Agriculture Roadmap 2032, enabling conditions for digital infrastructure and financial mechanisms has been facilitated to ensure the success of the scaling process.

4. Partnership network

Partnerships and networking with the right stakeholders, both local, subnational and national, are essential for fostering successful experimentation, learning, and scaling in agriculture. Effective scaling of an innovation requires institutional innovations for both horizontal and vertical integration. Partnerships are critical for achieving large-scale impact since no single actor typically has all the necessary resources—financial, knowledge-based, operational, or political [31]. To create inclusive and sustainable agricultural development, it's crucial to enhance local partners' participation and decision-making capacity through institutionalized interventions and empowerment [51]. In the case of Fertilizer Ethiopia Use Case, key stakeholders established a network to streamline the innovation scaling process. This network comprises actors committed to addressing scaling barriers along the value chain, building alliances, gaining political support, and promoting social innovations. The partners engage in activities, such as identifying and packages of good agronomic practices, organizing meetings, facilitating learning events, conducting joint monitoring and evaluation, sharing resources, and addressing scaling barriers. They aim to institutionalize the scaling of a landscape nutrient management innovation that promotes multifunctionality and sustainability approaches across zonal and district levels, coordinated by zone agriculture offices. Six key innovation package components for systems change were identified in stakeholder workshops to tackle them through public-private partnerships. The innovation package components were organized into thematic work packages to encourage collective actions aligned with the national digital agriculture roadmap. In Ethiopia, scalable solutions depend heavily on public sector support for extension services, input supply, and subsidies. These key areas of partner engagement [52] should guide responsible scaling efforts for inclusive innovation use. Details of the partnership network and work packages are illustrated in Fig. 5.

As shown in Fig. 5, the partnership network encompasses several key

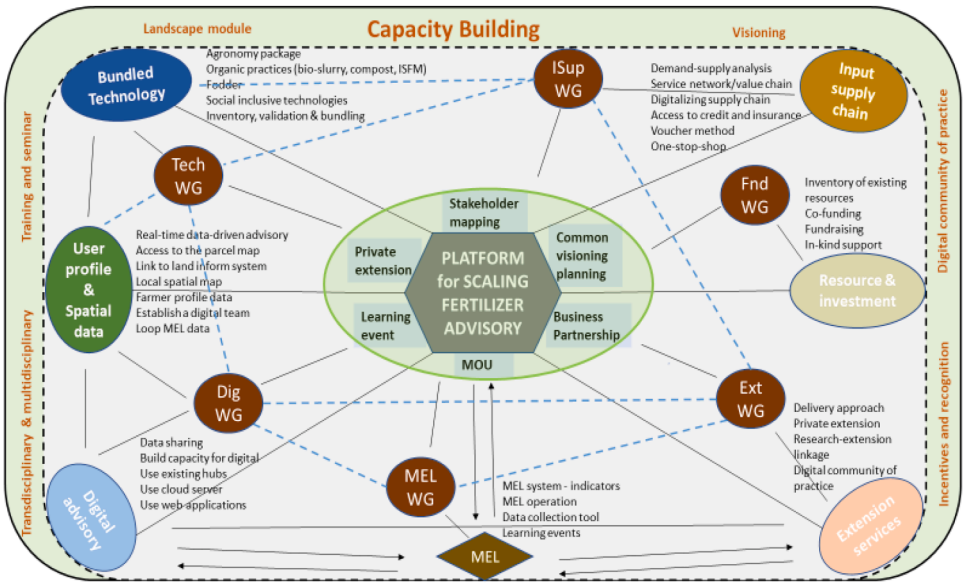

Fig. 5. An optimum scaling partners network that brings key scaling partners together to facilitate the scaling process and share responsibilities across working groups.

work packages that align with innovation components. (a) *Technology Bundling*: Partners transition from specific innovations to integrated bundles of technologies in soil, agronomy, fodder, climate, and land management to address local yield gaps and resource inefficiencies. Research institutes, universities, and NGOs collaborate to bundle solutions and tailor innovations to local demands across diverse contexts, including topographies, climate, soils, and cropping systems. (b) *User-Driven Digital Advisory*: There is a need for better data on end-user profiles and local spatial conditions that affect the dissemination of innovations. This work package aims to create a digital service environment (i.e., farmer profiles, parcel information, digital literacy) that diffuses context-specific and tailored innovations. (c) *Extension Service Functions*: Ethiopia's public extension service, organized from national, subnational, zonal, district to the kebele and village levels, faces challenges as an extension agent serves 400 to 600 farmers using traditional extension service methods. The extension agents currently operate using conventional paper-based guidelines and field demonstrations. It is, therefore, essential to strengthening their digital skills and providing smart ICT technologies for effective service delivery. (d) *Resource Mobilization and Scaling Investment*: The financial resources available for scaling implementation are limited. There is a common belief that financial responsibility lies with end-users. This work package focuses on developing investment models, mobilizing institutional support for co-funding, and collaborative fundraising efforts. (e) *Input Supply Services*: Access, availability, and affordability to agricultural inputs are significant constraints for smallholder farmers. This work package take role to ensure a responsive and effective value chain for input supply innovations. (f) *Monitoring, Evaluation, and Learning (MEL)*: The MEL work package guides the piloting and scaling of innovations by measuring progress and ensuring accountability. It tracks results, gathers feedback on adoption of agronomic solutions, and identifies areas for improvement, ultimately enhancing the use of advisory services for broader impact.

