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Coproducing water-energy-food Nexus actionable knowledge: Lessons from a multi-actor collaborative learning school in Uganda, East Africa

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ABSTRACT

The water-energy-food (WEF) Nexus is an integrative framework for addressing the multi-scalar interdependencies that challenge sustainability solutions across the water, energy, and food systems. However, challenges linked to scale and data availability often make WEF analyses more theoretical, limiting their ability to offer practical, implementable solutions in policy and decision contexts. This paper introduces Collaborative Learning Schools (CLS) as a transdisciplinary process that fosters stakeholder engagement, cross-cultural knowledge exchange, and participatory learning for actionable policy and management solutions from WEF Nexus research, which we tested in Buikwe district in the central region of Uganda, East Africa. Our CLS brings together scientists (professors and students), practitioners, policy makers and implementers, and farmers around a holistic, cross-scale analysis of WEF Nexus issues for innovative and appropriate solutions. The CLS also integrates cross-scale linkages (from community to local government, to national policy context), blended systems and design thinking approaches, and post-evaluations. Our analysis and findings start with an account of the CLS implementation process, while also assessing the utility of integrating the WEF Nexus with systems and design thinking tools. We also present the co-created outputs and evaluative reflections from the non-academic stakeholders. We discuss the CLS value, emphasizing its potential to support participatory co-creations of context-driven multi-scalar WEF-Nexus pathways for problem-solving-oriented knowledge co-production. Through this case study, we contribute promising practices for effective stakeholder engagement and transdisciplinary co-production of actionable knowledge, drawing from tangential but complementary systems thinking and design thinking perspectives. We also provide a real-world illustration of aspirations for true transdisciplinary approaches that include communities and stakeholders in research processes.

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1. Introduction

The water-energy-food (WEF) Nexus is an integrative framework for addressing the interdependencies and trade-offs across water, energy, and food systems (Nhamo et al., 2018; Bizikova et al., 2013; Mohtar and Daher, 2012). While still a relatively new concept, the WEF Nexus framework has gained traction since the late 2000s (Sušnik et al., 2022; Simpson and Jewitt, 2019a) in part due to the global recognition that these increased interdependencies have feedback loops that compound the climate change crisis and its impact on food, water, and energy security (Scott et al., 2018). Despite this global dimension, the extant WEF Nexus literature usually explores highly contextual solutions (Pahl-Wostl et al., 2021). During implementation, such solutions are often deployed in ways that limit the opportunity to derive broader value from the fundamental holistic perspective lying at the heart of WEF Nexus thinking.

Given the interconnected and multi-scalar nature of WEF resource systems, there is greater value in exploring and deploying WEF strategies across multiple scales (Scott et al., 2015), yet not often done. Shocks like the COVID-19 pandemic further reinforce such need as they revealed deeper vulnerabilities and cascading impacts within interconnected WEF resource systems (Al-Saidi and Hussein, 2021). Over-reliance on national or even regional averages to inform local or household-level decision-making could be misleading, just as looking at average effects of any one driver of WEF change may not be helpful. This linked challenge of scale and implementation is arguably one main reason why many WEF analyses remain theoretical with minimal outcomes in terms of practical, implementable solutions (Simpson and Jewitt, 2019b). Also, critics of the WEF Nexus framework have questioned the capacity to address power dynamics and socio-political contexts (Allouche et al., 2019; Hussein, Ezbakhe, 2023), highlighting the need for participatory and context-specific strategies that move beyond purely technocratic solutions. WEF researchers have suggested that the engagement of stakeholders in WEF analyses and solution generation earlier on could help to bridge this gap (Naidoo et al., 2021; Hoolohan et al., 2018; Daher et al., 2020). However, there are very few platforms for meaningful dialogue across policy and decision scales around WEF Nexus issues (Pahl-Wostl et al., 2021), suggesting unmet needs for more cross-scale approaches.

For resource-constrained contexts such as smallholder farming communities in Africa, collaborative research that includes more intentional community engagement will be critical in co-framing research questions and co-identifying implementable solutions in the WEF Nexus space (Botai et al., 2021; Mathetsa et al., 2023). Faced with the challenge of promoting human development and wellbeing while protecting land and water resources and biodiversity, Africa is increasingly center stage for WEF applied research and networking to enhance WEF security (Mabhaudhi et al., 2019; Maftouh et al., 2022; Muhirwa et al., 2022; Muwanika et al., 2023). The goal of ensuring food and nutrition security while maintaining water and energy security that meets the needs of the present and future generations requires a transdisciplinary (involving multiple scientific disciplines as well as stakeholders), systems approach that considers long-term dynamics, trade-offs, and feedback loops (UN General Assembly, 2015). Improving practice and policy through transdisciplinary engagement is essential to the development and deployment of effective solutions to the pervasive food, energy, and water insecurity challenges in Africa that are exacerbated by unprecedented population growth, rapid urbanization, and intensifying climate change (Ericksen, 2008; Van Ittersum et al., 2016). The anticipated population growth trends will exert additional pressure on an already rapidly rising demand for water, land, food, and energy systems as Africa's population is expected to exceed that of North and South America combined by 2050 (Godfray et al., 2010; Foley, 2011; Cleland and Machiyama, 2017).

Our research efforts seek to address the foregoing issues around WEF Nexus applied research. This paper introduces Collaborative Learning Schools (CLS) as a transdisciplinary process to better link WEF Nexus research with actionable knowledge in policy and practice. Our CLS approach was developed as part of a global network-of-networks initiative, centered on WEF Nexus solutions to sustainable food systems in Africa. We build on collaborative learning approaches that have been used for problem-solving around sustainable food system production (Hamidov et al., 2022, Muhirwa et al., 2022), including earlier approaches of farmer field schools widely applied in farm settings to accelerate learning and adoption rate of technologies and innovations (Suzanne Nederlof and Odonkor, 2006; Anandajayasekeram et al., 2007; Davis et al., 2012; Waddington et al., 2014; Phillips et al., 2014; van den Berg et al., 2020). Compared to these earlier approaches, our CLS focuses on innovative, integrative approaches and a bottom-up co-creation/production of solutions to complex interconnected WEF Nexus sustainability challenges (Adamsone-Fiskovica and Grivins, 2022; Maughan and Anderson, 2023). We have conceptualized the CLS as a stakeholder engagement and collaborative learning process that brings together scientists (professors and students), practitioners, policy makers and implementers, and farmers around a holistic, cross-scale analysis of WEF Nexus issues toward solutions. In our applied efforts, we sought to explore **two main questions**: 1) How can stakeholder engagement and collaborative learning processes be better designed to facilitate effective integration of cross-scale dimensions of WEF Nexus issues? 2) What is the potential of a design and systems thinking-based CLS for co-creating WEF Nexus practical solutions? We use the country case of Uganda, East Africa, with Buikwe district in the central region, to test its implementation. We discuss how our CLS approach offers a valuable engagement and learning process of co-producing solutions across scales toward actionable pathways to change for contextually identified WEF Nexus problems.

In Section 2, we review key concepts that provide the framework that grounds our findings and discussions. We then describe the CLS design, the research area, and the data that support our analysis in Section 3. In Section 4, we present the CLS implementation process, emphasizing cross-scale activities from community to local leadership, to the national policy context. We also describe the co-created CLS outputs in terms of WEF Nexus pathways to change for problem-solving and then provide feedback from evaluation of the effectiveness of the CLS process. Finally, we discuss the strengths and the challenges/limitations of the CLS as a participatory, engagement instrument or tool for linking WEF Nexus research and practice in Section 5, before concluding the paper in Section 6.

2. Advancing WEF Nexus through transdisciplinary knowledge co-production

2.1. WEF in transdisciplinary research

One of the major challenges in approaches used to implement sustainable resource solutions has been a lack of consideration of the inherent trade-offs between social, economic, and environmental wellbeing as well as the potential for unintended consequences. For example, the mass production and application of synthetic chemical fertilizers and pesticides made extraordinary contributions to global crop productivity and food security by combating pest pressures and enhancing nutrient availability, but their implementation also resulted in adverse human health and environmental consequences, including toxic residues, marine dead zones, nitrous oxide emissions, soil erosion, and biodiversity loss (Diaz and Rosenberg, 2008; Reay et al., 2012; Beketov et al., 2013). It is also widely acknowledged that most of the 20th-century Green Revolution-based innovations directed at meeting global food demands have unintentionally led to the widespread integration of harmful chemicals into food systems (de Bossoreille de Ribou et al., 2013), as well as less diverse diets despite increased food intake (Gomez et al., 2013). Despite this recognition of the significance of trade-offs and the potential for unintended consequences, WEF-related decision-making

for policy, planning, and management of WEF interactions is still primarily made in silos through sector-focused initiatives (Nhamo et al., 2018; Bizikova et al., 2013). WEF systems are complex and tightly interconnected, but there is an additional layer of context-specific factors such as resource availability, growth projections, technological capabilities, and human capacity. As a result, addressing these interconnected challenges requires approaches that integrate tools and methods across different sectors and disciplines. At the same time, developing implementable solutions must consider the local context (Daher et al., 2019; 2020).

