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A multi-criteria framework for scaling low-emission food systems innovations: a case study of Nandi County, Kenya

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Abstract

This study presents a framework for assessing the scalability of innovations aimed at achieving low-emission development, using a case study of Nandi County, Kenya. Food system emissions make up a significant portion of Kenya's total greenhouse gas emissions. Reducing these emissions is crucial for lowering the country's overall emissions, supporting Kenya's commitment to the Paris Agreement. To achieve this, Kenya must scale innovations that can transform the food system toward low emissions while meeting national development targets. The framework was thus tested, in the scope of two participatory workshops, on three CGIAR innovations with relevance to Nandi County: Improved Livestock Breeds and Feeds (ILBF), Integrated Aquaculture Practices (IAP), and Biogas Technology (BT). Stakeholders evaluated these innovations in a two-day participatory workshop using a multi-criteria scoring process. Based on established criteria, the participants developed scores that reflected an innovations' potential for scaling. ILBF scored 24 out of 33 points (75%), IAP scored 27 (81%), and BT scored 26 (76%). The results indicate varying potential for scaling among the innovations, highlighting the importance of context-specific and systemic enabling factors, beyond technical performance. These include institutional, social, and biophysical contexts, adoption barriers, market potential, costs of innovation, financial opportunities for scaling, environmental and social co-benefits and trade-offs as well as economic benefits, all of which are critical in creating an enabling environment for scaling. The framework serves as a support tool for evaluating potential opportunities, barriers, bottlenecks, and trade-offs to inform scaling strategies in a more systematic and responsible manner. Beyond its empirical findings, the study contributes methodologically by illustrating how participatory multi-criteria assessment can strengthen strategic decision-making for Agricultural Research for Development programs.

Introduction

The global food system is currently at a crossroads. Its adverse effects on planetary health are well known, yet it faces growing food demand within increasingly constrained conditions (Fraser and Campbell, 2019; Global Panel on Agriculture and Food Systems for Nutrition, 2020). To achieve emissions reductions while pursuing development objectives, it is therefore necessary to effectively scale innovations able to strengthen the sustainability of the food system while meeting national development targets (Li et al., 2014).

In agricultural research for development (AR4D), scaling initiatives typically begin with the goal of expanding a specific innovation or solution expected to drive positive change (i.e., emissions reductions) across extensive geographical areas (Woltering et al., 2024). Scaling efforts thus focus on how to systematically transition from initial farmer adoption in pilot projects to self-sustaining and widespread uptake of innovations (Chandy et al., 2013; Cooley and Kohl, 2016). However, for most food system innovations, the bottlenecks and opportunities for scaling exist not only in the innovation itself but in the non-technological factors that constitute the enabling environment for scaling (Van Loon et al., 2020b).

Scaling initiatives frequently face constraints—such as innovation costs, market access, and lack of capital, particularly in the case of women, among others—that impact their ability to equitably achieve positive outcomes across diverse social groups (McGuire et al., 2024; Schut, Leeuwis and Thiele, 2020). Although agricultural technologies and management practices can enhance the lives of adopters and contribute to climate change mitigation, these innovations may also entail significant environmental and socioeconomic trade-offs over the long term or when implemented at scale (Castro-Nunez et al., 2021). They can, for example, potentially lead to unintended harm or further marginalization of certain populations (Glover, Sumberg and Andersson, 2016; Schut, Leeuwis and Thiele, 2020; McGuire et al., 2024). Furthermore, while an innovation and intervention strategy may prove suitable and scalable in one context, it may not be in another context (Sartas et al., 2020). Thus, for effective scaling aiming to contribute to food system transformation, stakeholders should also evaluate innovations based on how they align with biophysical (Wigboldus et al., 2016), social, and institutional circumstances (Woltering and Boa-Alvarado, 2019) as well as the both economic and technological needs of a given context. These considerations for selecting innovations have often been either completely overlooked or only partially addressed in the scaling literature (Dossou-Yovo et al., 2024; Khatri-Chhetri et al., 2019; Wigboldus and Brouwers, 2016; Woltering and Boa-Alvarado, 2019). Additionally, in many Global South countries, where low-emission strategies in isolation are not necessarily prioritized, the environmental and social co-benefits of scaling innovations for low-emission food systems can motivate stakeholders and secure political support (Thornton et al., 2018).

Various approaches and methods have emerged within the food system sector to tackle the complexity of scaling, such as 'Scaling Readiness' assessments (Sartas et al., 2020), yet these often lack explicit attention to the non-technological factors that constitute the enabling environment for scaling, driven by institutional, biophysical, and social conditions, in practice (Van Loon et al., 2020b). This paper addresses this gap and presents a multi-criteria framework for assessing the potential of food system innovations to achieve low-emission development at scale (Fig. 1). This serves as a support tool for evaluating potential opportunities, barriers, bottlenecks, and trade-offs to inform scaling strategies. Using a participatory ranking methodology, stakeholders tested the framework for innovations relevant to Nandi County, Kenya. They applied the framework in a workshop, collaborative format, with diverse actors engaged in the local context. The method draws on transdisciplinary experts to answer reflective questions throughout the assessment process. Importantly, stakeholders should apply the low-emission strategy-focused framework early in the innovation process, even before a scaling ambition is defined. After a prioritization exercise, they assessed the potential of three CGIAR innovations for achieving low-emission development at scale: improved livestock breeds and feeds, integrated aquaculture systems, and biogas technology contribute to achieving Kenya's climate commitments outlined in its updated Nationally Determined Contributions (NDCs). These innovations not only align with Kenya's target to reduce greenhouse gas emissions by 32% by 2030 but also advance sustainable practices that bolster resilience in its food systems and promote the achievement of other sustainable development outcomes.

This paper is structured as follows. The 'Conceptual framework: The multi-criteria scaling assessment framework' section introduces

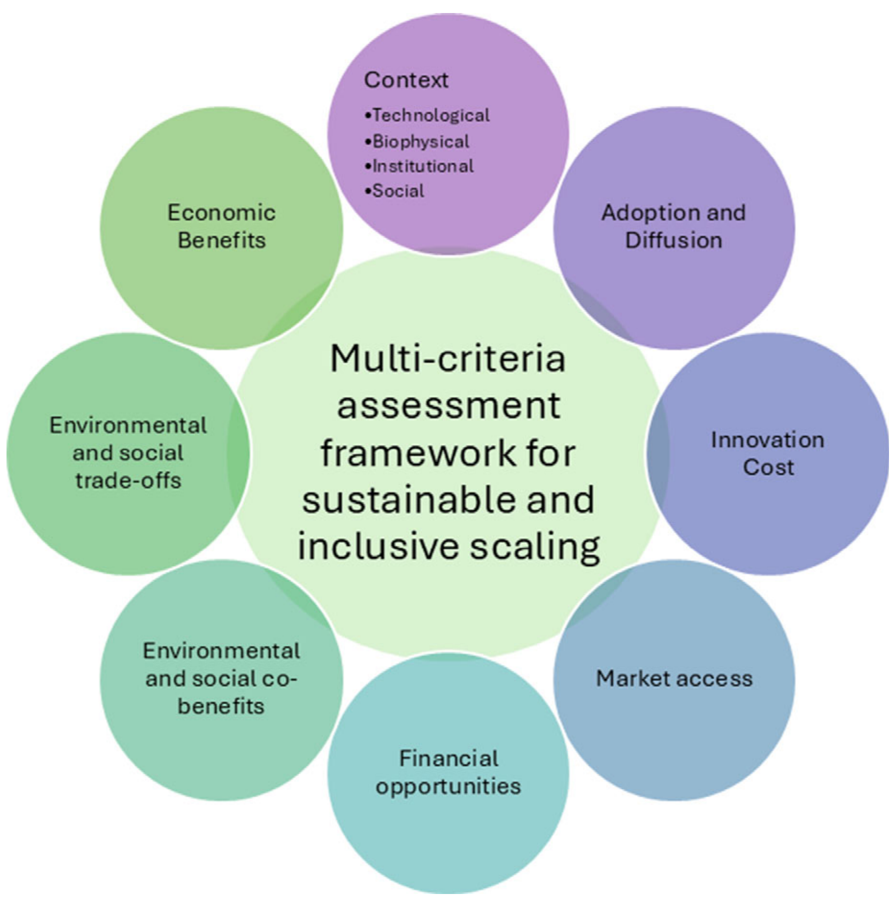

Figure 1. Eleven criteria of the multi-criteria assessment framework for sustainable and inclusive scaling. Each of the 'context' sub-criteria are accounted for individually and weighted equally.

the multi-criteria scaling assessment framework, with a literature review underpinning each criterion. The 'Case study' section provides background for the case study context, while the 'Methodology' section outlines the methodology applied. Within the Results section, the findings are clearly presented, while the Discussion section provides a thoughtful interpretation, highlighting key trade-offs and co-benefits. The conclusion section summarizes the key findings and opportunities for further research.

Conceptual framework: the multi-criteria scaling assessment framework

Many tools and approaches have been employed to prioritize innovations in agri-food systems, including simulation modeling (Shirsath et al., 2017), cost–benefit analysis (Kumar et al., 2018), economic surplus models (Stevanović et al., 2016), and integrated assessment modeling (Rosegrant et al., 2017). While these methods offer valuable insights, participatory methods are recommended because they incorporate expert and stakeholder perspectives before scaling, accurately reflect local or 'field' realities, and provide the flexibility to consider multiple variables and system objectives (Thornton et al., 2018). For instance, Khatri-Chhetri et al. (2019) used participatory approaches to evaluate innovations based on criteria such as adaptation benefits, adoption barriers, potential incentive mechanisms, and institutional support for scaling. Similarly, Dossou-Yovo et al. (2024) employed participatory methodologies considering factors such as productivity, income, climate change adaptation and mitigation potential, technology cost, technical feasibility, gender inclusivity, and market demand.