The scaling partners' network platform is driven by the scaling barriers, where each partner has a stake to address barriers along the value chain for mutual benefits and shared goals to deliver the innovation to end users. All partners took responsibility as per their value propositions and mandates of the stakeholders. The continuity of the scaling partners' network relies on the governance of the network, driven by evolving demands for innovation and the diffusion of services supported with an adaptive management approach through regular monitoring of key performance indicators and feedback, and accountability. The level of engagement is adaptive and evolves to the readiness to scale until the innovation scaling becomes mature and is adapted by users.

5. Capacity building through training and exchange visits

Scaling through learning and knowledge exchanges fosters social learning, a vital strategy for scaling innovations. Participants' technical knowledge and skills are essential throughout the innovation process, from development to piloting and scaling. Without this expertise, establishing a shared understanding of the innovation's usability becomes difficult, impacting its scalability and sustainability. The innovation scaling practice focused on providing technical training for farmers, extension agents, and district leaders, aiming to empower localized agronomic innovations, especially site-specific nutrient management, and promote broad dissemination. As local capacity improves and trust builds, evidence-based innovations piloted by extension agents gain traction. Extension agents are key in this process, training farmers, facilitating exchanges through field days, fostering vertical and horizontal networks, and monitoring innovation impacts. A blog[1] about an extension agent highlights the transformation of the knowledge system, showcasing how agents improve their technical skills and capabilities, understand landscape variations and cropping systems, collect agronomic data, and document crop productivity and economic outcomes across diverse landscape contexts.

6. Social media platforms serve as a community of practice for innovation dissemination

Social media has become essential for landscape-specific fertilizer applications, promoting learning and information sharing. Since 2021, Telegram channel platforms have served as Communities of Practice for practitioners and decision makers at districts and kebeles, with over 1063 members, including extension agents, researchers, agricultural experts, decision makers, and department directors (Fig. 6). The

[1] https://www.cgiar.org/news-events/news/transforming-ethiopias-agriculture-through-agronomy-innovation-the-landscape-segmented-fertilizer-advisory/

Telegram platform serves as a scaling network of partners and fosters participatory learning, validation, and dissemination of innovations; and facilitates the exchange of data, feedback, and best practices [53]. By the end of November 2024, the social media platform enabled the sharing of 9100 photos, 84 videos, and 1250 innovation implementation documents (Fig. 6). These exchanges have improved the feedback mechanisms from farmers on agronomic practices and collection of data from extension agents, enhancing continuous learning and innovation validation. The platforms also facilitate interactivity and timely reporting, serving as vital resources for sharing experiences and seeking advice. For decision-makers, these platforms provide insights for informed decisions and choices on access and distribution of fertilizer, tailored fertilizer use, and pest management, allowing for quick actions to prevent potential damage.

7. Creating market demand for innovation delivery services

This pathway aims to scale up digital delivery services by fostering market demand through tailored incentives, considering users' social, economic, and cultural contexts. A promising strategy is the engagement of farmer-producer cooperatives [54]. These cooperatives enable collective actions of farmers to achieve economies of scale, enhance bargaining power, and share knowledge, improving local communities' social and economic conditions. By delivering essential supplies like fertilizers, seeds, and machinery, cooperatives effectively provide affordable digital services for fertilizer applications bundled with other agricultural input services.

3.3.3. Ensuring responsible scaling

Responsible scaling is vital for expansion, especially regarding ethical considerations and future impacts. Scaling can inadvertently lead to social inequity and environmental harm. To effectively scale landscape-based fertilizer innovations, strategies should align with context-specific approaches for scaling out, up, and deep. Therefore, when designing and implementing scaling, we should deliberately plan and manage to minimize or avoid unintended changes and consequences. Cognizant of this fact, the scaling practice has planned actions that ensure equity and inclusion of heterogenous users based on their specific needs and capacity. In line with this, the scaling practices have identified segments of users based on production orientation, whether it is for subsistence or market, membership in local associations, risk aversion, digital literacy levels, and gender and youth considerations. This was intended to enable targeted service provision, matching smallholder farmers to the services they most need and can use.

Extension contact, use of inorganic fertilizer, credit use, and plantation methods are among the key determinants of the gender gap in agricultural productivity. Although female-headed households may have equal access to fertilizer, they have limited capacity to afford the required inputs [55]. If not specifically addressed, there is a potential danger that the landscape-based fertilizer innovation will further contribute to the structural barriers that inhibit women from input access and productivity-enhancing training. Gender tailored input access and financial incentives to women farmers should be in place and facilitated through the scaling partners' network platforms. The landscape fertilizer innovation enhances the efficient and optimum use of fertilizers based on crop nutrient requirements and minimizes fertilizer overuse and packaging of the innovation with integrated soil fertility management practices, with obvious benefits to water quality, soil quality (less acidification), and reduces emissions, which makes the innovation environmentally friendly.

The scalability and sustainable delivery of the innovation can be enhanced by recognizing the needs of different target users when digital solutions and scaling services are designed. Some digital agro-advisory services are of interest to just one segment of users, while others are of importance to most segments. Assessments have shown that there are disparities in accessing digital advisory tools between subsistence and market-oriented farmers, digital literate and illiterate, women and youth farmers. The different segments of farmers can access digital services through government and non-government partners that are actively engaged in agricultural extension services. Furthermore, institutions and platforms, such as NGOs, cooperatives, and the private sector, can provide services with different paths to reach different market segments.