International organizations such as the UN FAO and national entities such as Germany's development cooperation agency (GIZ) have seeded and catalyzed the uptake of WEF Nexus approaches to help minimize trade-offs and increase the synergy between the water, energy, and food sectors. However, a scaled implementation of the WEF Nexus has been impeded by a lack of operationalization and application of outcomes (Albrecht et al., 2018), albeit recent but limited attempts (see Hamidov et al., 2022 on WEF Nexus operationalization through a summer school). Data availability and access, scale, and tools are factors well noted in the literature limiting its application (Simpson and Jewitt, 2019b; Wichelns, 2017). Addressing these constraints requires an enabling environment characterized by at least three things: 1) opportunities for improved coordination between research disciplines as no single discipline will be able to develop the multi-faceted solutions needed; 2) mechanisms for improved coordination between different sectors, laying the foundations for more coherent policies and plans that do not compete with one another; and 3) the development of platforms for engaging cross-disciplinary researchers and cross-sectoral actors in the process of use-inspired, community-engaged research and solutions that respond to context-specific challenges with an adequate local knowledge base (Tilt et al., 2024).

2.2. Practices for WEF Nexus science-policy-society dialogue

In the face of cross-scalar sustainability challenges that are urgent, contested, and wickedly complex, scientific researchers and development practitioners have increasingly called for approaches that center on the collaborative production of knowledge (Chambers et al., 2021; Castree et al., 2014; Clark et al., 2016; Gerlak et al., 2023). Such an approach that engages researchers and non-academic stakeholders across traditional disciplinary and sectoral boundaries could potentially: 1) deepen our understanding of socio-ecological system behavior in the face of uncertainty through promoting the integration of diverse knowledge bases and lived experiences (Cash et al., 2003; Moallemi et al., 2023); and 2) develop more equitable solutions through a more inclusive and deliberative process (Vincent et al., 2020; Vincent, 2022). However, despite earlier attempted guides on "how to coproduce knowledge" (Djenontin and Meadow, 2018), implementations of knowledge co-production face many social, institutional, epistemological, and political barriers (Bremer and Meisch, 2017; Harvey et al., 2019; 2021; Verwoerd et al., 2023). Systematic reviews of the burgeoning transdisciplinary literature demonstrate that a persistent dearth of rigorous documentation of methods and outcomes can undermine our ability to build on the most effective approaches toward successful co-production projects (Gerlak et al., 2023; Moallemi et al., 2023). Knowledge co-production that fails to address power dynamics risks reinforcing the very inequitable outcomes that it is meant to change (Turnhout et al., 2020; Vincent et al., 2020; Vincent, 2022; Eaton et al., 2022). Scholars from the Global South remind us that the colonial legacy of science and development shapes sustainability outcomes (Chilisa, 2017). They have also proposed strategies for decolonizing knowledge production (Diversi and Moreira, 2016; Grosz-Ngaté, 2020), including critical participatory research and stakeholder engagement processes that leverage local experiential knowledge while co-creating knowledge for solving problems (Kincheloe, 2009).

While the WEF Nexus is used variously in knowledge creation (Mabhaudhi et al., 2024; Taguta et al., 2022; Muhirwa et al., 2022), action-oriented knowledge coproduction with stakeholder engagement is rare but critical for operationalizing WEF Nexus interventions and transforming the concept from theory to practice. Integrating the sectors from different scales requires stakeholder engagement at multiple levels while paying attention to the diversity of needs across different stakeholder groups. The ideal scenario is one in which outcomes representing multiple perspectives emerge because all the relevant stakeholder groups participated. Successfully targeting these desirable outcomes requires impact pathways that can help drive the changes needed. Naidoo et al. (2021)'s four-step methodology could help map pathways of change. These steps are as follows: 1) overcome barriers to collaborating and engaging different stakeholders from different disciplines and government levels; 2) consider the analytical tools for gathering useful ideas for intervention and informing decisions; 3) identify tools that can be used to deploy transformative methods such as scenario planning, circular economy, or sustainable food systems; and 4) assess the suitability of a specific tool or method- this depends on the scale and data availability of data. The authors contend that this four-step approach could help operationalize and scale the implementation of the WEF Nexus across diverse contexts. Drawing from detailed insights from applied studies on resource management and climate policy with stakeholder engagement in co-production endeavors (de Vente et al., 2014; Akpo et al., 2015; Bremer and Meisch, 2017; Djenontin and Meadow, 2018; Reed et al., 2018; Norström et al., 2020; Adamsone-Fiskovica and Grivins, 2022; Maughan and Anderson, 2023), we see promising pathways for applying knowledge co-production with stakeholder engagement to realize the promises of WEF Nexus thinking.

3. Research sites, CLS design, and evaluation

Although the research elements are described sequentially for the clarity of presentation, they occurred iteratively and in-parallel during the implementation. The choice of research sites, the arrangements and logistics, and the recruitment of participants (besides the research team) were simultaneously done while designing the CLS and its evaluation – an approach that allows iterations. Also, a combination of strategic partnerships, participatory decision-making, and site's relevance to WEF Nexus challenges justify the selection of our research country and site. We build on long-standing collaboration with Makerere University to facilitate engagement with local experts and institutions and to co-design the CLS approach.

3.1. Research sites, logistics, and participants

Our stakeholder engagement to co-analyze WEF Nexus challenges and co-generate potential solutions took place in Uganda, an Eastern African country that remains basically rural (73.84 % of the total population in 2022, making the rural population 34,889,566[1]) and highly dependent on rainfed agriculture (>90 %) (MAAIF, 2018; UBOS, 2020). The country experiences erratic rainfall patterns, which have a negative impact on the agricultural sector and food security. Uganda has nine (9) agroecological zones with different biophysical characteristics and climatic conditions that favor specific enterprises. Buikwe, our research site, lies within the Lake Victoria Crescent agroecological zone in the central region of Uganda (Fig. 1). This area has experienced rapid population growth, leading to wetland encroachment, land degradation, and deforestation from pressure to sustain livelihoods (DDP II., 2015). Buikwe district has a mixed cropping system and is characterized by both commercial and smallholder farming. Some areas within Buikwe can be considered a peri-urban community. Therefore, Buikwe

[1] https://www.macrotrends.net/countries/UGA/uganda/rural-population' Uganda Rural Population 1960–2024. www.macrotrends.net. Retrieved 2024-02-21.

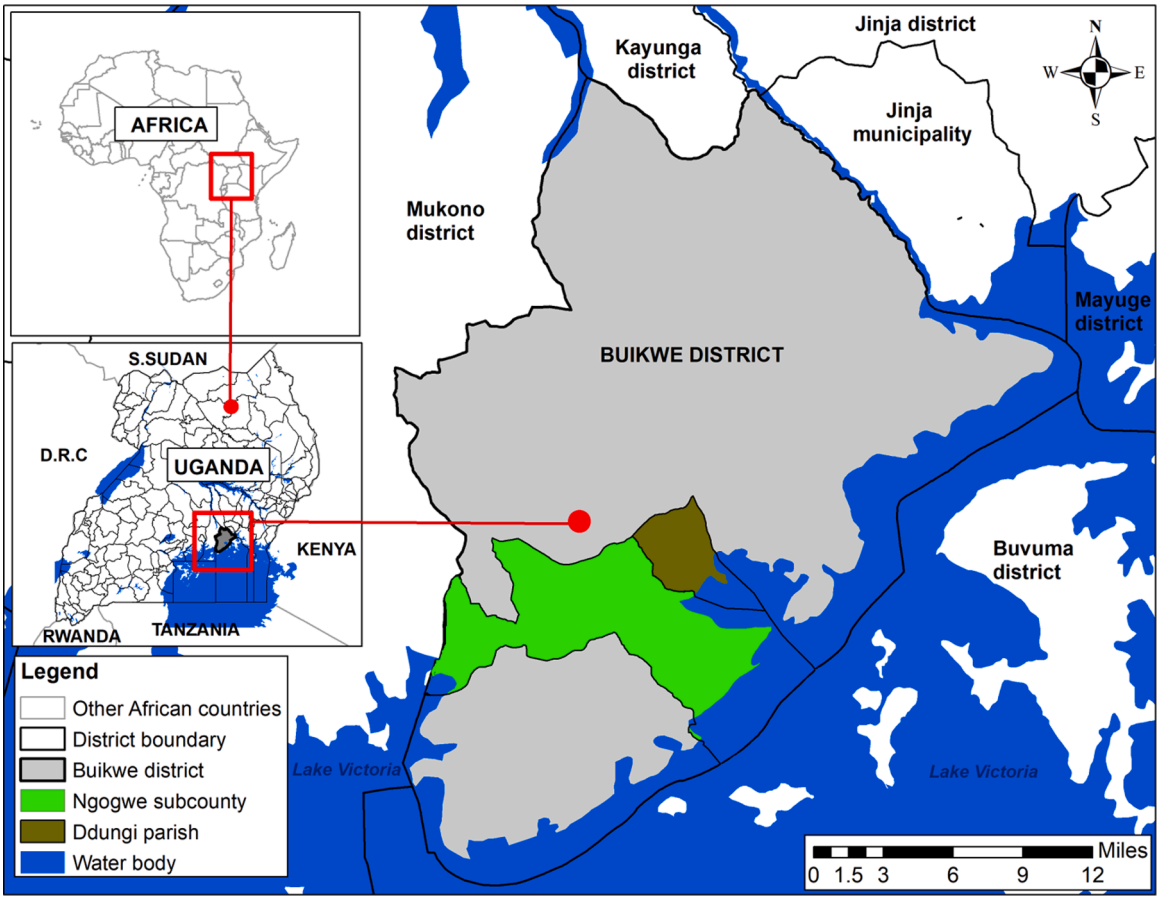


Fig. 1. Map of research engagement area.
Source: Authors own representation.

presented an opportunity to interact with farmers at different scales of production within rural and peri-urban contexts.