The multi-criteria assessment framework aims to support collaborative prioritization of innovations with high potential for inclusive and sustainable scaling to achieve low-emission development in food systems. It assumes that scaling innovations for low-emission food systems requires an integrated approach. The methodology promotes participatory evaluation with stakeholders embedded in the intended scaling context of innovations based on their suitability for the target context, their economic viability, and their environmental and social trade-offs and co-benefits, among others. By integrating these criteria, the framework provides rapid guidance to development practitioners and decision-makers. It helps relevant stakeholders co-evaluate innovations that can support transforming food systems through low-emission pathways while achieving sustainable development. The aim of this assessment framework is to guide developing an innovation's scaling strategy and gaining local insights that support it. The framework uniquely integrates the concept of environmental and social co-benefits and trade-offs into the scaling strategy, in line with responsible innovation approaches (Stilgoe, Owen and Macnaghten, 2013). Below, we present each criterion in detail and its basis in the literature (Fig. 1).

Context

Determining how well innovations can scale depends significantly on the political, business, social, and cultural context as well as their interactions—an idea encapsulated in the phrase 'context is king' (Woltering and Boa-Alvarado, 2019). In scaling for food system transformation, assessments of the contextualized 'innovation needs' are relevant for the identification of gaps and points of entry (Anandajayasekeram, 2016). Not only does there need to be a conducive technological environment, in terms of access to machinery and inputs (technological context), innovations for food system transformation also need to align with the climatic conditions, land, soil types, flora, and fauna of the target setting (biophysical context), especially at the agricultural production level (Shilomboleni and De Plaen, 2019; Westermann et al., 2018). Furthermore, they should align with the local and national regulations and laws to guarantee political support for scaling (political context) (Anandajayasekeram, 2016; Merrey, Loboguerrero Rodriguez and Zeppenfeldt, 2023; Minh et al., 2021). Since food systems have a strong link with the larger social system (social context), there is also a need to further consider these interlinkages when scaling innovations (Anandajayasekeram, 2016; McGuire et al., 2024; Minh et al., 2021; Shilomboleni and De Plaen, 2019). Scaling involves agency and decision-making in the household and the community and amongst stakeholder networks (McGuire et al., 2024). Schut, Leeuwis and Thiele (2020) thus call for a greater emphasis on the processes of learning, negotiation, and conflict resolution, practices that affect behavioral change and ultimately adoption and scaling of innovations (Schut, Leeuwis and Thiele, 2020). Whether or not an approach suits the local social context strongly affects the 'responsible' scaling potential. Focus on local context, for example, supports more inclusive approaches (McGuire et al., 2024). The four criteria that make up the 'context' are therefore technological, institutional, social, and biophysical (see 'Results' section).

Adoption and diffusion

In today's low- and middle-income countries (LMICs), current levels and patterns of innovation uptake are inadequate to facilitate the necessary transformations in food systems (Hambrey, 2017). For effective transformation to happen, food system innovations should be readily accepted or 'fit the system' (Woltering and Boa-Alvarado, 2019) to be dispersed among the target users. Adoption and diffusion are often slow. We cannot assume they will take place automatically if an innovation is introduced. Rather, to allow for effective adoption and diffusion, innovation efforts must analyze local perspectives on the barriers as well as the opportunities of adoption (Anandajayasekeram, 2016; Minh et al., 2021) identifying existing approaches and entrenched sociocultural practices that may hinder or enhance uptake. For example, there might be structural or normative constraints to adoption by different social groups (Rietveld et al., 2024). Furthermore, stakeholders may lack adequate access to required resources, such as machinery, inputs, and information, or they may lack decision-making power, as many women do in LMICs (Meinzen-Dick et al., 2012).

Innovation cost

The start-up, operational, and opportunity costs of innovations constitute a significant factor to be considered when scaling low-emission solutions for food system transformation (Merrey, Loboguerrero Rodriguez and Zeppenfeldt, 2023). Innovations need to be affordable and sustainable for end users beyond project time frames (Füller, Hutter and Kröger, 2021; Shilomboleni and De Plaen, 2019). Therefore, a participatory assessment by diverse end users should be conducted early on to anticipate affordability and willingness to pay (Olum et al., 2020). This will help stakeholders promoting an innovation to understand differing constraints faced by farmers, especially women, with varying resource limitations.

Market access

Potential market constraints need to be addressed when developing and scaling innovations for low-emission food systems to avoid

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negative prices and wage effects. Market systems can provide a built-in incentive for adoption at scale through the profit motive since the expectations of future profits encourage investment (Anandajayasekeram, 2016; Merrey, Loboguerrero Rodriguez and Zeppenfeldt, 2023; Minh et al., 2021). However, market systems also present one of the main bottlenecks for adoption in LMICs with limited formal market infrastructure (Jack, 2013). Infrastructural challenges also pose a threat to market access (Chamberlin and Jayne, 2013) as well as to the mobility of, in particular, women and vulnerable groups (Kihiu, 2020).

Financial opportunities

While farmers and other end users need access to innovations and to financial services, scaling low-emission innovations itself requires mobilizing a broad range of financial resources from public, private, international, and domestic sources. These funds are crucial for absorbing a significant portion of the scaling cost (Minh et al., 2021; Rosenstock et al., 2020). However, the burden of last-mile delivery costs—such as reaching farmers in remote areas, covering regulatory system costs for seed certification, and ensuring a steady supply from private vendors or agricultural input providers (agrovets)—is often overlooked in scaling strategies (Rosenstock et al., 2020). This oversight can lead to an overestimation of impact projections, without the so-called true cost accounting that also reflects (unintentional) environmental and social harm (Michalke, Kunz and Gaugler, 2025). Furthermore, project developers must ensure a viable 'exit strategy' for project-level implementation and ensure longer-term financing opportunities to allow for sustained use. Planning for financial considerations will enable innovations to continue being adapted and reach further geographies and more users beyond the scope of donor-funded or externally financed projects.

Environmental and social co-benefits

Identifying potential co-benefits of scaling innovations on the environment (land, water, air, and biodiversity) as well as on society (poverty, undernutrition, and inequality) can help to maximize the positive impacts of scaling (Anandajayasekeram, 2016). For example, Morales-Muñoz et al. (2022) examine the co-benefits of coordinating climate action and peacebuilding in two regions of Colombia. Their study focuses on the communal management of land and water resources and the restoration of ecosystems through climate- and conflict-smart agriculture. The authors find that communities can enhance social cohesion and promote peace initiatives by fostering climate action that intentionally facilitates dialogue on the sustainable management of natural resources.

Environmental and social trade-offs

Outcomes may be beneficial in one aspect (e.g., productivity or profit) but detrimental in others (e.g., biodiversity and gender equity) (Mausch, Hall and Hambloch, 2020). By examining the potential trade-offs and unintended negative downstream impacts of the innovation on both social and environmental dimensions (McGuire et al., 2024; Wigboldus and Brouwers, 2016), stakeholders can take measures to minimize unintended effects (Anandajayasekeram, 2016). McGuire et al. (2022) highlighted the need to apply unique gender and social considerations through ex-ante assessments to understand how innovations might unintentionally harm a group of people or be ineffective in achieving a social equity goal.

Economic benefits

Ideally, scaling innovations for food system transformation should improve general economic performance in that sector, increasing productivity and market development to ensure sustainability (Anandajayasekeram, 2016; Bachmann et al., 2016; Rosenstock et al., 2020; Shilomboleni and De Plaen, 2019). However, the extent to which innovations produce economic benefits is dependent on several intersecting dimensions, such as productivity increases, market access, or fit-for-purpose partnerships, and may not be felt equitably. These considerations call for inclusive and adaptive business models for climate-smart value creation (Rosenstock et al., 2020).

Case study

This study was embedded within the Low Emissions Food Systems Initiative (Mitigate+) of the global research partnership for a food-secure future (CGIAR) between 2022 and 2024, operating in Colombia, Kenya, Vietnam, and China (CGIAR, 2022). Nandi County in western Kenya was selected as a case study for applying the prioritization framework due it its diverse agricultural commodities and agroecological zones (Fig. 2). The priorities of Nandi County align with Kenya's national policy frameworks (Habermann and Zhang, 2022), including the Kenya Climate-Smart Agriculture Strategy (2017–2026), which specifically promotes livestock development.

In Kenya, emissions from the food system account for approximately 72% of the country's total emissions. Martius et al. (2023) highlighted two main priorities for action, in line with the national priorities identified in Kenya's latest NDC that commits Kenya to abate greenhouse gas (GHG) emissions by 32% by 2030 relative to the business-as-usual scenario of 143 Mt CO_2eq (Ministry of Environment and Forestry, 2020): (i) reduce emission intensities from enteric fermentation through improved management of livestock feed and manure on pastures and (ii) encourage climate-resilient food waste management.

Nandi County's food system is characterized by dynamic production systems, low-cost food processing, and a variety of food system actors (Jalang'o and Habermann, 2022). Biophysical drivers such as climate change, water scarcity, and soil degradation significantly impact Nandi's food system, with climate change effects, such as droughts, erratic rainfall, and floods, becoming increasingly common (County Government of Nandi, 2017). The location of Nandi County within Kenya is shown in Fig. 2.