The different segments of farmers allow for diversifying digital market segments (video, radio, IVR, SMS, chatbot, app, web, maps, etc.) through various pathways. Subsistence farmers have little access to cash, so they require credit or subsidies from a variety of sources, while market-oriented farmers who do farming for the market prioritize loans for expanding markets for their produce. The more literate farmers are likely to have high readiness and access to the digital advisory and are thus more likely to use agro-advisory services. While non-literate farmers have less incentive to use digital services and typically prefer to access the information through trained extension agents or video and audio digital solutions. Women farmers often had less access to information and advice [55]. Considerable effort on segmented services must be made to provide women farmers and women on the farm with efficient, effective, and appropriate technology, training, and information on digital innovations and solutions. Youth farmer segments are often targeted by technology delivery agents due to their unique needs, interests, and technology use behavior. There is a significant potential to reach young farmers for the scaling of the agro-advisories, as they have a strong affinity for digital innovations, such as SMS, chatbots, and mobile apps. To effectively reach the youth segment, specific delivery strategies and digital markets can be designed, and social media platforms can be exploited to engage with them and expand their access to important digital knowledge and information. Farmers who are registered members of cooperative institutions often have better access to inputs and bundled services than non-cooperative members.

The piloting of the innovation at different districts during 2021 to 2024 confirmed that the landscape-based fertilizer innovation was better than the blanket fertilizer recommendation and found to be relevant and adaptable to what farmers need and to the diverse landscape conditions. Many farmers were finding fertilizers unavailable when needed, and others found them too costly when available. With the landscape-based fertilizer advisory (LANDWise) being efficient in fertilizer use, it helped farmers reduce the total cost of fertilizer used and fulfill their fertilizer needs with what they were able to access. In addition, the advisory will be updated annually, responding to user needs and mitigating risks. The adaptation was made based on information that were collected through the gender sensitive and farmer-segmented MEL system.

According to CGIAR Science Leaders [56], successful scaling must adhere to established principles to ensure sustainable impacts. The scaling practices for the landscape-based fertilizer advisory has been guided by these principles that are contextualized to ensure a responsible scaling.

1. *Shared Vision of Change*: In scaling landscape-based fertilizer advisory, scaling partners have developed a scaling strategy plan with a clear vision. Partners aimed to reach 50,000 innovative users among sorghum, teff, and wheat farmers, engaging 30 scaling partners by 2030 [52]. The goals include a 30 % yield increase and a net profit of $6.00 to $10.00 per unit investment [4]. These efforts involve shared responsibilities to incorporate various perspectives, identify leverage points, and adapt based on feedback. The vision prioritizes sustainability and quality of impact, guiding the community toward sustainable farming practices.
2. *Be responsible for achieving the vision*: To effectively implement the vision of change, we started by identifying core and complementary innovations and assessing their scalability. Our scaling

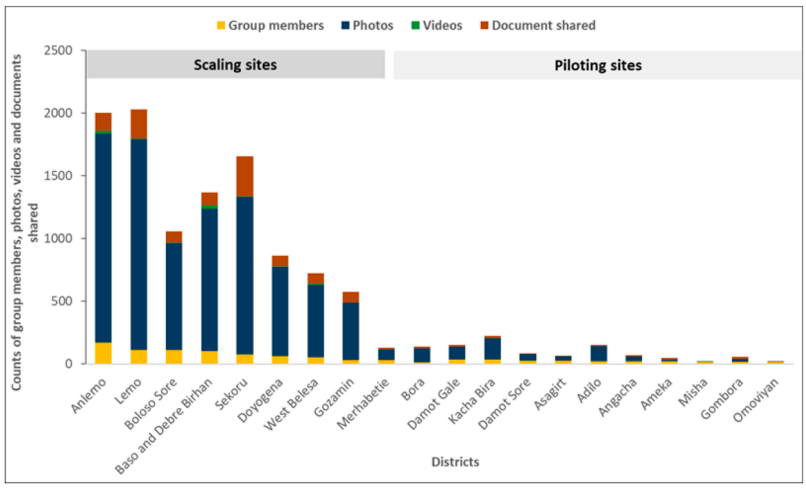

Fig. 6. Activities of the Community of Practices that are facilitated through Telegram Group Channels of each implementing District.

partners identified potential challenges and developed strategies to address them. We established monitoring, evaluation, and learning mechanisms to capture user adoption levels and feedback during training, field visits, and workshops. Additionally, our scaling partners' network consistently monitored these activities and adapted community actions for sustainable farming. In scaling operations, obtaining approvals for new digital solutions and ensuring compliance with environmental and ethical regulations is essential. Responsible scaling should focus on scalable innovation, collaboration, and sustainability, aiming to enhance crop yields, reduce costs, and protect soil health. This commitment drives economic growth and fosters a more sustainable and resilient food system for future generations.