The Uganda Bureau of Statistics (UBOS) estimates the total population in Buikwe district at 422,771 individuals, making a total of 97,933 households with an average household size of 4.2 people (UBOS, 2016). The most popular sources of energy for lighting among households are paraffin (50 %) and hydropower-generated electricity (28 %), while for cooking, it is firewood (58 %) and charcoal (37 %). The main economic activity is agriculture (69.6 % of households are engaged in either rain-fed farming and/or livestock raising) followed by fisheries (UBOS, 2017). Smallholder farmers grow both perennial and annual crops such as bananas, coffee, vanilla, cassava, maize, and beans. The district receives bi-modal rainfall patterns with an annual mean of 11000 mm distributed between March-May and September-November while the dry season spans June-August and December-February. However, the district is experiencing a significant seasonal variation in the rainfall distribution with late and early onset of rain seasons and frequent dry spells leading to food insecurity (Ssebisubi, 2013). Buikwe district lies on a high plateau (1000–1300 m above sea level) and has clay loamy soils. Its vegetation is characterized by patches of dense forest (Mabira forest) in the south, scattered trees, shrubs, and grassland.

Among Buikwe's six (6) sub-counties, Ngogwe sub-county is one of the largest with a large number of farmer groups and is home to the biggest 'model' farmer[2] of the district. The sub-county was thus purposively selected for the participatory process to facilitate interaction with a model farmer and learn from the diverse farmers. Ngogwe subcounty has six (6) parishes and seventy-three (73) villages. Two parishes of Lubongo and Ddungi were selected for learning from the model farmer and implementation of the system/design thinking activities, respectively. We selected farming communities in four villages from Ddungi parish, including Namukono, Lugasa, Wabusolo and Ddungi. These were selected through a consultative process involving researchers, practitioners, and community stakeholders to ensure representation of diverse socio-environmental conditions relevant to water, energy, and food security.

On the ground, logistics were coordinated with local research partners before and during the stakeholder engagement processes. The local research partners were heavily involved in the co-design of the collaborative learning school and its implementation as detailed in Section 4. Several of them are co-authors on this paper, reflecting a truly equal partnership where the in-country partners took the leadership.

After selecting the study sites, local research partners helped with identifying a community-based organization that facilitated planning, including a preliminary survey to link with local community leaders and

[2] A model farmer is a farmer household selected to be part of the agricultural extension system and knowledge and innovation diffusion, often based on their ability to demonstrate new technologies and practices as well as teaching the skills to implement the new technologies to peers (Taylor and Bhasme, 2018). This considers the farmer's uniqueness of sustainable agriculture practices undertaken and specific agricultural innovations on their farms.

get more information about the farmers and their livelihood activities. We then engaged in rapport building and, through the local leaders, organized a series of community meetings before the CLS. The focus during the initial discussions was on explaining to the farmers the objectives of the CLS and how we planned to engage with them. Local community leaders helped with on-the-ground logistics, such as identifying a suitable venue for the CLS that could be easily accessed by farmers from the four villages selected for the project – namely Namukono, Lugasa, Wabusolo, and Ddungi.

In terms of participants, a total of 16 locals (4 from each village) engaged with the research team closely as lead farmers throughout the CLS. In addition, some of our sessions (such as community focus groups, interviews, and field visits) also engaged 50 additional community members across the four villages, including individual farmers, a model farmer household, cultural leaders, and representatives of community groups. This diverse group constituted the main stakeholders targeted for the community-level engagements. Through our community-based organization partner, we successfully recruited representative traditional authorities and local governments of Buikwe district, Ngogwe sub-county, and Ddungi parish. These stakeholders participated in the district-level engagements process in addition to agricultural extension officers and local NGOs, totaling 12 representatives. The workshop engagements at the national level included 18 representatives from government, private industry, and non-governmental organizations such as UN FAO Uganda representation. Finally, the CLS included graduate students and early career researchers from African, U.S., and E.U. universities (n = 20) and the research team of U.S. and African researchers who acted as facilitators. The selection process for student researchers prioritized diversity in disciplinary backgrounds, experience, gender balance, and regional representation. Upon their recruitment, student researchers were engaged through pre-CLS webinars for training sessions, including ones that helped ensure a culturally sensitive and respectful community engagement.

3.2. The CLS design components

The CLS embodies an approach used to co-produce actionable knowledge through leveraging participatory research processes to promote two-way community-university knowledge exchanges. Table 1 summarizes our CLS approach, illustrating all phases, activities, and instruments used. The CLS was designed collaboratively by the research team members (including the local research partners), who later served as facilitators during the field activities. A crucial design element was a detailed plan that encompassed a wide range of logistical tasks on the ground. As described above, the choice of local research collaborators and a community-based organization at the grassroots level that work directly with the smallholder farmers was central and instrumental, given their active role in the selection of the study area and identification of communities and key contacts. They facilitated the mobilization of farmers, local authorities, and policy actors at the community and district levels.

Our CLS had both a substantive, conceptually driven aspect; and a scalar, process-oriented dimension. For the conceptual dimension, we drew insights from *design thinking* and *systems thinking* approaches. *Design thinking* is a human-centered, iterative problem-solving approach that emphasizes the inclusion of stakeholders from various backgrounds during the early stages of the problem-solving process (Buhl et al., 2019). In recent years, design thinking has been increasingly used alongside other participatory and co-creative approaches to address complex societal problems (Katoppo and Sudradjat, 2015). The *Systems thinking* approach seeks to enhance our understanding of the dynamic and adaptive behavior of complex systems through shedding light on the linkages, relationships, interactions, and dependencies among various system components (Fiksel, 2006; Kayendeke et al., 2024). *Systems thinking* focuses on the whole system rather than analyzing its components in isolation and its holistic approach provides unique perspectives on the root causes of problems that otherwise are not apparent when the components are analyzed independently. It utilizes analytical and qualitative methods such as causal loop diagrams, systems mapping, network analysis, agent-based modeling, and scenario analysis to gain insights into the inner workings of systems. *Systems thinking* is particularly useful when one seeks to address root causes rather than symptoms of problems, and *design thinking* is helpful in understanding root causes at an individual level and generating alternative solutions. For the process-oriented dimension, our CLS design followed a multi-scale approach. We started our summer research by engaging with farmers at the community level before interacting with policy actors at both the district and national levels. This approach was intentionally adopted to address the cross-scale linkage demands of WEF Nexus approaches.

We built the CLS around four phases: problem identification, system mapping and solution ideation, solution prototyping, and validation. The first two phases were iterative. Our CLS **problem identification phase** used both design thinking with systems thinking techniques to support the identification of problems in collaboration with our non-

Table 1
CLS design elements, objectives, activities, and instruments.

Level of engagement process	Phase	Objective	Activities	Instruments / Tools use
Community scale	**Problem identification**	Problem scoping: general community WEF nexus problems	Discussion with a larger set of farmers collectively	Focus Group Discussions
		Problem scoping: Centering and deepening identification of WEF nexus problems	Field visits Discussion with selected representative farmers	Direct observations Transect walking Focus Group Discussions
	System mapping & solution ideation	Systems Mapping Solution Generation + Assumption testing	Participatory system mapping with inputs from farmers' representative	Causal loop diagrams Individual ideations Brainstorming Iterative interview
	Solution prototyping **Validation**	Solution prototyping Feedback to farmer communities and Validation of solution prototypes	Creative Design exercises with farmers Presentation of solution back to general farmer communities Debriefing and discussions of feedback on prototypes	Community workshop
District scale		Understand political dynamics and relationships, and pathways for change	Student-led presentations of co-created solution prototypes Political Economy Analysis (PEA)	Workshop with local government officers and authorities
National scale			Student-led presentations of co-created solution prototypes and findings from PEA	Workshop with national government officers and policy makers

academic stakeholders. Combining these two approaches during the problem identification and scoping phase provided a better understanding of community-identified issues and why they were happening. The problem identification process involves a deep understanding of the users and their needs. Engaging with the farmers at this level enabled us to empathize with them and also identify potential "influencers" based on how they interacted with one another. We leveraged this understanding to (re)framing the problem from multiple perspectives. During the **system mapping and solution generation phase**, systems and design thinking approaches were again used to identify collectively with farmers some central challenges, visualize the systems components and their interactions and feedback loops, and envisage innovative solutions collaboratively with the stakeholders to improve sustainable food production at the community scale. The solution identification process involved rapidly generating potential solutions, gathering feedback, refining them based on collected feedback, and iterating the process. Potential solution ideas are generated using both divergence and convergence thinking methods. For the **solution prototyping phase**, physical models of the conceptually envisioned ideas were developed to communicate the generated solutions and rapidly test them through multiple lenses. The emerging solutions were subsequently refined using insights derived from gathered feedback. In the **validation phase**, the refined prototypes were analyzed to gauge their feasibility and viability for deploying them as sustainable solutions. The assessment was extended to include a policy perspective through performing a political economy analysis (PEA). PEA is an approach that can generate deeper insights into the political dynamics and relationships that could influence the societal change needed to translate research outcomes such as our prototypes into practical, real-life solutions (Whaites et al., 2023; Rocha Menocal et al., 2018, Whaites, 2017). Our PEA included discussions with stakeholders to identify key influential actors and factors. We also mapped and analyzed their relationships while considering elements such as power, interests, historical legacies, and inequalities. The exercise helped us better understand their contributions to the existing situation, and their potential impact on the desired change(s) sought in the proposed solutions. Ultimately, we used the PEA exercise to identify pathways to fostering meaningful and sustainable change.