The northern part of Nandi receives rainfall ranging between 1,300 mm and 1,600 mm per year, while the southern half is affected by the lake basin atmospheric conditions and receives rainfall as high as 2,000 mm per year. Annual temperatures range between 18 °C and 22 °C during the rainy season but can rise as high as 26 °C in the lowlands of the Nyando escarpment (County Government of Nandi, 2017). These conditions make the county suitable for a wide range of agricultural activities including livestock production. The national census in 2019 noted that Nandi is one of the highest-producing dairy regions in Kenya with 309,038 dairy cattle, representing about 10% of the national dairy herd, due to the favorable biophysical conditions.

Livestock production, practiced by more than 80% of households, is a major economic activity in Nandi, with semi-intensive dairy systems dominating and contributing significantly to GHG emissions (Jalang'o and Habermann, 2022). GHGs from soil, such as carbon dioxide and nitrous oxide, are also emitted during crop production. However, monitoring capacity limits specific data on GHG emissions for Nandi County (Jalang'o and Habermann, 2022;

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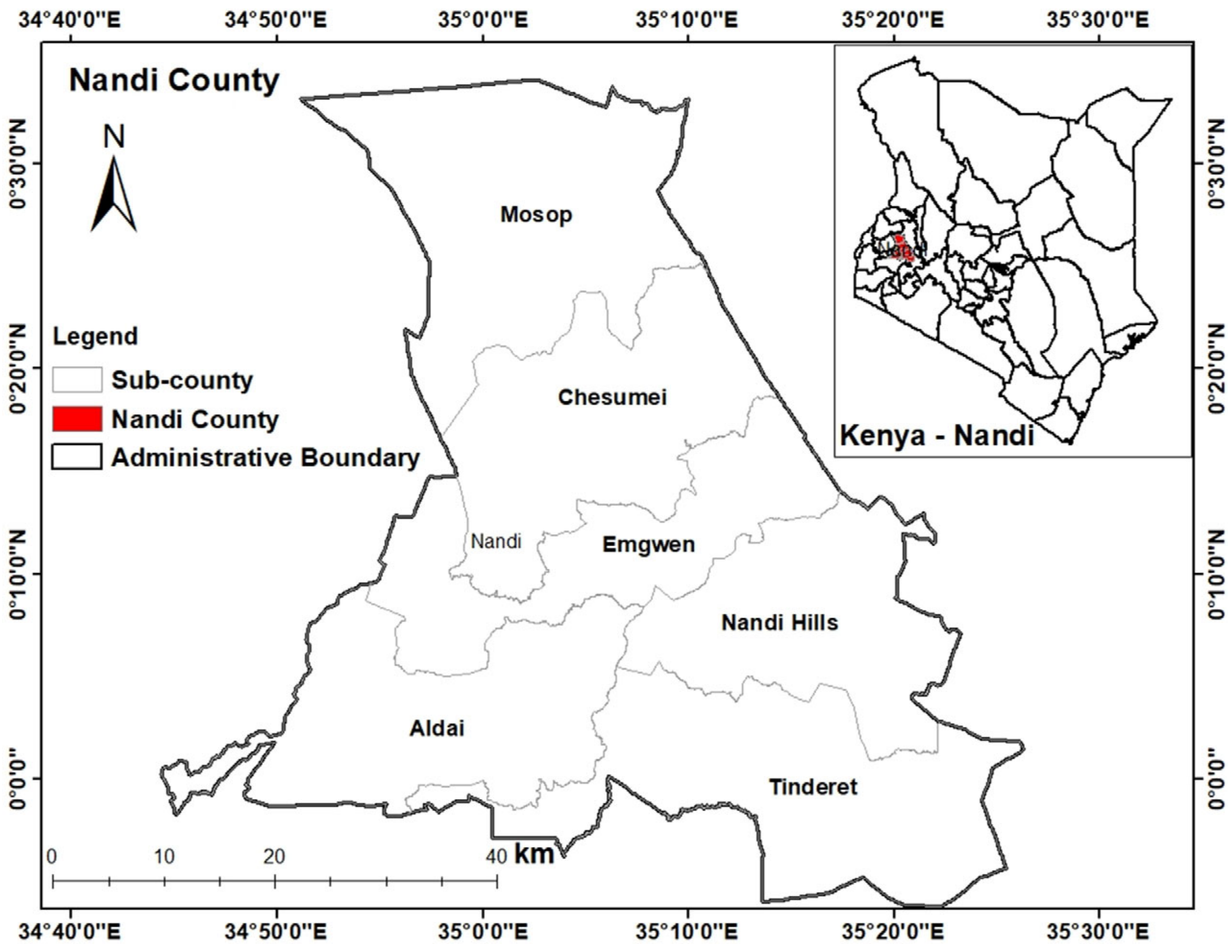

Figure 2. Location map of Nandi County in Kenya.

Oertel and Erasmi, 2016). Current reporting to the national government relies on production indices compiled from livestock and crop production reports from extension officers (Jalang'o and Habermann, 2022).

Methodology

Development of the framework for selecting innovations

The multi-criteria framework for assessing scaling potential and prioritizing innovations distinguishes itself from previous frameworks by incorporating environmental and social co-benefits and trade-offs as assessment criteria to contribute to the building of a scaling strategy. The framework uses 11 criteria to assess the enabling environment for scaling innovations and their potential to transform low-emission food systems. The literature cites similar approaches, such as the scaling scan tool that uses the 'scaling ingredients' for assessing the bottlenecks and opportunities for achieving a scaling ambition (Jacobs, Ubels and Woltering, 2018). While we recognize these are not exhaustive, they enable us to evaluate potential innovations for low-emission food system development.

Pre-selection of innovations for analysis

The study adopted the approach used by Khatri-Chhetri et al. (2019) for pre-selecting innovations for scoring. First, we surveyed scientists from several CGIAR organizations working on low-emission food systems. The survey yielded a list of 18 CGIAR innovations with the potential to reduce food system GHG emissions in Nandi County, originating from five CGIAR research centers: the Alliance of Bioversity International and CIAT, the International Maize and Wheat Improvement Center (CIMMYT), the International Livestock Research Institute (ILRI), the International Rice Research Institute (IRRI), the International Water Management Institute (IWMI), and WorldFish. Scientists were selected based on their research experience on low-emission food systems and were asked to suggest innovations based on three criteria: the food system GHG mitigation potential of the innovation, applicability in the Global South, and the likelihood of the innovation generating co-benefits if scaled.

From this list, three innovations or bundles of innovations were pre-selected by the research scientist working on low-emission food systems in Kenya and local government representatives from Nandi County. The selection was based on the GHG mitigation potential of the innovation or innovation bundle, their ability to deliver Sustainable Development Goal (SDG) co-benefits as well as their alignment with Kenya's and Nandi County's development goals. The selection of the innovation or innovation bundles were also based on their ability to contribute to the achievement of Kenyan government NDC. The selected innovations include improved livestock breeds and feeds (ILBF), integrated aquaculture practices (IAP), and biogas technology (BT). A brief description of the GHG reduction potential of these technologies is provided in Table 1.

Table 1. Description of the selected innovations with their GHG mitigation potential

Innovation	GHG reduction potential and other co-benefits	Source
Improved livestock breeds and feeds	Improved livestock breeds and feeds increase livestock productivity and can contribute to reduced emission intensity in livestock production systems. These innovations decrease the amount of GHG emitted per kilogram of meat and milk produced because they improve productivity and feeding and digestive efficiency.	Brandt et al., 2018, 2020; Wilkes et al., 2020
Integrated aquaculture practices	Dominated by multiple species such as shrimp, mud crab, milkfish, seaweed, and bivalves, IAP reduces waste through the utilization of existing resources. Organic wastes and by-products on and around the farm are recycled as much as possible as nutrient inputs to the pond and to other agricultural enterprises. Waste recycling functions as fertilizer, stimulating natural food webs that become the central catalytic component of the integrated aquaculture system.	Dey et al., 2010; Tran et al., 2023
Biogas technologies	Biogas digesters produce methane from manure that farmers can use as cooking fuel, reducing household demand for firewood. The manure residue from the biogas is used as fertilizer. Furthermore, biogas results in energy saving and reduction of household air pollution.	Arndt et al., 2022; Eipa et al., 2019

Data collection and analysis

Two participatory assessment workshops—held on December 7, 2022, and February 20, 2023—provided data for the study, in line with previous participatory approaches in the literature for prioritizing innovations for scaling (Jacobs, Ubels and Woltering, 2018; Khatri-Chhetri et al., 2019). The participants invited to the workshops were representatives of member organizations of the multi-stakeholder platform of climate-smart agriculture (CSA) in Kenya who had carried out field activities in the Nandi Country for at least 2 years. This specific audience was chosen for the exercise due to their expertise in CSA and food systems within the Kenyan context as well as their understanding of Nandi agri-food system dynamics and needs.

The stakeholders included representatives from Kenya's Ministry of Agriculture and Livestock Development, NGOs working on CSA, Nandi's local government, farmer associations, consumer protection organizations, universities, and local research organizations. Participants were invited as experts on the innovations being discussed during the scoring process. In total, the first workshop included 30 participants (of whom 13 were women), while the second included 28 participants (of whom 15 were women) from the Kenya CSA multi-stakeholder platform and research centers.

Participants were first introduced to the scoring framework. Subsequently, scientists delivered a presentation on each innovation, based on their direct involvement in the innovation's research and development. Key topics covered during the presentations included an overview of innovation, requirements, shortcomings, and an example of the innovation's implementation.

After each presentation, workshop participants were divided into two groups, each with a facilitator and a rapporteur from the workshop organization team. In these groups, the innovations to be scored were discussed in detail, following the criteria in the framework and the accompanying questions developed from the criteria. Stakeholders were asked to score the innovations, considering Nandi County as the target context for scaling the technology. They provided a score ranging from 0 to 3 for each criterion (Table 2). A score of 3 meant that the criterion was highly favorable for scaling, while 0 indicated unfavorable.