3. *Design for scaling from the start*: The scaling process for the landscape-based fertilizer advisory is driven by demand. As a result, the development, validation, piloting, and scaling of the fertilizer innovation began by examining the needs, opportunities, and challenges associated with scaling throughout the fertilizer value chain. The scaling approach considered strategies to mitigate barriers and risks, identifying opportunities and enabling conditions for effective scaling. These insights were incorporated into an operational scaling strategy plan, which was executed by a network of scaling partners. The lessons learned from this process helped generate broader demand and motivation, informing the creation of a comprehensive scaling delivery strategy for digital agronomy advisories at the national level.
4. *Nurture institutional space, partnerships, and leadership for a culture of collective action*: A strong culture of collective action and institutional capacity is essential for deploying community institutions that support the scaling process. Providing training and networking opportunities empowers communities and scaling partners, fostering collaboration and innovation. Establishing local and national partnerships is crucial for sustaining scaling efforts, helping to reach grassroots communities and connect with various stakeholders. The scaling partners' network and social media communities that are operating at different levels are vital in ensuring an institutional space for collective actions. We employed four key approaches to institutionalize scaling practices: (i) integrate diffusing and scaling pathways into existing government extension services; (ii) mainstream scaling practices within NGOs' development programs through public private partnerships; (iii) incorporate scaling science into academic and research programs; and (iv) engage political leaders to support vertical scaling. The national Digital Support Tool (DST) coordination platform promotes strategic policy engagement for responsible digital delivery.
5. *Monitor the use of innovation and adapt the scaling process*: Monitoring the scaling of innovation and investment is essential for tracking both positive and negative outcomes, promoting learning and accountability. The dynamics of innovation scaling should be continuously monitored, evaluated, and learned. Responses to changes should be implemented, and strategies should be adapted to meet the evolving needs of farmers and extension agents. Importantly, the innovation scaling process should adopt a tailored approach that considers different farm types, focusing on gender and youth.

Table 1
Piloting participant farmers' feedback evaluation.

Variable	Event feedback evaluation ($N = 72$)		Telephone survey ($N = 543$)	
	% Agree	% Disagree	% Agree	% Disagree
Understanding the content	86 %	14 %	94 %	6 %
Application/being able to apply	75 %	25 %	91 %	9 %
Logistics in organizing events	63 %	37 %	99 %	1 %
Usability and usefulness rating (on a scale of 1–7)	5.2		4.2	
Net Promoter Score (NPS)	67 %			

3.3.4. *Usability of the landscape-based fertilizer advisory*

Table 1 provides feedback from farmers who attended awareness training and field day events in 2023 (72 sample groups), as well as those who participated in a telephone survey in 2024 (543 respondents). Farmers who piloted the innovation were surveyed to evaluate their understanding, the applicability of the advisory content, and the logistics involved. In 2023, 86 % of the farmers participating in training and field day events reported a better understanding of the innovation. Despite challenges with input supply services, 75 % applied the innovation at acceptable costs and risks, while 63 % found the logistics satisfactory. A telephone survey was conducted in 2024 to further assess the use of the advisory tool. Respondents were randomly selected from all innovation users and event participants as sampling frame and conducted by the monitoring and evaluation team. The response rate stood at 99 %. The telephone survey revealed that 94 % of farmers found it easy to understand, 91 % found it easy to apply, and 99 % agreed that the logistics were satisfactory and acceptable. The innovation was also assessed by the farmers in terms of its usability. The usability score metric aims to measure the relative assessment of farmers on the

understanding, practicability and benefits of the advisory tool. It uses a set of 10 questions to gather user feedback using Likert scale of seven levels (1 to 7). As the landscape-based fertilizer advisory tools are new and smallholder farmers have not done similar assessment before, the benchmark was based on the level of awareness, knowledge and the practice acquired during piloting stages. The usability score was estimated as the average score across the different responses. The value approach to 7 indicated higher and easier usability of the advisory and 1 difficult usability of the advisory. Accordingly, the landscape-based fertilizer recommendation received a usability score of 5.2 out of 7, and a net promoter score of 67 % indicated a substantial likelihood of recommendations. The usability score was 4.2 out of 7.

3.3.5. Scaling outcomes

Desta et al. [4] and [47] provided data on the impacts of the landscape-based fertilizer advisory as compared to standard recommendations. The landscape-based advisory optimizes profits and nutrient use efficiency based on different landscape positions and is aligned with local farmers' practices [4]. Farmers' income, yield, and productivity were all greatly impacted by the advisory. Additionally, the innovation's pilot program increased end users' revenue by 17–20 % under marginal conditions and 25–30 % under ideal ones, with a net benefit–to-cost ratio of $6–$10.00 for every dollar invested [4]. The pilot expanded partnerships across 23 districts, involving 8 NGOs and 2 national universities, benefiting farmers, experts, and decision-makers. Social media engagements with experts and partners exceeded 1063, fostering a community of practice. The innovation's users grew over years, reaching more than 25,000 farmers both directly and indirectly.[2] The machine learning model predictive accuracy for the innovation has reached 85 % to 95 % for the different crops.