3.3. CLS evaluation

We conducted a post-assessment survey at each scale of the engagement and collaborative process. The analysis in this paper relies on three sources of data. First, we used the CLS facilitators' observations during the two-week long process, which were reconciled and discussed during debriefing sessions. The second data source consisted of students' blogs written to capture the daily process and summary reports documenting the WEF-related outputs of the CLS. The third source of data was interviews, which aimed to capture feedback from farmers (N = 10), district-level officers and authorities (N = 7), and national-level participants (N = 6) at different stages of the CLS. Policy makers and implementers at district level included a Member of Parliament, the Chief Administrative officer, local council chairpersons, agricultural officers, environmental officers, and NGO representatives, who all participated in discussions with the four CLS groups. At the national level, participants included representatives from the Ministry of Agriculture, Animal Industry, and Fisheries, the Ministry of Water and Environment, the Ministry of Gender, and the private sector. Interview questions were posed to each group, and their responses are detailed in Section 4.4.

4. The implementation process, outputs, and participants' feedback

While the CLS implementation was staggered across scales from community, district, and national levels, the bulk of the process took place at the community level.

4.1. Community-level processes and outputs

4.1.1. Identification of problems

The CLS participants, together with the farmers and local authorities organized into four groups (1 per village), initiated discussions to gain a sense of the general community-level WEF-related problems. Several problems were identified and described by representative farmer members from each village, including (1) land fertility and crop production issues threatening food security, (2) water needs in cropping systems, (3) energy needs for water and crop handling, storage, and distribution, (4) energy from crop and agroforestry systems (biomass burning, charcoal, biogas), among others. Following up with farm visits where they engaged in smaller group discussions, the CLS participants gained a deeper understanding of the problems raised during the community-level focus group discussions. Continuing the collaborative process, both CLS participants and farmers substantiated and confirmed the WEF Nexus issues being faced locally. Table 2 summarizes the major themes identified from the community-level WEF Nexus needs assessment phase. Discussions revealed that the major themes sum up the interlinkages among the several other WEF-resource challenges listed. Such interlinkages were further mapped to understand the potential WEF-related trade-offs and synergies that could be created from addressing them. Hence, the teams (of students and farmers) moved into collaboratively creating systems mapping of the issues identified.

Note: An x indicates that the theme was identified in the corresponding village

4.1.2. Systems mapping and solution ideations

The iterative dimension of the problem identification and systems mapping phases transpired in the collaborative processes that followed the problem identification. To address the issues collaboratively for effective solution ideation, both CLS participants and farmers gathered over two days to map the WEF-related issues using causal loop and systems mapping diagrams in combination with storytelling aspects of design thinking through iterative interviews. These diagrams enabled further understanding of interconnections that were not obvious at first glance prior to the development of possible solutions. The teams visualized each local system along with its components and their interactions, while considering a central problem, its causes, resulting effects, and feedback loops between causes and effects. The ensuing holistic understanding of the local systems enabled open-mindedness and creativity for the solution generation stage. To reduce the negative aspects of group collaborative problem-solving, CLS team members, including the farmers, generated many alternatives individually first, and shared their solutions together. The teams then worked collaboratively to understand individual ideas, including gauging possible solutions attempted by the farmers hosting the conversations. Engaging in a brainstorming technique used in design thinking sessions, the groups ensured that everyone's voices were heard. Table 3 illustrates the outputs from this iterative, collaborative phase. It shows the embedded system mappings (mapped cause-effect relationships of the root causes of the key challenges the communities are facing), with a short description of the village-level priority challenges for which solutions were later modeled.

4.1.3. Modeling solutions: four coproduced WEF-Nexus pathways to change

One of the key features of the CLS is the WEF-Nexus "pathways to change" that were coproduced for each of the four villages as implementable solutions. During this phase, the groups were guided by eight priority criteria and justification to agreeing and retaining their collaborative solutions. These priority criteria included: (i) fit for purpose, including relevance and affordable to the community at stake; (2) easy to use, harnessing farmer knowledge and innovation; (iii) foster sustainability and income generation; (iv) importance on short, medium, and long-term for farmers livelihood; (v) cost-effective (low input

Table 2
Summary of the major problems identified from the needs assessment phase.

Major Themes	Villages				Examples	
	Dundji	Namukono	Lugasa	Wabusolo		
Access to Technical Knowledge	x	x	x	x	▪ Lack & insufficiency of extension services ▪ Lack of knowledge in soil conservation	▪ Farmers unwilling to adopt new technologies ▪ Lack of skills sharing
Access to Agricultural Inputs	x	x	x	x	▪ Fake/bad quality of pesticides and fertilizers ▪ Finances ▪ Access to chemical inputs (pesticides, fertilizer)	▪ Reliable seed or crop genetics ▪ Livestock breeds ▪ Livestock Feed
Access to Markets	x	x	x		▪ Low selling prices for goods and produce ▪ Fluctuations in market prices ▪ Lack of market for livestock	▪ No leverage to negotiate prices (with middlemen) ▪ Strict produce quality standards
Pests & Diseases	x	x	x	x	▪ Coffee (disease) ▪ Maize (armyworm) ▪ Banana (wilt diseases)	▪ Cassava (mosaic virus) ▪ Mango (insects) ▪ Livestock (tsetse fly)
Soil Infertility		x	x	x	▪ Declining crop productivity	
Farmer Trust Issues in Cooperation	x	x	x	x	▪ Lack of farmer communication and gathering ▪ Lack of trust in local input supply chain	▪ Untrustworthy retailers and sales agents
Social	x		x		▪ Lack of market governance ▪ Gender Equity	▪ Thieves (vanilla)
Energy			x		▪ Access to electricity	
Climate variability			x	x	▪ Longer dry spells	

and build on existing institutions); (vi) strengthen capacity building; (vii) generate immediate (modest) results to build trust; and (viii) facilitate local and intergenerational collaboration and mentorship. We describe in Table 4 each coproduced solution considered as pathways to change for the contexts where we worked.

The CLS participants and farmers prototyped concept models of their solutions (Fig. 2), which were later presented to district-level government officials, local authorities, and national-level policymakers and implementers. These prototyped models facilitated the process of presenting complex ideas to various stakeholders, furthering understanding, and gathering feedback for validation.

4.1.4. Solution validation: feasibility and sustainability analysis

Examining the feasibility and sustainability of the prototyped solution (Table 4 – Column 4) supported the initial validation of the co-designed and proposed solutions. Overall, the fundamental and shared requirements for the feasibility and sustainability of these prototype solutions are 1) greater farmer collaboration, 2) sharing of technical knowledge, and 3) accumulation of capital/financial resources.

4.2. District-level processes and outputs – PEA analysis

At the **district level**, the feasibility and sustainability of the coproduced solutions were further explored with the PEA analysis, which consisted of exploring the question: How to address the need for (1) collaboration and capital/financial accumulation and (2) collaboration and knowledge sharing. This question was central to the PEA analysis because all four groups' coproduced pathways to change were unified by these major themes – the positive changes that will enable practical realization. Engaging with the district-level local authorities as well as the representative farmers that took part in the community-level exercises, the CLS participants explored what outcomes would be achieved if these two elements or conditions were met and the factors and actors that would play a critical role and/or serve as powerful entry points to bring about the needed positive changes over a short and longer term (Table 5). Such an engaging process offered an opportunity for local authorities and farmers to meaningfully interact, reach common ground on systems challenges, and discuss solution options as well as what change(s) is/are needed for their implementation and scaling up; thereby enhancing further the validation of the prototyped solutions.