After the group discussion for each innovation, individual surveys were conducted with participants to obtain their perception of the relative importance (in percentage) of each criterion for scaling the low-emission food system innovations. The data collected was inputed into Microsoft Excel, and the average score per question, the average score per criterion, and the relative importance of each criterion for scaling the innovations was calculated. The reasons justifying each score, collected through qualitative responses, were compiled along with each criterion. In cases where the scores per question were less than 2, information on the necessary measures to ensure successful scaling was also solicited. The results of the workshops are complemented by a review of literature relevant to the potential of the innovations in Nandi County.

Results

Scoring results overview

The results of this study provide a comprehensive analysis of the potential of three CGIAR innovations to scale toward low-emission development in the food system within Nandi County, Kenya. Table 2 presents the findings from the scoring process, highlighting the average scores per criterion and perceived relative importance of each criterion to scaling. Here, we show that out of a total score of 33 points, ILBF obtained 25 out of 33 (75%), IAP 27 points (81%), and BT 26 (76%) (Table 2). We now provide quantitative and qualitative insights gathered from stakeholders for each of the criteria.

Assessing the conditions for sustainable scaling of CGIAR innovations in Nandi County

Technological context

The workshop participants identified the difficulty in accessing improved livestock breeds and fodder as a key barrier to scaling the ILBF innovation package, leaving the technological context with a low score (1.75/3). This is in line with previous reports from the Nandi County government (County Government of Nandi, 2017), which noted that key dairy production bottlenecks included inadequate feed availability, especially during the dry season, high infertility, and poor adoption of production technologies in livestock husbandry. With less than 1% of the animals under zero grazing (County Government of Nandi, 2017), the problem of available pasture becomes highly significant. Stakeholders also noted a lack of supporting or complementary innovations. They discussed that scaling ILBFs in Nandi requires more milk collection

Table 2. Results of the scoring exercise to identify potential innovations for food systems transformation based in Nandi County, Kenya

Multi-criteria for assessment	Improved livestock breeds and feeds		Integrated aquaculture production		Biogas technology	
	Relative importance to scaling (%)	Score given (3)	Relative importance to scaling (%)	Score given (3)	Relative importance to scaling (%)	Score given (3)
Technological context	10.35	1.75	7.74	2.25	9.18	2.25
Biophysical context	10.05	3	5.59	2.75	7.76	3
Institutional context	7.19	3	9.03	3	8.6	3
Social context	5.17	3	9.61	2.75	7.62	2
Potential adoption and diffusion	10.76	1.25	10.33	2.12	9.8	1.75
Technology cost	9.15	1.12	8.15	1.75	10.97	1.75
Market	11.85	3	11.74	3	8.24	3
Financial opportunities	10.94	2	12.29	2.5	9.16	1.5
Environmental and social co-benefits	6.65	2.25	9.07	2.87	10.74	2.5
Environmental and social Trade-offs	6.31	2.25	7.17	2	8.87	2
Economic benefits	10.87	2.25	9.27	2	9.06	2.5
Total	**100**	**24.83**	**100**	**27**	**100**	**25.67**

facilities and better milk collection systems, especially transportation systems. Therefore, to successfully scale this innovation, lead organizations must ensure equitable access to improved breeds and feeds and to information on their management as well as create a well-functioning milk collection system.

The results show that for IAP, the technological context of Nandi had a mid-high score (2.25/3). Nandi County lacks supporting technologies needed to scale IAP, such as fingerlings, storage support, transportation, and drying facilities. According to stakeholders, aquaculture farmers can bypass these barriers by forming cooperatives through which they can ensure the availability of these services.

For BT, participants noted that although there was an urgent need for the innovation, Nandi County has limited supporting technologies and services available after deploying the BT technology. These complementary services and technologies are crucial for biogas users. As a result, this innovation also received a mid-high score for this criterion (2.25/3). The supporting technologies and services include biogas chambers as well as repair and maintenance facilities within the county. This finding aligns with another study which noted that inadequate post-installation support and a lack of sufficient technicians and artisans are factors restricting the adoption of biogas technology in Nandi, despite the county's great potential (ETC Group, 2017).

Biophysical context

The biophysical context received a high score (3/3) for the ILBFs innovation package, indicating that the technology is well-suited to the biophysical environment in Nandi County. Most parts of the county receive substantial rainfall (>1,200 mm), yielding favorable biophysical conditions for the innovation.

This criterion received a high score (2.75/3) also for IAP. Nandi County, with its 8 dams and 12 major rivers, has significant potential for fish farming and fishing (County Government of Nandi, 2017). However, this potential remains untapped due to the substantial investment and capital required for boats, harvesting gear, and skilled personnel (County Government of Nandi, 2017). For BT, the biophysical environment of Nandi is highly suitable due to high livestock rearing and availability of cow dung (the main feedstock for biogas digesters). The livestock sector is crucial in Nandi, contributing to more than 94% of enteric methane production (Ndung'u et al., 2018), thereby making biogas technology a suitable measure for reducing methane emission at the household level.

Institutional and social context

The institutional and social context for ILBF received the highest score possible (3/3). The ILBF innovation package aligns well with the county's policies and fits seamlessly with the cultures and lifestyles of potential adopters. An example of such a policy is the Kenya Climate-Smart Agriculture Strategy (2017–2026), which promotes livestock development in Nandi County and across the country. The ownership of cows plays a significant role in Nandi culture. Productivity gains associated with ILBF attract livestock keepers to this innovation (Ndung'u et al., 2018).

The high score (3/3) for IAP indicates that existing laws and policies support this innovation. Respondents noted that the Kenyan government has promoted IAP in various ways, such as including IAP in national climate action plans and training youths in aquaculture management to enhance fish production. Hambrey (2017) also noted that the government of Kenya is supporting improved production efficiencies and the reduction of post-harvest losses. Workshop participants identified the social setting of Nandi County as favorable for scaling, with a score of 2.75/3. However, respondents indicated the need to consider cultural differences in fish consumption within the county.

The national and Nandi County governments promote biogas, indicating favorable institutional conditions (3/3) for BT innovations. One notable initiative is the creation of the national biogas program by the Kenyan government. According to stakeholders, BT aligns with Kenya's NDCs and the National Climate Change Act. BT is also supported by Kenya's Climate-Smart Agriculture Strategy and is listed in the national climate change policy.

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However, stakeholders noted that the technology is not socially appealing. Farmers face challenges in transporting cow dung from grazing spots to processing facilities, with limited resources available for zero grazing. Additionally, there is limited social acceptance of the technology among men, posing a problem to its implementation.

Adoption and diffusion

This study found that the potential adoption and diffusion of ILBFs is unfavorable, receiving a low score of 1.75 out of 3. Contributing factors to this score include a lack of expensive technical support and limited access to new breeds and fodder. Although platforms such as DigiFarm and DigiCow provide digital access to information on farm inputs and cow management, they either ignore the specific needs of ILBFs or have limited reach (Jalang'o and Habermann, 2022). Furthermore, improved livestock breeds often require artificial insemination, which is expensive and labor intensive (Jalang'o and Habermann, 2022). To overcome these adoption barriers, stakeholders emphasized the need to increase the number of farmer cooperatives to raise funds and facilitate capacity building. This approach can help disseminate improved breeds and information on optimal feeding practices more effectively.

The potential adoption of IAP was found to be low, with a score of 1.25 out of 3. Workshop participants said the low score is due to several factors, including limited capacity for implementing IAP, lack of access to (organic) feeds, low awareness about the technology, high initial investment capital, and limited market linkages. Addressing these challenges requires the provision of extension services and the implementation of financial mechanisms for scaling, such as low-interest loans and grants.

The widespread adoption of biogas as cooking fuel and lighting could significantly reduce GHG emissions and alleviate energy poverty. However, the initial cost of constructing biogas units remains a major barrier to widespread adoption (Mwirigi et al., 2014). Stakeholders highlighted that the adoption potential of biogas technology is relatively low, with a score of 1.75 out of 3, particularly among young people who perceive the maintenance process as difficult and aesthetically unappealing. Similar findings were noted in Kiambu County by Wamuyu (2014). Another factor hindering biogas adoption in Nandi is the need for customized cooking stoves, which adds to the financial burden since households willing to adopt biogas technology must purchase these specialized stoves. However, stakeholders also pointed out that the provision of slurry from biogas digesters, which serves as a source of bio-fertilizer, is a co-benefit that motivates household adoption.

Innovation cost

The cost criterion for the ILBF innovation received a low score of 1.125 out of 3. Stakeholders perceive the cost of purchasing new breeds and improved feeds to be high for the average farmer in Nandi. Factors contributing to the high start-up costs include the expenses for purchasing semen, seeds for fodder, and extension services. Practicing zero grazing may bring unfavorable trade-offs, including difficulties to allocate land for feed crops. Ongoing managerial costs also add to the burden, including maintenance of fodder, harvesting, labor for feeding and milking, veterinary services, irrigation, and processing.

Currently, livestock keepers apply zero grazing to less than 1% of animals in the country. They graze 75% of animals in the county on natural pasture, with the remaining animals partly grazed and partly housed (Jalang'o and Habermann, 2022). Additionally, dairy cows in the county consist mainly of exotic breeds (Friesians and Ayrshire) and their crosses with local breeds, which aligns with the views of stakeholders in this study. Respondents identified the use of government subsidies and increased mechanization as potential solutions to reduce start-up and operational costs. According to the County Government of Nandi (2017), dairy production can be doubled with adequate investment, as it is currently far below its potential.