Implementing the landscape-based fertilizer rate has improved average productivity per hectare by 13 % for wheat, 17 % for teff, and 29 % for sorghum during the validation phase. The benefit-cost ratio (BCR) varied across different landscape segments due to site-specific differences. Among the three crops, sorghum achieved the highest BCR, followed by wheat, while teff had the lowest across all landscape strata in both the 2021 and 2022 validation and piloting phases. The landscape-segmented fertilizer recommendations help farmers apply fertilizers according to the marginal returns, which should help reduce the overall fertilizer cost per kilogram of grain. The net benefit analysis during the validation and piloting stages indicated crop and landscape strata variations. The economic analysis found that landscape-specific fertilizer application resulted in an optimized net benefit per hectare increase over the current extension recommendation, where $176 and $333 at foot slopes and $159 and $64 at mid slopes for wheat and teff, respectively. For the case of sorghum, the optimum net benefit was $526 for the foot slope and mid slopes and $438 for the hill slope landscape strata. The hill slope generated the lowest net benefit for all crops because of its depleted soil conditions that result in low yield potential. The results of the benefit-to-cost ratio (BCR) per hectare demonstrated that applying landscape-targeted fertilizer resulted in an optimum return on investment ($10.0, $12 and $30 net profits for teff, wheat and sorghum, respectively), while also enhancing optimized nutrient use efficiency across the three landscape positions [4]. The direct benefits need to consider changes in crop yield and prices, output prices, and the amount and value of fertilizer "saved" by using the landscape-specific recommendations.

3.3.6. Scaling barriers

Despite positive outcomes and acceptance of the innovation, its expansion and scaling faced several barriers. A report on the readiness of decision support tools for field-specific advisory services identified key constraints, including limited multi-stakeholder information exchange and low integration of landscape principles in nutrient management [57]. Other issues included the tools being knowledge-intensive, inadequate farmer profile and typology information for achieving a market-segmented delivery of the advisory, low digital literacy of farmers and extension agents to utilize available digital delivery channels and overlooking farmers' investment limitations. Institutional challenges also hinder effective advisory delivery, such as inadequate input supply, low extension service capacity, low digital literacy, and limited access to finance and digital infrastructure [8]. If scaling is not well-planned to tackle these barriers, site-specific fertilizer innovations may not achieve desired outcomes. Consultations with partners revealed that scaling processes can limit innovation, with risks affecting farmers' behavior and investment returns. Key risks include the fluctuations of input and output markets, limited finance, climate variability, and pest occurrences. Some risks can be mitigated within the public-private partner network, while others require policy interventions and collaboration with additional actors in the innovation ecosystem.

Despite the current scenario of inadequate infrastructure and low digital literacy, Ethiopia has huge potential for the digital innovation market that ensures the continued scaling of the innovation. To tap this potential, the government clearly outlined short- and long-term solutions to address the digital infrastructure and digitalization services. In the short term, potential alternative digital solutions that are identified to target different segments of farmers with infrastructure and literacy challenges include video extension, interactive voice response (IVR), SMS and agent-based delivery. In the long term, the government has embraced the advisory system and started actively working to facilitate an enabling environment to address these limitations through the Digital Ethiopia 2025 and Digital Agriculture Roadmap 2032 strategies. In the long term, for example, infrastructure improvement efforts center on developing robust digital infrastructure to support connectivity across the country and expand internet access through expanding mobile networks, building data centers, and promoting digital literacy. Currently, mobile penetration has reached 85.4 million cellular connections, representing 60.4 % of the population. In 2023, more than 85 % and 33 % of the population were reportedly covered by 3 G and 4 G internet connectivity, respectively.[3]

4. Discussions

4.1. What does it take to transition from delivery to scaling?

The agricultural extension system in Ethiopia aims to enhance farming technologies and build the capacities of stakeholders. It promotes advanced technologies, such as improved crop varieties and fertilizers, through extension methods like model farmer and local development group structures. De Roo [58] notes that these mechanisms have created a reciprocal relationship between local authorities and model farmers, often excluding many farmers. The research for development (R4D) community views on-farm trials to promote technology, although these trials struggle to demonstrate scalability due to limited access to technologies and inputs. Political connections and social networks influence traditional technology promotion. Therefore, adopting sociotechnical network approaches within a mission-oriented innovation systems framework is essential for fostering partnerships along the value chain [23,59]. To scale the landscape-based fertilizer advisory solution, partners must collaboratively pursue a scaling agenda while exploring pathways and strategies throughout the development and delivery process. Integrating horizontal and vertical scaling strategies is crucial, ensuring that the impact is proportional to the challenge [31].

In our case study, we identified seven diffusion and scaling pathways: participation, context-based innovation bundling, partnership,

[2] https://pressroom.icrisat.org/icrisats-landscape-based-fertilizer-advisory-tool-to-benefit-over-15000-farmers-in-ethiopia

[3] https://datareportal.com/reports/digital-2025-ethiopia

market demand creation, capacity building, social media-facilitated communities of practice, and policy engagement. These pathways, well aligned with the scaling factors from Kohl [31] and the dimensions outlined by [33], highlight their varying significance based on the nature of the innovation and local contexts. It is for this fact that we emphasized the co-creation and co-validation of the innovation from the start as reported by Sartas et al. [57]. The landscape-based fertilizer recommendation advisory, co-designed with national researchers, extension agents, and leading farmers, includes ten performance innovation components which are categorized into principles, knowledge, procedures, tools, practices, and organizational arrangements that impact productivity and profitability [57]. Development and delivery processes were outcome-oriented, focused on solving specific problems with proven technologies, and process-oriented, targeted in addressing systemic issues and emerging constraints.