Expanding further on such analysis and representing the direct and indirect relationships among actors and factors as well as the nature of those relationships, each group diagramed their overall PEA analysis as illustrated in Fig. 3, showing one example of each positive change sought. Taking Lugasa village as an example, one significant observation from their PEA analysis and diagram was the substantial influence and power held by political leaders over other factors and actors identified. This underscores why the group stressed mindset change and support for agriculture from political leaders. Furthermore, farmers emerged as a critical actor group, highlighting their significant role in shaping sustainable agricultural practices. Hence, their active participation and engagement are crucial for effective solutions. Still, technical and extension staff were also recognized as essential actors, emphasizing the value of their expertise and guidance in implementing sustainable practices. Besides, the focus on working primarily with women also stood out as a notable factor, indicating the recognition of women's potential in driving sustainable agriculture forward and/or perhaps the need to be more gender-inclusive during intervention efforts. Another key finding was the interplay between climate change and education. Educating farmers about climate change becomes vital in empowering them to adapt to and mitigate its impacts effectively. Lastly, the availability of low-interest rate loans to farmers and the support from financial institutions were identified as important factors that can facilitate agricultural development and sustainability.

The PEA engagement and reflective process enabled the district-level actors to acknowledge the widening divide between farmers (and their needs) and decision makers and implementers, which prevents effective tackling of WEF-related issues that farmers face. In particular, one district-level high officer stated that there was still a big gap between the extension system and the local farmers and encouraged farmers to press for their integration by requesting that *"…whatever you do without us is not for us"*. Yet, this policy actor also underscored the need for greater collaboration among farmers to overcome such challenges, calling farmers to share their Indigenous knowledge on agricultural practices and not just wait for external, theoretical knowledge held by extension workers. But overall, a major suggestion to help bridge the divide between national extension efforts and local farmers' needs was to organize and integrate farmers better into the existing extension system. In

Table 3
Outputs of the system mapping and solution ideation phase and description.

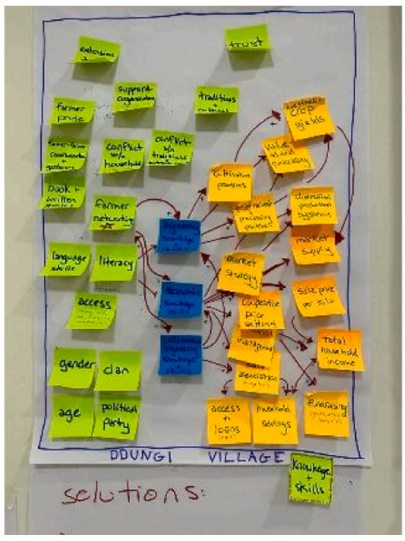
Villages	System Map Outputs & Primary Challenge	Reflections toward Solution Ideation
Ddungi	 Lack/Limited Knowledge & Skills	By determining the lack and limited knowledge and skills as the main challenge driving their local system, the group brainstormed on how to enhance farmer knowledge and skills, with ideas around having a hub or platform to help with acquiring and sharing information. The group also discussed how to help farmers strengthen their existing savings and credits cooperative organizations and leverage/expand these systems. These complementary solutions were deemed important to increase knowledge on best agronomic practices, socioeconomic, market opportunities and others, besides mobilizing resources and production. They were also seen as a good fit with the country's effort and vision 2040 around *"reforming the extension system to increase information access, knowledge and technologies to the farmers"*.
Lugasa	 Declining Soil Fertility	With declining soil fertility retained as a central challenge undermining their local system, the group discussed how farmers can better reach out to and benefit from extension services that could be used to identify soil problems by conducting soil profiling and soil testing on their farms. Having better access to extension workers and other relevant agricultural NGOs and improved training can increase knowledge on advanced and sustainable farming practices. The group also discussed how to address farmers' needs for securing expensive equipment and facilities that are hard to access individually.
Namukono	 Declining/ Low Crop Productivity	After identifying crop productivity as the primary challenge, the group reflected on the three most significant attributes that any solution to address this challenge would need. Farmers felt that a significant barrier to productivity was a lack of knowledge. Hence solutions that include the transmission of both Indigenous and technical knowledge were prioritized. These include mechanisms to share knowledge as well as to obtain new knowledge and skills. Sustainability was also a priority. Any solution would need the ability to continue to grow and thrive over the long term rather than relying solely on outside resources. Finally, any solution would have to include income generation, though income generation may not be immediate and may also consider the ability to save money rather than exclusively make more.
Wabusolo	 Longer Dry Spells	Noting longer dry spells as the defining challenge of their local system, the group brainstormed solutions to tackle such an issue within the farmer community, including notably irrigation if the farmers could have a collective pump for water supply. Cognizant that pump ownership is costly and may be beyond farmers' capacity, they noted that external support from, for instance, loan institutions might be needed. Therefore, organizing farmers into a savings group was a first step to address the financial difficulties and to seek grants and/or securing community loans that will be used to buy a pump for irrigation and collective maintenance.

Table 4
Summary description of the prototyped solutions.

Village	Solution as "Pathway to change"	Description	Requirements for Sustainability
Ddungi	**Cooperative Formation** (Coffee Production) **& Establishing a WhatsApp group** (enhanced farmer-to-farmer networks for knowledge and skill sharing)	Organize to join existing coffee farmer cooperative, for instance Kikakanya Coffee Farmers SACCO Ltd. WhatsApp group connecting Ddungi farmers with other stakeholders (extension, business, NGOs, Universities)	■ Ownership of cell phone, cell signal, Wi-Fi ■ Low cost and short-term results ■ Build on existing institutions ■ Farmer Cooperation ■ Money Savings
Lugasa	**Farmer-Based Organizations** (for enhanced cooperation to benefit from extension services and markets)	Farmer cooperatives can pool collective resources to leverage access to extension services, agricultural inputs, and markets.	■ Farmer cooperation ■ Money savings
Namukono	**Cooperative Formation** (extension services and markets) & **Establishment of Farmer Field School** (agriculture)	Farmer cooperatives can pool collective resources to leverage access extension services, agricultural inputs, and markets. Farmers can then benefit more from training and workshops on best practices in agriculture. These training are often facilitated by extension and participating farmers graduate to become local experts. This organizational strategy will also involve farmers working to achieve a common goal.	■ Farmer Cooperation ■ Money savings ■ Support of relevant stakeholders for initial training and facilitation ■ Demonstration Sites ■ Farmer Priorities: Business Skills, Agronomic Practices, Demonstration Farm for training of trainers
Wabusolo	**Cooperative formation** (money-saving groups) & **Drip irrigation pumps** (agriculture)	Farmers should organize into cooperative money-saving groups. Cooperatives can pool existing savings to purchase and distribute water pumps to members. The pumps and drip irrigation systems will enable crop irrigation and efficient water use.	■ Training and capacity building (use and maintenance of drip irrigation) ■ Farmer cooperation ■ Loan repayment and reinvestment

fact, this suggestion aligns with the pluralistic extension system that is already part of the country's extension guidelines and standards document (MAAIF, no date). Nonetheless, the effective operationalization of such an extension system to reach out to local farmers according to the planned channels of information and knowledge transfer from national, district, sub-county, parish, to village levels needs to be enhanced. Within such a pluralistic extension system, the sub-county appeared as the operational scale where actions could be directed.

4.3. National level processes and outputs

At the national level, the WEF-Nexus pathways to change, identified and validated at the community and district levels, were presented to national-level policymakers, including representatives from the Ministry of Gender, Ministry of Agriculture, Animal Industry, and Fisheries, and others. After the presentations, participants divided into small groups to discuss the opportunities and challenges for enabling and scaling up the proposed solutions from a national perspective, reflecting further on the widening gap between farmers (vis-à-vis their needs) and the related policy and governance system in place. These discussions yielded more information about programs operating at the national level that were not always reaching communities (for example, grants programs for funding solar pumps). They also reinforced the earlier market issues raised, pointing to the need to reassess existing agriculture value chains and examine how to incentivize farmers to self-organize and adopt enhanced practices around those value chains to increase their revenues.

4.4. Feedback evaluation from different stakeholders

Our evaluation of the CLS indicates a number of important points that illustrate the perceived likelihood of the CLS contributing to actionable knowledge and its overall value as a collaborative stakeholder engagement and learning process.

Farmers overwhelmingly indicated that they were very satisfied with their experience taking part in the CLS (Fig. 4a). They perceived the CLS activities as instrumental in helping them identify and understand the root causes of some of the key agricultural challenges they are facing (Fig. 4b), noting especially that the collaborative sessions they had with students provided a great deal of new insights to their farming practices (Fig. 4c). Notably, farmers rated the systems mapping and solution generation exercises that they were engaged in with students to think about ways to address their identified and prioritized challenges as extremely valuable (Fig. 4d). Farmers also perceived that they were able to develop a wide range of innovative solutions, were very satisfied with the prototype development and testing process (Fig. 4e) and would completely implement the learning acquired (Fig. 4f).

We summarize in Table 6 some of the learnings farmers underscore and a sample of their general reflections on their CLS experience.