Stakeholders also noted the expensive IAP startup costs for the creation of ponds, purchasing feed, fingerlings, and providing energy. Operational costs, such as maintenance, labor, and feed purchases are also unaffordable for many people, explaining the low score of 1.75/3. This finding is consistent with the findings of Tran et al. (2023), who also observed a high initial cost of implementation, which may be challenging for small-scale farmers to afford. Additionally, Tran et al. (2023) noted a lack of technical expertise and infrastructure to support the use of IAP technologies.

Participants also noted the high cost of BT, at $600–$900 per household, making it less affordable for lower-income households. This is consistent with other studies in the literature (Mwirigi et al., 2014; Nguu et al., 2014; Patman and Moronge, 2015; Wachera, 2009), which have reported high initial installation costs as a major hindrance to adoption. To overcome these challenges, stakeholders highlighted the need to explore other financial mechanisms, such as incentives, subsidies, extension of loan facilities to small-scale farmers, and social investments, to aid in the scaling of this innovation.

Market access

The 'availability of markets' criterion received a high score (3/3) for the ILBF innovation package, indicating that markets for milk and beef are highly accessible in this context. According to the County Government of Nandi (2017), both Nandi County and Kenya are high consumers of dairy products. For instance, milk is sold through both formal and informal markets. In informal markets, milk is sold to intermediaries, brokers, milk hawkers, urban center consumers, and other farmers or hotels. In formal markets, milk is marketed through farmer organizations.

The markets for IAP products are also promising, with stakeholders awarding a full score of 3/3. Respondents reported a high demand for fish in Kenya, and the government promotes fish markets through sensitization campaigns on fish consumption. The market for biogas remains strong in Nandi (3/3), as cooking energy and organic fertilizer are in high demand, especially in rural and peri-urban areas. However, the limited supply of materials and their costs are factors that restrict the potential market value.

Financial opportunities

Smallholder farmers seeking to purchase improved breeds and seeds face a significant bottleneck in access to low-risk financing options as well as to entering into service provider arrangements. The financial opportunities for scaling ILBF recorded a mid-score of 2 out of 3. Finance is crucial for scaling technologies, especially among smallholder farmers. When finance is absent, scaling technologies among these farmers becomes difficult. Bisheko and Rejikumar (2023) also noted the lack of access to finance as one of the barriers to scaling innovations in Sub-Saharan Africa and Asia. Similarly, Van Loon et al. (2020a) reported that farmers had low access to finance for scaling agricultural innovations in Zimbabwe and Mexico. To overcome financial challenges for scaling, stakeholders identified the need for governments, international donors, and private finance schemes to subsidize the scaling of innovations or provide loans for scaling high-risk innovations.

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For scaling IAP (2.5/3), stakeholders noted that financial opportunities exist through loans from government agencies, programs, donors working on low-emission development, and the private sector. But these opportunities remain underexplored. For BT, stakeholders highlighted the need to explore other financial mechanisms, such as incentives, subsidies, extending loan facilities to small-scale farmers, and attracting social investors to aid in scaling this innovation. However, the possibility of leveraging finance from these sources and other external funding is low, which explains why financial opportunities received a mid-high score of 2.5 out of 3. Despite the availability of various financial mechanisms, there is a need for sensitizing farmers, as stakeholders believe that many in the sector are unaware of these different streams of income for scaling.

Environment and social co-benefits

Co-benefits have become a major topic in climate mitigation discourse and are often cited in climate-related decision-making as factors that can significantly influence the outcomes of direct cost–benefit evaluations (Intergovernmental Panel on Climate Change, n.d.). The criteria for environmental and social co-benefits received a score of 2.25 out of 3 for ILBF. The potential of improved fodder to trigger carbon sequestration and reduce per-unit GHG emissions from dairy production were identified as environmental co-benefits. A social co-benefit noted was the anticipated increase in income due to the increased production of milk and meat, leading to improved living standards.

IAP recorded a high score of 2.85 out of 3, with several environmental and social co-benefits identified. These include the potential to reduce resource use, such as water and fertilizer, diversification of income sources for adopters, and improved nutrition. According to Hambrey (2017), aquaculture can help offset GHG emissions through carbon sequestration.

BT has many co-benefits, such as the conservation of forests through reduced logging as a source of fuelwood, reduction in GHG emissions, and soil conservation through fertilizer application. Stakeholders also noted that this innovation has the potential to reduce conflicts between households, as they will not have to compete over wood fuel for cooking. This aligns with the findings of Jain et al. (2019), who reported that biogas technology offers environmental and social co-benefits such as climate change mitigation, contribution to a circular economy, and improvement in health and sanitation through better solid waste management.

Environmental and social trade-offs

When determining an optimal mitigation measure to limit GHG emissions (Verspecht et al., 2012), stakeholders should consider both potential ‘winners and losers’. Trade-offs that might arise when scaling ILBF include the prevalence of insects and the use of chemical sprays in fodder, the risk of water scarcity due to livestock intensification, and the potential loss of local, more-resilient breeds. For IAP, stakeholders noted that introducing fish species might negatively impact native species in rivers. The workshop participants also highlighted some environmental and social trade-offs with scaling BT, such as the disruption of social interactions during activities such as firewood fetching and the aesthetically unappealing process of managing biogas digesters. Scaling organizations must be aware of these trade-offs to maximize the positive impacts and minimize the unintended consequences of scaling on lives, livelihoods, and the environment in Nandi. The average score across all three innovations for this criterion was 2 out of 3.

Economic benefits

This criterion received a score of 2.25/3 for ILBF. According to participating stakeholders, while the adoption of ILBF production may not necessarily reduce production costs, productivity is likely to increase. However, many factors affect productivity and profits, such as farm management, scale of production, and business models, which were not examined in the survey. Therefore, an in-depth study of the factors affecting profit margins is needed before drawing conclusions about the economic benefits of innovation.

Stakeholders further anticipated high IAP returns as economic benefits of scaling, due to increased productivity and the potential rise in employment. However, they indicated a need for detailed risk evaluation and cost–benefit analysis before implementing the technology. The economic benefits of BT were perceived by stakeholders as high (3/3). The ability of BT to save time and replace inorganic fertilizer and firewood, which appear to be cheaper, were highlighted as key benefits. Stakeholders also noted that project promoters of anaerobic digestion can obtain additional funding from carbon credits by using appropriate monitoring, verification, and reporting methodologies to demonstrate the GHG mitigation potential of the technology.

Our findings indicate that for ILBF, the demand (availability of a market) for the product promoted by the innovation was rated by participants as having the highest relative importance to scaling (11.85%), while social context was given the lowest relative importance (5.17%). This disparity suggests a need for greater awareness among partners regarding the significance of understanding ‘for whom’ scaling is pursued and highlights the importance of expanding the use of social suitability studies. For IAP, financial opportunities for scaling were rated the highest (12.29%), while the biophysical context received the lowest score (5.59%). This underscores the need to identify bankable business models for IAP. For BT, technology cost was rated the highest in relative importance (10.97%), while social context, once again, received the lowest rating (7.62%).

Discussion

The role of context-specific non technological factors

The participatory assessment used in this study highlights that non-technical dimensions play a decisive role in shaping the scalability of agricultural innovations. For the innovations considered in our study, ILBF obtained a score of 24 out of 33 (75%), IAP obtained 27 points out of 33 (81%), and BT 26 out of 33 (76%) reflecting their scalability potential. These outcomes offer insights into the enabling conditions required and adjustments needed for scaling these technologies effectively ILGF, IAP and BT Innovations which demonstrated strong biophysical suitability and mitigation potential were constrained by high cost of implementation, limited access to finance and perceived limited acceptance, reducing their scalability potential despite favorable agronomic indicators.

These findings support systemic accounts of agricultural scaling that technological performance alone is insufficient to predict scaling success, and rather that scaling depends much more on perceived complexity and ‘enabling conditions’ such as governance, social norms and economic structures, than only on the innovation itself (Brouwers, 2016; McGuire et al., 2024; Thornton et al., 2018; Wigboldus et al., 2016; Woltering et al., 2024). For instance, Khatri-Chhetri et al. (2019) focused on adaptation benefits, barriers to adoption, potential incentive mechanisms, and institutional support

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for scaling. Similarly, Dossou-Yovo et al. (2024) emphasized productivity, income, climate change adaptation and mitigation potential, technology costs, technical feasibility, gender inclusivity, and market demand as key factors. Merrey, Loboguerrero Rodriguez and Zeppenfeldt (2023) underscored the importance of mission-oriented communication systems, strong partnerships (local, national, and international), supportive policies and institutions, access to financing, and market demand as essential components of the enabling environment for scaling. Although these factors may vary slightly between studies, they all underscore the need to understand the specific contextual realities where the innovation is being scaled. This idea is further supported by Woltering and Boa-Alvarado (2019) who reiterate the importance of considering context-specific factors for the success of any scaling venture.

The analysis further reveals that policy frameworks and institutional incentives create both enabling and constraining conditions for innovation uptake. In Nandi, innovation alignment with county development strategies and existing agricultural programs such as the Kenya Climate-Smart Agriculture Strategy (2017–2026), Kenya's NDCs and the National Climate Change Act facilitated stakeholder buy-in and coordination, while gaps in limited public financing mechanisms were perceived to slow implementation. Cultural norms and livelihood priorities also influenced adoption dynamics, particularly where innovations required changes in household labor allocation, gender roles, or consumption practices. Socio-economic factors such as land tenure security, access to credit, and farmers' risk tolerance emerged as critical determinants of investment willingness and sustained adoption. Together, these non-technical factors shape not only whether innovations are adopted, but also who benefits, at what scale, and under what conditions, raising important equity and inclusiveness considerations for scaling strategies.