The innovation scaling process, informed by the agricultural innovation system (AIS) framework, starts with assessing the demand, analyzing constraints and opportunities, and incorporating regular feedback. It employed a bottom-up approach that engaged partners with specific interests across multiple levels: kebele level (extension agents and farmers), district level (local authorities and researchers), zonal and regional levels (decision-makers and agronomists), and national decision-makers (department directors, NGOs, and private sector representatives). The network's activities contributed to the effective implementation of innovations and facilitated learning [4,60], enhancing partners' capabilities to support the scaling platform.

To ensure responsible scaling pathways, Kohl [31] emphasized the significance of a structured sequence of activities that begins with innovations and leads to large-scale sustainable implementation. Woltering et al. [32] pointed out that for innovations to be impactful, they must drive sustainable change by integrating technological, institutional, and market innovations. In this case study, enhancing localized digital extension services by categorizing farm typologies and creating farmer profiles linked to spatial parcel information is essential. Aligning the activities of scaling partners with local and national agricultural strategies—such as soil health management and climate-smart agriculture—can accelerate the scaling process. Effective scaling necessitates nationwide engagement, including policy dialogue and institutional innovations. Innovations produce positive development outcomes when backed by necessary changes in the institutional environment [7,28,31].

Schut et al. [61] emphasized a holistic approach to innovation portfolio management by integrating organizational processes with systems that encourage partnerships among government, public, and private sectors for sustainable food system transformation. Cooley and Linn [28] highlighted the importance of partnerships among public, private, and civil organizations in scaling innovations, as detailed in IFAD's Scaling Up Framework. Private partners contribute a market approach, public sectors provide capital financing and a supportive policy environment, while NGOs engage communities. Trust and commitment among partners are essential for success [33,62]. Addressing institutional and financial constraints is critical, as neglecting them often hinders scaling efforts [28,31]. Future research could explore how institutional innovations and market delivery pathways refine the scaling process and influence outcomes.

4.2. Adaptive governance of the scaling practice embeds institutional bricolage processes

The scaling process involves integrating both downstream and upstream engagements to foster continuous learning and feedback, ensuring that various perspectives and needs related to landscape-based fertilizer advisory are contextualized and adapted. As shown in Fig. 5, the network platform of scaling partners, which includes work packages aligned with thematic innovation components, facilitates the development of practice-based approaches and solutions tailored to specific contexts. The cases of delivering and scaling landscape-based fertilizer advisory reveal adaptations that were not deliberately designed but evolved in the scaling practice where localized contexts challenged conventional technology diffusion and adoption, the co-creation process involving multiple partners with diverse experiences and demands, as well as emerging environmental impacts and market fluctuations—all of which drive adaptive governance at both local and higher levels. This process demonstrates how partners adapt to local contexts and challenges. At the operational level, partners work together to promote scaling through informal cooperation among public entities, private sector, civil society, and community organizations.

This bricolage perspective also highlights opportunities for change. The way the national agricultural research systems (NARS) adapt the cocreation and non-linear innovation diffusion approach from CGIAR and NGOs enables the introduction of data-driven digital solutions and co-investment opportunities. NGO actors benefit from collaborating with knowledge partners to access contextualized portfolios of innovations that can be scaled. Practitioners, such as extension agents and lead farmers, gain tailored methods for delivering extension services and more practical, effective innovation scaling strategies and pathways. The institutional setup for adaptively scaling the fertilizer advisory at the national level, aligned with the delivery unit of the digital agriculture roadmap, is crucial for fostering adaptive governance in scaling digital solutions.

The institutional logic deals with enabling conditions in regulating the big data management, governance of innovation delivery services and partnerships and standardization of scaling protocols. On the other hand, the place-based adaptation refers to user tailored and site-specific services and strategies that adapt to local contexts and requirements. The scaling partner network platform that deals with horizontal and vertical scaling helps to ensure complementarity of upstream institutional and regulatory logics of sustainability and landscape-based adaptation of the innovation for inclusive economic and environmental benefits for segments of users.

The timing for scaling the landscape-based fertilizer advisory presents a unique opportunity due to several favorable conditions. Ethiopia has achieved notable progress in its digital agriculture roadmap, supported by government policies that promote innovation and technological adoption, along with private sector participation. Significant improvements in digital infrastructure, such as better internet connectivity and mobile coverage, are crucial for expanding digital solutions in agriculture. Moving forward, the focus will be on coordinating efforts among existing and new players in Ethiopia's digital space, reducing duplication, improving delivery channels, and extending advisory services to more farmers in new areas. Ongoing collaboration with local stakeholders, including smallholder farmers, ensures that the recommendations are based on local needs, practical considerations, and align with real-world requirements.

4.3. What should the science of scaling for landscape-based fertilizer advisory look like?

Schut et al. [11] provide valuable insights into the science of scaling for agricultural research and development. The authors define the science of scaling as "the design, testing, and validation of scientific theories, concepts, and methods to understand and guide the scaling of innovation to achieve societal outcomes." They emphasize the necessity of outcome-oriented scaling beyond mere technology adoption, positioning the science of scaling as a crucial approach for understanding and guiding scaling processes. Their study highlights three key research domains essential for practicing the science of scaling: (1) understanding the broader context of scaling innovation to develop more realistic ideas about the factors, conditions, and dynamics that influence both innovation and scaling processes; (2) developing tools to support efficient and responsible scaling, which includes new approaches, concepts, and instruments that facilitate evidence-based scaling strategies; and (3) establishing an enabling environment for scaling innovations that

focuses on institutional arrangements, partnership models, and mechanisms for monitoring and learning related to the scaling of innovations.