District-level policy makers and implementers shared six key messages, which collectively indicate a wider range of opinion from positive to negative compared to the farmers. They believed that the coproduced pathways to change are implementable (Fig. 5a) as they are highly aligned with the goals of the district (Fig. 5b). However, these pathways to change are also believed to have a moderate potential to address the challenges faced by farmers (Fig. 5c) and resource availability at the district level may render the feasibility of implementation to moderate toward highly feasible (Fig. 5d). District-level policy makers and implementers are also very likely to support and allocate resources toward the implementation of these actionable solution ideas (Fig. 5e). Finally, they perceived the CLS to have highly influenced the quality of the proposed pathways to change (Fig. 5f). This latter key message is substantiated by the following excerpts drawn from their overall reflections/thoughts.

> *"This kind of meeting is the way to go. You brought farmers and students who were able to come up with practical solutions"* (District-level Policy Actor)

> *"This workshop allowed us to hear from real people on the ground - MP [Member of Parliament] will be speaking from a much more informed point of view now"* (District-level Policy Actor)

Fig. 2. Illustration of the four coproduced prototype WEF-Nexus solutions.

Table 5
Summary of PEA analysis.

Positive Change	Expected Outcomes Year 1	Expected Outcomes Year 5	Instrumental Actors	Instrumental Factors
Capital Accumulation	■ Improved health through access to quality foods ■ Enhanced teamwork among farmers ■ Positive changes in the local market ■ Improved food security in homes, ■ Shift in farmers' attitudes towards farming ■ More farmers will join the collaboration, further strengthening the initiative	■ Financial means to acquire water pumps, leading to improved irrigation practices ■ Increased job/employment opportunities for farm workers ■ Growing market demands will stimulate economic growth, while the collaborative approach will ensure sufficient food availability ■ Knowledge sharing and training among farmers will lead to higher yields and the adoption of improved farming methods. ■ Improved family incomes and a positive change in farmers' way of living, which will positively affect family sustainability. ■ Ultimately, the collective efforts of the farmers will contribute to the overall development of the country, leveraging agriculture as a vital pillar of progress.	■ Farmers ■ NGOs ■ Technical and Extension Staff ■ Financial Institutions ■ National Policy makers ■ District leadership ■ Universities	■ Economic knowledge and skills ■ Agronomic knowledge and skills ■ Gender equity ■ Climate change
Knowledge Sharing	■ Self-organization of farmer groups, including identification of meeting/demonstration sites and training of lead farmers ■ Identification of strengths and weaknesses to mobilize Increased collaboration, trust, and knowledge transfer among farmers. ■ Effective communication between farmers, local government, and community leaders ■ Improved crop yield ■ Increased food security	■ Knowledge and information diffusion from farmer field schools to other farmers, with efficient flow of technical and indigenous knowledge ■ Growing farmer networks across the district ■ Expansion of farms from small holdings to larger farmlands and increased productivity in livestock and crop enterprises ■ Access to sustainable markets ■ Increased employment opportunities ■ Access to education ■ General improved livelihoods: better standards of living and improved incomes to fight poverty.	■ Farmers ■ Community development workers ■ Local Government ■ Central Government ■ Research institutions	■ Capital ■ Mindset change ■ Trust ■ Attitude towards work ■ Infrastructure ■ Local regulations ■ Road infrastructure ■ Access to markets

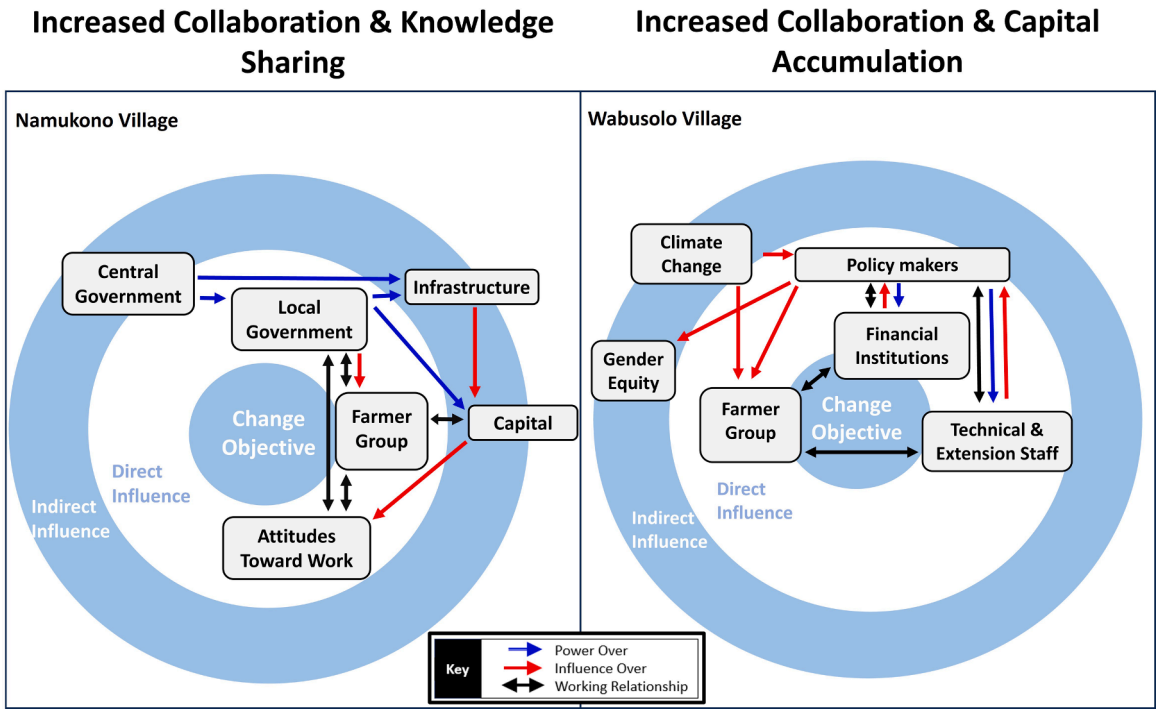


Fig. 3. Illustration of diagrammed PEA analysis.

"The workshop is an eye opener: we might have been overlooking the process of involving farmers in determining how they could create change within their groups without forcing it down their throat" (District-level Policy Actor)

"Such workshops are the best way to have these kinds of discussions, bringing policy makers,farmers, and students together; it helps people help themselves" (District-level Policy Actor)

"Through this CLS, you also exposed them [farmers] to how easy it can be to learn new things (even if you can't read or write), through creating models. etc." (District-level Policy Actor)

National-level policymakers agreed with the feedback shared by the district-level actors, even with more positivity. They reiterated, among others, that the collectively identified pathways to change can address the key challenges faced by farmers (Fig. 6a), are feasible to implement (Fig. 6b), and are highly aligned with national goals (Fig. 6c). In addition, these national-level policymakers perceived the pathways to change to be highly replicable in other regions or communities across the country (Fig. 6d) and believed that these could be effectively scaled up to have a significant impact at the national level (Fig. 6e). For that, they were moderately to very likely to consider integrating the CLS-based pathways to change co-created into existing national policies and programs (Fig. 6f) and to support further and allocate resources towards a national scale implementation (Fig. 6g). This actor group also found the collective learning approach between students, farmers, and policymakers to be extremely valuable in generating innovative solutions for national-level challenges (Fig. 6h).

Such values seen in the CLS is illustrated further with the following excerpts:

"We need better collaborations between universities, public and private sectors – this is still missing – by bringing us today, one thing you contributed to is 'demystifying the research work'" (National-level Policy Actor)

"… these ideas could be replicated to great extent through the government systems – this collaborative learning approach is very valuable, yet there's a big question about its effectiveness (due to lack of follow up, and the large number of stakeholders, who have different goals) ——> we need to have some kind of a coordinating unit" (National-level Policy Actor)

"My favorite idea is the farmer field school because of the participatory and capacity building nature of the activity. Also, the development of co-operatives." (National-level Policy Actor)

5. Learning points

We discuss here the strengths and challenges of the CLS design, implementation, outputs, and evaluation in our holistic, cross-scale analysis of WEF Nexus issues for appropriate and actionable solutions for policy and practice. Before elaborating on specific aspects, we note that as a case study within the African context, our CLS provides contextual, place-based WEF Nexus application, with some cautions for overgeneralization. While Uganda presents several similarities with other African countries and even broader Global South countries where WEF Nexus research applications have been experimented (See Hamidov et al., 2022), paying attention to how the diverse ecological, socio-institutional, cultural, and economic contexts may play out in a CLS implementation is key. In offering the CLS as an example that can be tailored, we draw attention to consideration of place-specific needs. By providing a structured, detailed description of the CLS approach, the findings offer elements for comparisons and benchmarking with other similar exercises worldwide.