Importantly, the application of a multi-criteria assessment framework generated insights that would not have been captured through economic methods of innovation assessment such as a conventional cost–benefit analysis. A conventional cost–benefit analysis in Nandi may prioritize short-term financial returns like productivity gains and input–output efficiency, favoring technologies with rapid 'payback'. However, this only offers a partial view because it assumes stable institutions and uniform farmer behavior, overlooking structural constraints, inequality, gender and distributional effects, environmental externalities, governance feasibility in a complex smallholder system (Klerkx, Van Mierlo and Leeuwis, 2012; Wigboldus et al., 2016; van Wijk et al., 2020). By contrast, the multi-criteria framework enhances investment and policy decisions by integrating economic, social, institutional, environmental, and governance factors. It reveals hidden adoption barriers, supports trade-off analysis between short-term profitability and long-term sustainability, and guides complementary interventions.

The value of accounting for co-benefits and tradeoffs for sustainable food system transformation

A key contribution of this paper is the assessment of environmental and social co-benefits and trade-offs, which are often overlooked in the food system innovation scaling literature (Morales-Muñoz et al., 2022). Organizations need to actively consider these co-benefits in each scaling effort to maximize positive impacts on livelihoods, ecosystems, and communities in the target areas, thus promoting more responsible scaling (McGuire et al., 2024). In the broader context of climate change mitigation, particularly within low-emission food systems, co-benefits have become a focal point and are frequently emphasized in climate-related decision-making, as they can significantly influence the outcomes of traditional cost–benefit analyses (Intergovernmental Panel on Climate Change, n.d.). By incorporating a co-benefits approach when scaling low-emission food system innovations, stakeholders can adopt a holistic framework that not only supports ambitious climate mitigation policies but also addresses non-climate objectives simultaneously. Therefore, it is essential for any scaling initiative to understand the co-benefits of low-emission food system innovations. Doing so will help build a robust knowledge base, facilitate more effective mitigation strategies, and identify synergies with other development outcomes (Cohen et al., 2021).

Furthermore, not all scaling efforts result in positive outcomes (Herrero et al., 2020). In some cases, scaling can lead to unintended consequences for environmental and social systems (Castro-Nunez et al., 2021; Mausch, Hall and Hambloch, 2020). Our study demonstrates that while the evaluated innovations represent key breakthroughs in Nandi's food system, they can also generate significant trade-offs and unintended negative impacts on other SDG indicators in the region, such as increased poverty, reduced social inclusion, rising inequality, and challenges in healthcare, among others. These trade-offs and unintended consequences must be carefully addressed to achieve genuine food system sustainability.

Limitations

Conducting this study was not without its challenges and limitations. One of the key difficulties encountered was the perceived complexity of the numerous criteria involved. The assessment framework has 11 criteria, each of which can be interpreted in multiple ways and depends on the availability of technical expertise and sufficient contextual information as shown in section 'Conceptual framework: The multi-criteria scaling assessment framework'.

While the study provides valuable insights into the potential of these innovations to contribute to low-emission food systems and future scaling efforts, it offers only a snapshot of opinions and interpretations that may evolve over time. Adoption behavior, institutional capacity, climate risks, market incentives, and policy frameworks evolve over time. This means that future changes such as improved extension services, new subsidies, climate shocks, or market shifts could alter the feasibility and attractiveness of innovations in ways not captured by the current analysis.

Furthermore, the workshop relied on secondary data presented and contributions to scalability, limitations and trade-offs discussed by the workshop participants were anecdotal or based on their expertise in similar locations. Although structured facilitation and triangulation reduce bias, personal experience, institutional interests, as well as group dynamics may still have influenced scoring outcomes. This bias introduces uncertainty and means that results reflect informed, though subjective perspectives rather than purely objective measurements. As a result, certain indicators rely more heavily on qualitative assessment rather than robust statistical validation. The results should therefore be complemented by formal analyses, such as through foresight studies and scenario modelling.

Also the pre-selected innovations by a group of scientists and local government representative from Nandi County prior to the workshop may differ from the innovation that would be selected by other stakeholders in Nandi County. It is thus critical to ensure that the needs and preferences of intended users are accounted for early in the design process, rather than only at the final stages of delivery, which may be too late to adjust significantly and ensure sustained adoption.

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Lastly, the analysis focuses on one geographical and institutional context (Nandi County, Kenya). While this allows for deep contextual understanding, the results may not automatically apply to other regions with different agro-ecological conditions, market access, cultural norms, governance systems, or policy environments. Adoption barriers, institutional readiness, and economic viability may differ substantially elsewhere, so the findings should be interpreted as context-specific rather than universally representative. The framework therefore needs to be seen as adaptable to local contexts.

Conclusion

This study demonstrates the value of applying a participatory multi-criteria framework to assess the scalability of agricultural innovations beyond technical performance alone. By systematically incorporating institutional, policy, socio-cultural, financial, markets and environmental dimensions, the approach provides a more realistic understanding of the enabling conditions and constraints that shape scaling pathways in complex food systems. Applying the framework, we aimed to identify the key conditions for facilitating the scaling of selected CGIAR innovations (ILBF, IAP, and BT) toward achieving low-emission food system transformation and sustainable development in Nandi County, Kenya. The case of Nandi County illustrates that innovations with strong technical potential may face significant barriers related to context specific institutions, policy, socio-cultural, financial, markets or even environmental dimensions.

The study concludes that significant scaling challenges stem from both technological and non-technological factors shaping the enabling environment for these innovations. Overall, our findings thus position 'scaling' less as a linear process of dissemination (Rogers, Singhal and Quinlan, 2014), and more as a system-building challenge, where technological performance must be matched by institutional capacity, affordability pathways, and socio-cultural fit for adoption to become durable (Wigboldus et al., 2016). This approach improves strategic alignment with enabling conditions and societal priorities, increasing the likelihood of inclusive, scalable, and durable outcomes (Geels, 2004; Hermans et al., 2017; Thornton et al., 2018).

Beyond its empirical findings, the study contributes methodologically by illustrating how participatory multi-criteria assessment can strengthen strategic decision-making for AR4D programs. Compared to conventional cost–benefit approaches, the framework enables the identification of trade-offs, distributional impacts, and institutional feasibility considerations that are critical for responsible and sustainable scaling (Ewell et al., 2025, submitted; Woltering et al., 2024). However, this approach also instroduces methodological challenges, including the subjectivity of scoring, the need for facilitation capacity, and potential variability in stakeholder perceptions, highlighting the importance of transparent processes and complementary analytical tools. While the approach requires careful facilitation and transparency to manage subjectivity, it offers a replicable pathway for integrating diverse stakeholder perspectives into innovation prioritization and investment planning.

To ensure these findings reflect the practical realities, further on-the-ground technical feasibility studies and validation workshops with a broader, and more localized audience are essential. This will help to address critical issues within the enabling environment for scaling and determine how these issues can be effectively managed. By integrating this framework early in the scaling process and engaging a diverse group of stakeholders, we can effectively capture their perspectives on the technological and non-technological factors that shape the contextual enabling environment. This approach is especially crucial in contexts like Nandi County and the broader Global South, where innovations aimed at reducing emissions often receive limited support from stakeholders. Furthermore, these stakeholders, as intended users and practitioners, should be engaged throughout the innovation development, piloting and delivery process (Ewell et al., 2025, submitted). Future applications across different value chains and geographic contexts can further refine the framework and support the development of coordinated, inclusive, and climate-aligned scaling strategies to support both low-emission and development-oriented agri-food system transformation.

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References

Anandajayasekeram, P. (2016) 'Scaling up and scalability: concepts, frameworks and assessment', *Vuna Research Report.* Pretoria: Vuna [Online]. Available at: http://www.vuna-africa.com.

Arndt, C., Hristov, A.N., Price, W.J., McClelland, S.C., Pelaez, A.M., Cueva, S.F., Oh, J., Dijkstra, J., Bannink, A., Bayat, A. R., Crompton, L. A., Eugène, M. A., Enahoro, D., Kebreab, E., Kreuzer, M., McGee, M., Martin, C., Newbold, C. J., Reynolds, C. K., Schwarm, A., Shingfield, K. J., Veneman, J. B., Yáñez-Ruiz, D. R. and Yu, Z. (2022) 'Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 C target by 2030 but not 2050', *Proceedings of the National Academy of Sciences*, **119**(20), e2111294119.

Bachmann, E., Natcher, D., Kulshreshtha, S., Baco, M.N., Akponikpe, P.B.I. and Peak, D. (2016) 'Profitability and institutional constraints to the adoption of fertilizer micro dosing in Northwest Benin', *Sustainable Agriculture Research*, **5**(3), p. 11.

Bisheko, M.J. and Rejikumar, G. (2023) *Major barriers to adoption of improved postharvest technologies among smallholder farmers in sub-Saharan Africa and South Asia: a systematic literature review*. World Development Sustainability.

Brandt, P., Hamunyela, E., Herold, M., De Bruin, S., Verbesselt, J. and Rufino, M.C. (2018) 'Sustainable intensification of dairy production can reduce forest disturbance in Kenyan montane forests', *Agriculture, Ecosystems & Environment*, **265**, pp. 307–319.

Brandt, P., Yesuf, G., Herold, M. and Rufino, M.C. (2020) 'Intensification of dairy production can increase the GHG mitigation potential of the land use sector in East Africa', *Global Change Biology*, **26**(2), pp. 568–585.