This paper presents a practical scaling process that integrates the science of scaling, explicitly focusing on the Fertilizer Ethiopia Use Case innovation. Developed and validated under specific local conditions, the case study highlights a practice-oriented approach guided by existing perspectives and the local context for innovation development and scaling. Supportive implementation methodologies and regular feedback mechanisms enhance the scaling process. Context-specific factors shape the relevant pathways and strategies, considering technology, knowledge, resources, and advisory services. The network of scaling partners and innovation platforms is crucial for stimulating demand and promoting technological and institutional innovations that facilitate scaling.

The study significantly contributes to the scaling literature but has a limited focus on the regional contexts of scaling. Future research is needed to better define and understand these contexts. Key questions for future studies include: What is the nature of the innovation being scaled, and at what scale? How are delivery and scaling implemented within National Agricultural Research and Extension Systems (NARES)? How can top-down and bottom-up approaches enhance scaling processes? Additionally, how can partners such as the government, private sectors, and NGOs harmonize resources and interests to support agricultural innovation? What scaling pathways are effective for different innovations and under what conditions? Lastly, how do extension service strategies and digital agriculture address the challenges of scaling?

4.4. What is a successful partnership for scaling landscape-based fertilizer advisory?

The landscape-based fertilizer advisory solution primarily targets smallholder farmers and extension agents as its main users. However, the demand analysis has revealed various prospective target groups, including decision-makers, non-governmental organizations, and research and academic institutions, each with specific interests in benefiting from the developed innovative solutions. Therefore, defining the scale of operations and identifying the types of relevant innovation services tailored to each target group is vital. This approach will help create a diversified and inclusive scaling pathway that remains relevant and sustainable over the long term.

During the piloting and scaling process, it is essential to address the interests of both partners and clients through various services and manage this using adaptive operational modalities within the scaling network. To meet the diverse demands of partners, a network of scaling partners was established at the agriculture office level, bringing together key stakeholders involved in the fertilizer and agronomy technology value chains. The partners share responsibilities for input delivery, research and advisory services, resource mobilization, capacity building, facilitating meetings and dialogue events, monitoring and evaluation, and extension services. This case study recognizes that an optimal partnership network is functioning successfully and is dynamic enough to align with evolving pathways and strategies for broader scaling.

4.5. Scalability of the landscape-based fertilizer advisory

Scalability of the fertilizer advisory solutions refers to the ability to effectively and efficiently expand the reach and impact of the solutions to a larger number of farmers, while maintaining their effectiveness and sustainability. Scalability of the fertilizer advisory entails aspects of the technology, operational services, financial mechanisms, and long-term impacts. This can involve increasing the number of users, the geographical area covered, or the scope of services offered, and influencing policy actions and long-term economic and environmental impacts. The scalability and sustainable delivery of the innovation can be enhanced when the digital solutions and scaling services meet the needs of different target users. The long-term viability of the fertilizer and agronomy advisory and its complementary innovations is recognized by the national scaling partners, who committed to implementing the scaling. The advisory solutions have been translated into a fifteen-year scaling delivery strategy [47].

Supportive policies and regulations are needed to facilitate the adoption and scalability of the landscape-based fertilizer innovation. To broaden the adoption of landscape fertilizer and nutrient management advisories, multistakeholder governance through public-private partnerships (PPPs) can leverage policy-level interventions to create a supportive environment, including incentivizing private sector participation, promoting knowledge sharing, and providing financial and technical support [47]. PPPs are increasingly used in agricultural innovation to leverage public funds, enhance efficiency, and improve the adaptation of innovation to demand to foster wider and faster diffusion [63]. The scaling practice involves public and private partnership pathways that are the key mechanisms in developing reliable delivery and governance by bridging the gap between the competencies of the public and private sectors. As outlined in detail in the scaling delivery strategy [47], the partnership governance is well aligned with the Digital Agriculture Extension and Advisory Services (DAEAS) strategy and the Digital Agriculture Roadmap (DAR) 2032 to leverage the policy and regulatory support services. The scaling practice has benefited greatly from the data governance and digital agriculture delivery units of DAR and the Decision Support Tools harmonization platform, constituting a multisectoral scaling partnership at national, subnational, and local levels. Hence, the scaling partners' network that deals with the horizontal and vertical scaling ensure complementarity of upstream institutional and regulatory logics of sustainability and context-based adaptation of the innovation for inclusive economic and environmental benefits for various segments of users. To ensure sustained investment in fertilizer and nutrient management advisory services, the private sector participation is incentivized with the facilitated input supply, regulations on innovation standards and use, data governance, research support for the development and adaptation of bundle of digital innovations suitable for local conditions, and monitoring and learning to track the progress and adaptation of advisory services.

To ensure sustainable scaling practices, examining the potential long-term environmental impact of widespread fertilizer use in Ethiopia's varied landscapes is crucial. While fertilizer application can boost crop yields, its overuse and improper application can lead to various ecological problems, including water pollution and emissions [64,65]. Ethiopia's diverse landscapes (from high-altitude to low-altitude) require tailored fertilizer management approaches to minimize environmental impacts. As the digital model development is built on economic and environmental optimization principles that considered nutrient use efficiency and landscape-dictated nutrient gradients, the scaling of landscape-specific fertilizer innovation proved to lead to potential economic and environmental impacts in the period of the piloting stage [4]. Moreover, the long-term environmental impact can be achieved through the integrated use of inorganic fertilizer with organic inputs and appropriate land use and land management practices [47].