On the CLS design: the strength, added value, and challenge of systems mapping approach and causal loop diagrams. Systems mapping and causal loop diagrams were instrumental in identifying, assessing suitability, and prospecting for the operationalization of the WEF Nexus solutions from a multi-scalar and multiple stakeholder perspectives, including considering local farmers, community development organizations, and local and national government officials' perspectives. It was evident that bringing systems and design thinking approaches together enhanced stakeholder engagement and contributed to revealing the root causes for some of the challenges facing farmers. By integrating design thinking and systems thinking with other participatory approaches, the CLS offered a tool to promote critical thinking for both academic and non-academic participants more effectively while addressing complex issues. Our experience and efforts echoed similar endeavors where the use of causal loop diagrams and/or group model/scenario building were found to be effective strategies for exploring WEF

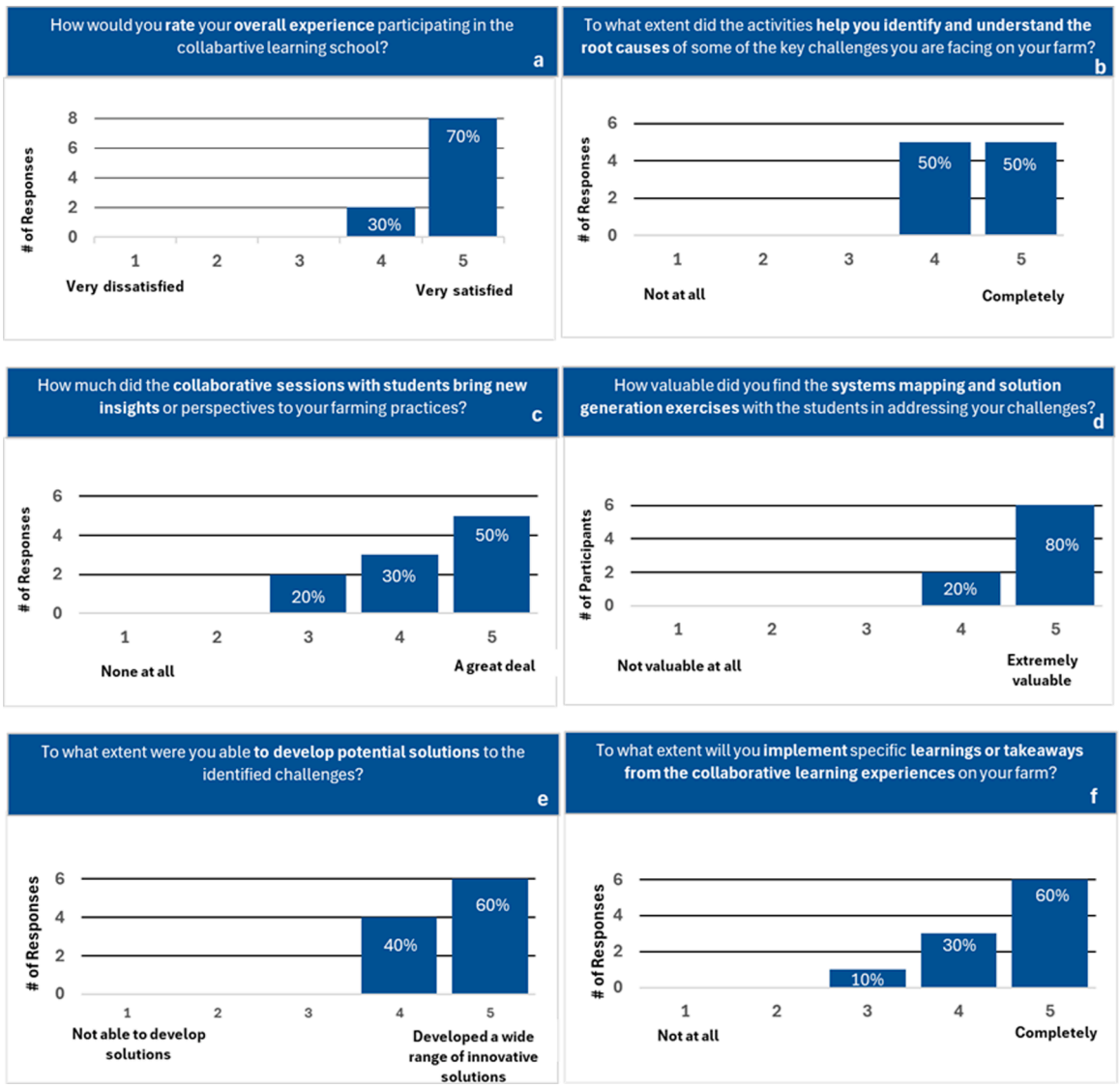


Fig. 4. Feedback evaluation from farmers (n = 10).
Source: Post evaluation surveys

Table 6
Learning points and general reflections from participating farmers.

Learning points from Farmers	General reflections on CLS experience
Formation of cooperatives, savings groups, and farming groups built on trust will support use of improved agronomic practices, sharing of knowledge, finding stable market for produce	Knowledge creation and skill sharing are vital aspects of improving agricultural activities and addressing challenges, both to learn and to share.
Increased knowledge of specific agronomic practices such as crop rotation, mulching, agroforestry, terracing, and utilizing compost and manure as organic fertilizer as well as skills to control pests and diseases	The CLS was a good networking opportunity as well as a reminder that they were more connected to potential resources than they thought they were
Leveraging networks and mobilizing community resources help to achieve goals	By increasing knowledge, improving practices, and prioritizing farming, they can become more competitive

Source: Post evaluation surveys

Nexus interactions, enhancing stakeholder engagement, and developing shared understandings and operational solutions relevant at multiple scales (Purwanto et al., 2019; Rich et al., 2018; Inam et al., 2015; Mirchi et al., 2012). Our CLS approach confirms what Johnson and Kalberg (2017) contended from their WEF modeling and solutions creation work in Ethiopia, noting the potential of participatory processes to promote critical thinking and balance the views of technical experts and non-experts. Further, our CLS experience resonates with the conclusions reached by Williams et al. (2023) in the U.S. context, stating that co-produced models help stakeholders involved to assess the practicality of potential WEF solutions, potential drawbacks, along with the likelihood of local adoption.

Nonetheless, a challenge with this approach from a reflective analysis was constraining and defining the problems and solutions identified, particularly in relation to the WEF framework. Because the systems thinking approach encouraged the identification of root causes of problems (a strength of the approach), it led to two groups proposing solutions that were similar to one another and not necessarily engaging multiple components of the WEF Nexus. Going forward with the CLS approach while keeping a systems thinking lens, we intend to address this challenge by identifying specific categories of problems supplied by the local communities for teams to engage with in advance of the CLS

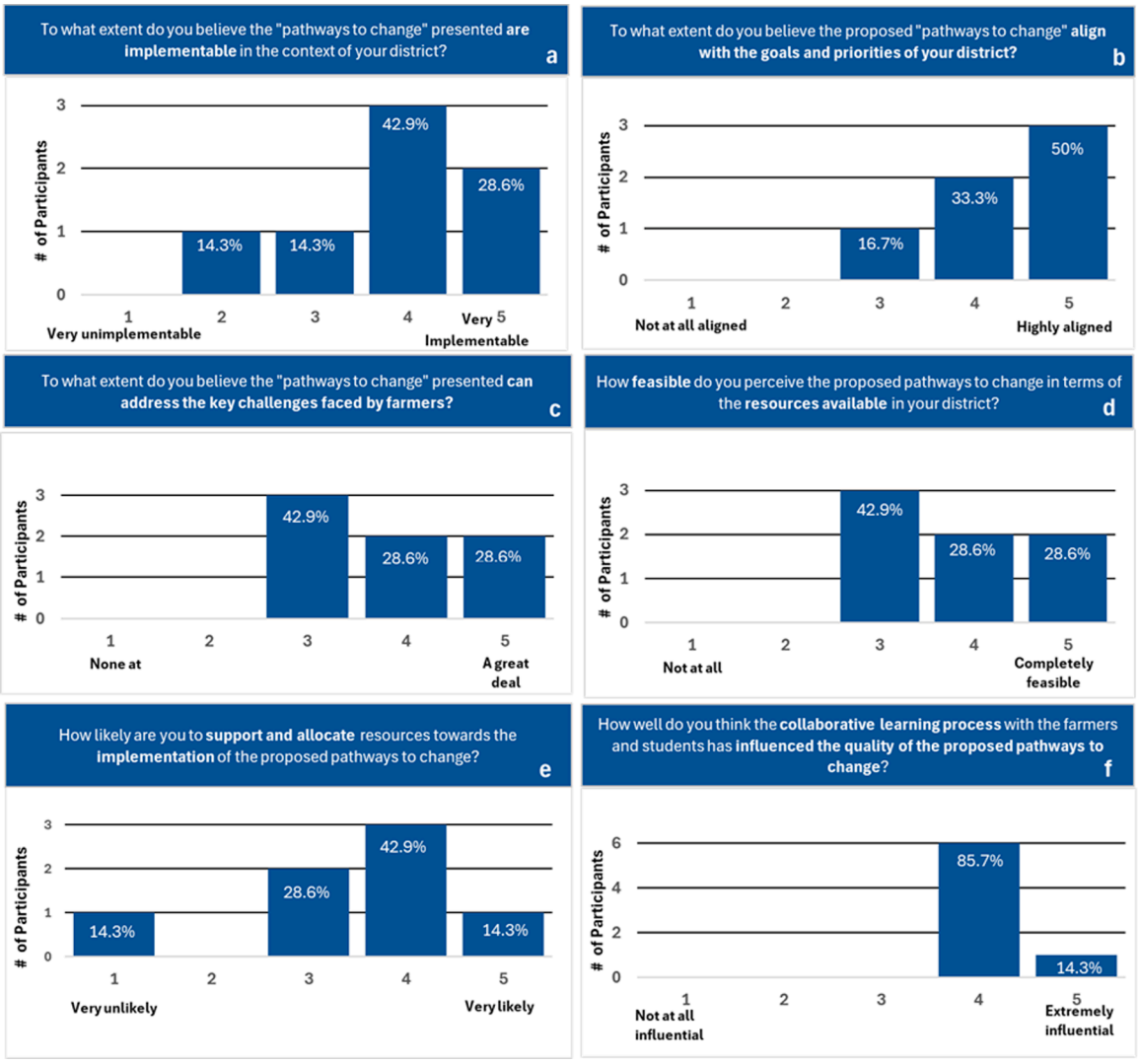


Fig. 5. Feedback evaluation from district-level authorities (n = 7).
Source: Post evaluation surveys

(for example, 'agricultural waste management', or 'sustainable water use for crop production'). Teams will be prompted to identify cross-cutting themes and influences between the problem categories, to avoid a siloed approach to solution generation. Teams will also be prompted to better incorporate the different elements of the WEF framework in their solutions.