Brouwers, J. (2016) *Theory of scaling towards a structured approach to support responsible scaling of innovations in the context of agrifood systems to guide decision making Seerp Wigboldus using a* [Online]. Available at: www.theoryofchange.nl/resource/using-theory-scaling-guide-decision-making.

Castro-Nunez, A., Buriticá, A., Gonzalez, C., Villarino, E., Holmann, F., Perez, L., Del Río, M., Sandoval, D., Eufemia, L., Löhr, K., Durango, S.,

Romero, M., **Lana, M.**, **Sotelo, S.**, **Rivera, O.**, **Loboguerrero, A.M. and Quintero, M.** (2021) 'The risk of unintended deforestation from scaling sustainable livestock production systems', *Conservation Science and Practice*, **3**(9). https://doi.org/10.1111/csp2.495.

CGIAR (2022) 'Mitigate+: low-emission food systems'. *Brief* [Online]. Available at: https://cgspace.cgiar.org/server/api/core/bitstreams/afa30345-aa37-47ef-bd56-5796d57ae888/content.

Chamberlin, J. and Jayne, T.S. (2013) 'Unpacking the meaning of 'market access': evidence from rural Kenya', *World Development*, **41**, pp. 245–264.

Chandy, L., **Hosono, A.**, **Kharas, H. and Linn, J.** (2013) *Getting to scale: how to bring development solutions to millions of poor people*. Brookings Institution Press, Washington, DC.

Cohen, B., **Cowie, A.**, **Babiker, M.**, **Leip, A. and Smith, P.** (2021) 'Co-benefits and trade-offs of climate change mitigation actions and the sustainable development goals', *Sustainable Production and Consumption*, **26**, pp. 805–813.

Cooley, L. and Kohl, R. (2016) *Scaling up—from vision to large-scale change: a management framework for practitioners*. 2nd edn. Washington, DC, USA: Management Systems International (MSI).

County Government of Nandi. (2017) *County integrated development plan (CIDP) 2013–2017*. Kapsabet, Kenya: County Government of Nandi.

Dey, M.M., **Paraguas, F.J.**, **Kambewa, P. and Pemsl, D.E.** (2010) 'The impact of integrated aquaculture–agriculture on small-scale farms in Southern Malawi', *Agricultural Economics*, **41**(1), pp. 67–79.

Dossou-Yovo, E.R., **Arouna, A.**, **Benfica, R.**, **Mujawamariya, G. and Yossa, R.** (2024) 'A participatory framework for prioritizing climate-smart agriculture innovations in rice-based systems: a case study of Mali', *Smart Agricultural Technology*, **7**. https://doi.org/10.1016/j.atech.2023.100392.

Eipa, S.J., **Nganga, J.K. and Muthama, N.J.** (2019) 'Utilization of livestock manure based biogas for climate change mitigation in Nakuru county, Kenya', *Journal of Sustainability, Environment and Peace*, **1**(2), pp. 39–44.

ETC Group. (2017) *Promoting biogas systems in Kenya: a feasibility study*. Leusden, The Netherlands: ETC Group.

Ewell, H. (2025) 'Beyond "reach"–advancing responsible pathways to impact at scale', *CGIAR*. https://cgspace.cgiar.org/server/api/core/bitstreams/cdc97146-abbe-4ee0-a715-0d607b1066ed/content.

Fraser, E.D.G. and Campbell, M. (eds.) (2019) 'Agriculture 5.0: reconciling production with planetary health', *One Earth*, **1**(1), pp. 9–11. https://doi.org/10.1016/j.oneear.2019.08.010.

Füller, J., **Hutter, K. and Kröger, N.** (2021) 'Crowdsourcing as a service–from pilot projects to sustainable innovation routines', *International Journal of Project Management*, **39**(2), pp. 183–195.

Geels, F.W. (2004) 'From sectoral systems of innovation to sociotechnical systems: insights about dynamics and change from sociology and institutional theory', *Research Policy*, **33**(6-7), pp. 897–920.

Global Panel on Agriculture and Food Systems for Nutrition. (2020) *Future food systems: for people, our planet, and prosperity*. London, UK: Global Panel on Agriculture and Food Systems for Nutrition.

Glover, D., **Sumberg, J. and Andersson, J.A.** (2016) 'The adoption problem; or why we still understand so little about technological change in African agriculture', *Outlook on Agriculture*, **45**(1), pp. 3–6. https://doi.org/10.5367/oa.2016.0235.

Habermann, B. and Zhang, W. (2022) *A living lab for people for low-emission food system development in*. Kenya: Working Document.

Hambrey, J. (2017) *The 2030 agenda and the sustainable development goals: the challenge for aquaculture development and management*. FAO Fisheries and Aquaculture Circular.

Hermans, F., **Sartas, M.**, **Van Schagen, B.**, **Van Asten, P. and Schut, M.** (2017) 'Social network analysis of multi-stakeholder platforms in agricultural research for development: opportunities and constraints for innovation and scaling', *PLoS One*, **12**(2), e0169634.

Herrero, M., **Thornton, P.K.**, **Mason-D'Croz, D.**, **Palmer, J.**, **Benton, T.G.**, **Bodirsky, B.L.**, **Bogard, J.R.**, **Hall, A.**, **Lee, B.**, **Nyborg, K.**, **Pradhan, P.**, **Bonnett, G.D.**, **Bryan, B.A.**, **Campbell, B.M.**, **Christensen, S.**, **Clark, M.**, **Cook, M.T.**, **de Boer, I.J.M.**, **Downs, C.**, … **West, P.C.** (2020) 'Innovation can accelerate the transition towards a sustainable food system', Nature Food, **1**(5), pp. 266–272). https://doi.org/10.1038/s43016-020-0074-1.

Intergovernmental Panel on Climate Change (n.d.) *Climate change 2007: mitigation of climate change contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge, UK/New York: Cambridge University Press.

Jack, B.K. (2013) 'Market inefficiencies and the adoption of agricultural technologies in developing countries', *Agricultural Economics*, **44**(1), pp. 1–14.

Jacobs, F., **Ubels, J. and Woltering, L.** (2018) The scaling scan: a practical tool to determine the strengths and weaknesses of your scaling ambition. *PPPlab and CIMMYT* [Online]. Available at: https://repository.cimmyt.org/handle/10883/20505?locale-attribute=en.

Jain, S., **Newman, D.**, **Nizhou, A.**, **Dekker, H.**, **Le Feuvre, P.**, **Richter, H. and Thompson, R.** (2019) *Global potential of biogas*. London, UK: World Biogas Association.

Jalang'o, D. and Habermann, B. (2022) *Food system in Nandi County: a situational and stakeholder-focused analysis on low-emission food system development*. Cali, Colombia: Alliance of Bioversity International and CIAT.

Khatri-Chhetri, A., **Pant, A.**, **Aggarwal, P.K.**, **Vasireddy, V.V. and Yadav, A.** (2019) 'Stakeholders prioritization of climate-smart agriculture interventions: evaluation of a framework', *Agricultural Systems*, **174**, pp. 23–31. https://doi.org/10.1016/j.agsy.2019.03.002.

Kihiu, E. (2020) *Access to agricultural markets: gender considerations towards improved dietary diversity in Kenya*. Nairobi, Kenya: Kenya Institute for Public Policy Research and Analysis (KIPPRA).

Klerkx, L., **Van Mierlo, B. and Leeuwis, C.** (2012) '*Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions*' in Darnhofer, I., Gibbon, D. and Dedieu, B. (eds.) *Farming systems research into the 21st century: the new dynamic*. Netherlands: Springer, pp. 457–483.

Kumar, S., **Murthy, D.**, **Gumma, M.K.**, **Khan P, E.**, **Khatri-Chhetri, A.**, **Aggarwal, P.K. and Whitbread, A.M.** (2018) *Towards climate-smart agricultural policies and investments in Telangana*. CCAFS Info Note.

Li, D., **Wang, X.**, **Chan, H.K. and Manzini, R.** (2014) 'Sustainable food supply chain management', *International Journal of Production Economics*, **152**, pp. 1–8. https://doi.org/10.1016/j.ijpe.2014.04.003.

Martius, C., **Wassmann, R.**, **Mwambo, F.M.**, **Pingault, N. and Guérin, L.** (2023) *Food systems emissions in Colombia and their reduction potential: a country profile*. Occasional Paper, Cali, Colombia: Alliance of Bioversity International and CIAT.

Mausch, K., **Hall, A. and Hambloch, C.** (2020) 'Colliding paradigms and trade-offs: Agri-food systems and value chain interventions', *Global Food Security*, **26**, p. 100431.

McGuire, E., **Al-Zu'bi, M.**, **Boa-Alvarado, M.**, **Luu, T.T.G.**, **Sylvester, J.M. and Leñero, E.M.V.** (2024) 'Equity principles: using social theory for more effective social transformation in agricultural research for development', *Agricultural Systems*, **218**. https://doi.org/10.1016/j.agsy.2024.103999.

McGuire, E., **Rietveld, A.M.**, **Crump, A. and Leeuwis, C.** (2022) 'Anticipating gender impacts in scaling innovations for agriculture: insights from the literature', *World Development Perspectives*, **25**, p. 100381.

Meinzen-Dick, R., **Behrman, J.**, **Menon, P. and Quisumbing, A.** (2012) 'Gender: a key dimension linking agricultural programs to improved nutrition and health', *Reshaping Agriculture for Nutrition and Health*, **16**, pp. 135–144.

Merrey, D.J., **Loboguerrero Rodriguez, A.M. and Zeppenfeldt, L.** (2023) *An enabling innovation ecosystem to accelerate agriculture breakthroughs*. Montpellier, France: CGIAR System Organization.