In this scaling practice, farmers are advised to use a bundle of agronomic and fertilizer advisory tools that encourage the use of integrated inorganic and organic fertilizers, liming, crop rotation, cover cropping, and soil and water conservation practices that minimize nutrient losses [47]. This precision application reduces the excess application of nitrogen-based fertilizers, a major source of nitrous oxide (N_2O) emissions, which is approximately 298 times more potent as a greenhouse gas (GHG) than CO_2. This makes the innovation environmentally friendly. In addition, the packaging of the innovation includes liming as one component. In subsequent phases, other Integrated Soil Fertilizer Management innovations, such as crop rotation, farmyard manure, compost, mulching, vermicomposting, and double cropping will be added as complements. Therefore, this will further make the innovation environmentally sound. Nevertheless, the landscape-based fertilizer advisory tools provide farmers with locally specific fertilizer

recommendations based on landscape positions, soil type, climate, and crop need that optimize nutrient use. For example, the recent data-driven site-specific fertilizer application model by [66] showed that the N recovery efficiency can increase by 30 %, from the current average of 48 % to 78 %, using optimal combinations of nutrient (27 %), crop (6.6 %) and soil (0.6 %) management. This sustainable nutrient management approach, including integrated use of fertilizer with liming and organic inputs, indirectly mitigates emissions by improving soil carbon sequestration potential, as healthy soils can retain organic carbon more effectively. In addition, less reliance on blanket nitrogen applications reduces the risks of nitrogen leaching and runoff into water bodies, which can contribute to the reduction of indirect emissions of nitrous oxide from water systems.

5. Conclusion and policy implications

Agricultural production systems in Ethiopia face increasing threats from nutrient depletion, environmental degradation, climate change, and various socio-ecological risks. To meet the growing demand for improved productivity and nutritious food, it is crucial to implement and promote cost-effective, productive, and sustainable farming solutions. The Fertilizer Ethiopia Use Case, the focus of this study, has introduced a landscape-based fertilizer advisory solution. This innovation was analyzed using insights from agricultural innovation systems (AIS) through co-creation, involving contributions from farmers, extension agents, researchers, and broader scaling partners. The scaling process was driven by the specific needs of farmers and extension service providers, alongside the relevant socio-technical and institutional systems. Key considerations for the development, testing, validation, and scaling of the Use Case include engaging with the networks of scaling partners, hosting policy workshops, providing rigorous capacity building, and facilitating social media communities of practice.

In this case study, we aim to gain a better understanding of the context of scaling innovation on a large scale by ensuring integration both upstream and downstream within the framework of scaling out and scaling up strategies. Throughout the innovation development and delivery process, we conducted a demand analysis to consider the diverse perspectives and needs of target groups, identifying the drivers, pathways, and approaches to scaling. Consequently, we co-designed suitable combinations of scaling pathways (i.e., mechanisms) within the scope of the existing network of scaling partners. This approach helped us to achieve a clearer understanding of the innovation scaling process, integrating both upstream and downstream dimensions. The innovation scaling has delivered significant agronomic and economic benefits, ensuring farmers' continued adoption and scalability.

Feedback evaluations from end-users revealed that 86–94 % comprehended various aspects of the innovation, while 75–91 % have implemented it. Usability scores varied between 4.2 and 5.2 out of 7, and the net promoter score stood at 67 %. These results indicate that a majority of users feel confident recommending the advisory to other farmers. Nonetheless, the scaling process also unveiled several limitations regarding use case expansion, including gaps in knowledge and information, insufficient digital literacy and infrastructure, challenges in the supply chain for effective inputs, and a lack of evident demand for scaling via a market approach or business model for digital solutions. Through partner workshops, field experiences, and dialogues within current partner networks, strategies were identified and proposed to address these scaling challenges effectively. The objective is to facilitate a responsible transition from delivery to scaling through partnership networks and digital platforms, aiming to broaden the sphere of influence while improving productivity and environmental sustainability. In this regard, the sustainability of the scaling practice can be ensured with further efforts on scaling partner network analysis, transformative learning from various scaling pathways, and conducting trade-off analyses. The study also emphasizes key policy implications for creating, diffusing, and scaling digital agriculture solutions, such as co-creating digital agriculture strategies, developing and localizing digital content and services, enabling digital platforms and infrastructure, aligning digital agriculture services with extension services and governance, and monitoring and evaluating digital platforms and partner networks to improve the overall performance of the innovation system continuously.

CRediT authorship contribution statement

Gizaw Desta: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mequanint B. Melesse:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Murat Sartas:** Writing – review & editing. **Getachew Agegnehu:** Writing – review & editing, Investigation, Data curation. **Abiro Tigabie:** Writing – original draft, Investigation, Formal analysis, Data curation. **Gizachew Legesse:** Writing – review & editing, Investigation, Data curation. **Henok Desalegn:** Investigation, Data curation. **Tilahun Amede:** Resources, Conceptualization. **Mangi Lal Jat:** Writing – review & editing, Supervision. **Rebbie Harawa:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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