Michalke, A., **Kunz, J. and Gaugler, T.** (2025) *True cost accounting: assessing environmental and social damages of production*. London, UK: Earthscan from Routledge Taylor & Francis Group.

Minh, T.T., **Zwart, S.**, **Appoh, R. and Schmitter, P.** (2021) *Analyzing the enabling environment to enhance the scaling of irrigation and water management technologies: a tool for implementers*. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Ministry of Environment and Forestry, Kenya. (2020) *Kenya's nationally determined contribution (NDC)*. Nairobi, Kenya: Ministry of Environment and Forestry.

Morales-Muñoz, H., **Bailey, A.**, **Löhr, K.**, **Caroli, G.**, **Villarino, M.E.J.**, **Lobo-Guerrero, A.M. and Castro-Nuñez, A.** (2022) 'Co-benefits through coordination of climate action and peacebuilding: a system dynamics model', *Journal of Peacebuilding & Development*, **17**(13), pp. 304–323.

Mwirigi, J., **Balana, B.B.**, **Mugisha, J.**, **Walekhwa, P.**, **Melamu, R.**, **Nakami, S. and Makenzi, P.** (2014) 'Socio-economic hurdles to widespread adoption of small-scale biogas digesters in sub-Saharan Africa: a review', *Biomass and Bioenergy*, **70**, pp. 17–25.

Ndung'u, P.W., **Bebe, B.O.**, **Ondiek, J.O.**, **Butterbach-Bahl, K.**, **Merbold, L.** and **Goopy, J.P.** (2018) 'Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: livestock systems of Nandi County, Kenya', *Animal Production Science*, **59**(6), pp. 1136–1146.

Nguu, J., **Ndivo, S.**, **Aduda, B.**, **Nyongesa, F. and Musembi, R.** (2014) 'Livestock farmers' perception on generation of cattle waste-based biogas methane: the case of Embu West District, Kenya', *International Journal of Innovative Research and Development*, **3**(1), pp. 300–306.

Oertel, C. and Erasmi, S. (2016) 'Greenhouse gas emissions from soils—a review', *Geochemistry*, **76**(3), pp. 327–352.

Olum, S., **Gellynck, X.**, **Juvinal, J.**, **Ongeng, D. and De Steur, H.** (2020) 'Farmers' adoption of agricultural innovations: a systematic review on willingness to pay studies', *Outlook OnAgriculture*, **49**(3), pp. 187–203.

Patman, I.N.D.A. and Moronge, D.M. (2015) 'Determinants of successful implementation of domestic biogas projects in Kenya: a case of Githunguri Sub-County', *The Strategic Journal of Business & Change Management*, **2**(62), pp. 189–211.

Rietveld, A.M., **Farnworth, C.R.**, **Nawaz, M.**, **Timler, C.J.**, **Tittonell, P.A.**, **Van der Burg, M. and Groot, J.C.J.** (2024) 'Understanding diversity in gender norms within farming communities: a Q-methodology approach applied in Uganda', *NJAS: Impact in Agricultural and Life Sciences*, **95**(1), p. 2337274.

Rogers, E.M., **Singhal, A. and Quinlan, M.M.** (2014) 'Diffusion of innovations' in Stacks, D. W. and Salwen, M. B.(eds.) *An integrated approach to communication theory and research*. Routledge, pp. 432–448.

Rosegrant, M.W., **Sulser, T.B.**, **Mason-D'Croz, D.**, **Cenacchi, N.**, **Nin-Pratt, A.**, **Dunston, S. and Willaarts, B.** (2017) *Quantitative foresight modeling to inform the CGIAR research portfolio*. Washington, DC, USA: International Food Policy Research Institute (IFPRI).

Rosenstock, T.S., **Lubberink, R.**, **Gondwe, S.**, **Manyise, T. and Dentoni, D.** (2020) 'Inclusive and adaptive business models for climate-smart value creation', *Current Opinion in Environmental Sustainability*, **42**, pp. 76–81.

Sartas, M., **Schut, M.**, **Proietti, C.**, **Thiele, G. and Leeuwis, C.** (2020) 'Scaling readiness: science and practice of an approach to enhance impact of research for development', *Agricultural Systems*, **183**. https://doi.org/10.1016/j.agsy.2020.102874.

Schut, M., **Leeuwis, C. and Thiele, G.** (2020) 'Science of scaling: understanding and guiding the scaling of innovation for societal outcomes', *Agricultural Systems*, **184**. https://doi.org/10.1016/j.agsy.2020.102908.

Shilomboleni, H. and De Plaen, R. (2019) 'Scaling up research-for-development innovations in food and agricultural systems', *Development in Practice*, **29**(6), pp. 723–734.

Shirsath, P.B., **Aggarwal, P.K.**, **Thornton, P.K. and Dunnett, A.** (2017) 'Prioritizing climate-smart agricultural land use options at a regional scale', *Agricultural Systems*, **151**, pp. 174–183. https://doi.org/10.1016/j.agsy.2016.09.018.

Stevanović, M., **Popp, A.**, **Lotze-Campen, H.**, **Dietrich, J.P.**, **Müller, C.**, **Bonsch, M.**, **Schmitz, C.**, **Bodirsky, B.L.**, **Humpenöder, F. and Weindl, I.** (2016) 'The impact of high-end climate change on agricultural welfare', *Science Advances*, **2**(8). https://doi.org/10.1126/sciadv.1501452.

Stilgoe, J., **Owen, R. and Macnaghten, P.** (2013) 'Developing a framework for responsible innovation', *Research Policy*, **42**(9), pp. 1568–1580. https://doi.org/10.1016/j.respol.2013.05.008.

Thornton, P.K., **Whitbread, A.**, **Baedeker, T.**, **Cairns, J.**, **Claessens, L.**, **Baethgen, W.**, **Bunn, C.**, **Friedmann, M.**, **Giller, K.E.**, **Herrero, M.**, **Howden, M.**, **Kilcline, K.**, **Nangia, V.**, **Ramirez-Villegas, J.**, **Kumar, S.**, **West, P.C. and Keating, B.** (2018) 'A framework for priority-setting in climate smart agriculture research', *Agricultural Systems*, **167**, pp. 161–175. https://doi.org/10.1016/j.agsy.2018.09.009.

Tran, N., **Ogello, E.**, **Outa, N.**, **Muthoka, M. and Hoong, Y.** (2023) *Promising aquaculture technologies and innovations for transforming food systems toward low-emission pathways in Kenya: a review*. Penang, Malaysia: WorldFish (CGIAR).

Van Loon, J., **Woltering, L.**, **Krupnik, T.J.**, **Baudron, F.**, **Boa, M. and Govaerts, B.** (2020a) 'Scaling agricultural mechanization services in smallholder farming systems: case studies from sub-Saharan Africa, South Asia, and Latin America', *Agricultural Systems* **180**, 102792.

Van Loon, J., **Woltering, L.**, **Krupnik, T.J.**, **Baudron, F.**, **Boa, M. and Govaerts, B.** (2020b) 'Scaling agricultural mechanization services in smallholder farming systems: case studies from sub-Saharan Africa, South Asia, and Latin America', *Agricultural Systems*, **180**. https://doi.org/10.1016/j.agsy.2020.102792.

Verspecht, A., **Vandermeulen, V.**, **Ter Avest, E. and Van Huylenbroeck, G.** (2012) 'Review of trade-offs and co-benefits from greenhouse gas mitigation measures in agricultural production', *Journal of Integrative Environmental Sciences*, pp. 147–157.

Wachera, R. (2009) *Assessing the challenges of adopting biogas technology in energy provision among dairy farmers in Nyeri County*. Kenya: Kenyatta University.

Wamuyu, M.S. (2014) *Analysis of biogas technology for household energy, sustainable livelihoods and climate change mitigation in Kiambu County, Kenya (Master's thesis)*. Nairobi, Kenya: University of Nairobi.

Westermann, O., **Förch, W.**, **Thornton, P. and Körner, J.** (2018) 'Scaling up agricultural interventions: case studies of climate-smart agriculture', *Agricultural Systems*, pp. 283–293.

Wigboldus, S. and Brouwers, J. (2016) *Using a theory of scaling to guide decision making: towards a structured approach to support responsible scaling of innovations in the context of agri-food systems*. Wageningen, The Netherlands: Wageningen Centre for Development Innovation, Wageningen University & Research.

Wigboldus, S., **Klerkx, L.**, **Leeuwis, C.**, **Schut, M.**, **Muilerman, S. and Jochemsen, H.** (2016) 'Systemic perspectives on scaling agricultural innovations. A review', *Agronomy for Sustainable Development*, **36**(3). https://doi.org/10.1007/s13593-016-0380-z.

Wilkes, A., **Wassie, S.E.**, **Tadesse, M.**, **Assefa, B.**, **Abu, M.**, **Ketema, A. and Solomon, D.** (2020) *Inventory of greenhouse gas emissions from cattle, sheep and goats in Ethiopia (1994–2018) calculated using the IPCC tier 2 approach*. Addis Ababa, Ethiopia: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Woltering, L. and Boa-Alvarado, M. (2019) *Insights on scaling of innovations from agricultural research for development: views from practitioners* [Online]. Available at: www.km4djournal.org/.

Woltering, L., **Valencia Leñero, E.M.**, **Boa-Alvarado, M.**, **Van Loon, J.**, **Ubels, J. and Leeuwis, C.** (2024) 'Supporting a systems approach to scaling for all; insights from using the scaling scan tool', *Agricultural Systems*, **217**. https://doi.org/10.1016/j.agsy.2024.103927.