Also, stakeholder engagement and understanding of WEF dynamics could be enhanced through quantitative modeling and subsequent focus groups with multiple stakeholders. While we planned such next-level quantitative modeling using the Water Evaluation and Planning (WEAP) and the Long-range Energy Alternatives Planning (LEAP) system modeling tools, this was not implemented, given time constraints. Future CLS activities should strive to combine participatory qualitative approaches with quantitative modeling to assess the relative magnitude of potential impacts (Daher and Mohtar, 2015; Bala et al., 2014; Reinhardt et al., 2018; Hagemann et al., 2020).

On advancing the WEF Nexus for science-policy-society practice through the CLS implementation Building on the utility of systems thinking tools synthesized above, the WEF Nexus offers a broad conceptual and applied approach with both strengths and challenges for the CLS implementation as a co-production process, similar to Hamidov et al. (2022) international summer school experience in Central Asia. At the core of our CLS process was the concept of co-creating with the farmers to ensure that engagement outputs were fit for the purpose and addressed local farmers' actual WEF needs. The contextualization and solution prototyping stages demonstrated clearly that, from a food systems, production, and consumption perspective, water and energy are important resources and solution inputs, but both have high access and cost barriers for farmers in the four communities. However, the adoption of an integrated approach was seen as important by both farmers and researchers, especially as it complements more narrowed approaches, such as crop pest management or irrigation practices, by revealing the ultimate underlying causes of some visible challenges. This points to the importance of engagement and collaboration methods that are at the core of any co-production process.

Moreover, cross-scale linkage was sought to integrate the local community, local government (district-level), and national policy context. However, as the institutional level shifted from village/community to sub-district, district, and national, greater emphasis was needed for relevant CLS outputs to engage with and balance the not-so-subtle changes from practice to policy. In other words, local farmers were interested in production, storage, marketing, and related practices. Our experience with farmers indicated that their priorities were around agricultural production through improved soil fertility, access to technological inputs, crop diversification, markets, and increased access to savings and credit. Nonetheless, at the national level, stakeholders were

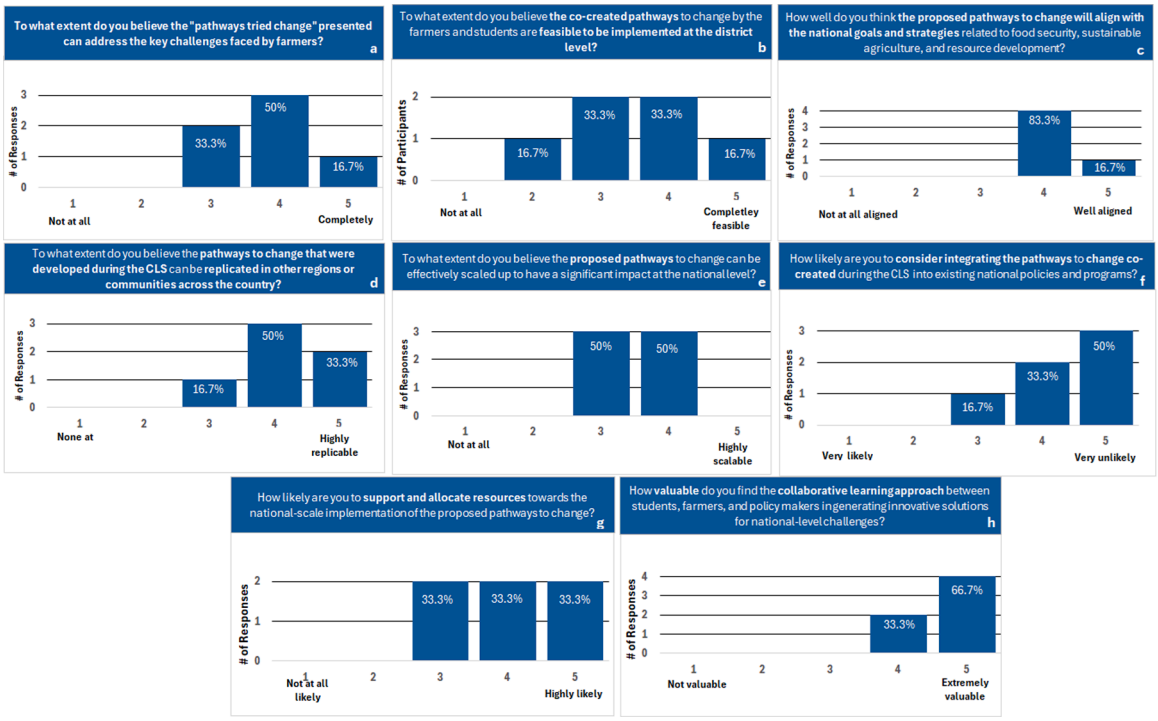


Fig. 6. Feedback evaluation from national-level policy makers and implementers (n = 6).
Source: Post evaluation surveys

solely focused on policy and programmatic initiatives. Such a disconnect between community priorities and the priorities of regional and national institutions was previously raised in the Uganda context (Butler and Mazur, 2007). Similar types of disconnects were also noted by Miller Hesed et al., (2020) in the Eastern Shore of Maryland, USA. The authors emphasized that community participants from all sectors were concerned with the immediate impacts of climate change (coastal flooding and immediate needs for properties). However, management priorities were considered at different time scales by regional and national institutions (longer-term planning to prevent large-scale flooding in the region). Such situations raise the need for attention to CLS design, participant selection, and a certain degree of 'coerced' emphasis, i.e., explicitly addressing policy with farmers and, conversely, examining local practice with policymakers. It is also important for all engaged in the CLS processes to be sensitive to the contextual realities of the landscape in which they are working and not put local participants at risk for advocating solutions that are controversial or unfit for both policy and politics.

Besides, the political situation in Uganda, as in many other places and contexts, presents challenges related to coordination, political will, and the gap between policy intent and implementation. This was very evident in the disconnect between processes/policies for production and marketing (beyond the locality), as expressed by the lack of equally available extension services. While the learnings from the project were well received by policymakers at the national level, barriers to solutions implementation were identified at multiple levels by stakeholders familiar with the system, as especially reflected in the district-level feedback. Main barriers included: 1) lack of access and knowledge about federal programs on the part of communities; 2) lack of cooperation among farmers; 3) lack of funding or motivation on the part of extension agents to engage the community; and 4) lack of channels of communication in both directions (bottom up and top down). These limitations, which translate into a persistent lack of support from relevant institutions, are a prominent feature of Uganda's national policy frameworks that limit success on the ground (Butler and Mazur, 2007). For instance, cooperatives in Uganda are not supported by the national government. Our experience confirmed what these authors previously raised on the gaps in facilitating implementation of solutions, in addition to horizontal integration needs that are often difficult to realize (Pardoe et al., 2018). Butler and Mazur, 2007 further noted for instance that Makerere University had limited ability to participate in extension activities and that their need for funding to participate was considered a potential pitfall, as donor NGO priorities may not align with local priorities. Nonetheless, one should note the contributions of the department of Extension and Innovation Studies to the national agricultural extension and advisory service and to formulations of policy frameworks and strategies. In addition, this university department conducts extension research and engages different institutions and communities, including through student internships annually. For all of these reasons and potentials, we identify the sub-county and district level as the political scale where the learnings from any research-to-action project could best find traction. Local and district-level policymakers are frequently more accountable to communities than national policymakers and targeting them through a collaborative learning process may be more effective.

On stakeholder engagement for coproducing context-fit solutions: discovery, flexibility, adaptive process, and managing power displays. A strength that the stakeholder engagement process codified in the CLS offers was the ability to experience a deep dive quickly into community situations. The process enabled a quick and better understanding of the root causes of the key farmers' challenges, while increasing trust and mutual respect for knowledge co-creation, aligning with previous calls for such methods that build knowledge, capacity, trust, and respect among participants (Johnson et al., 2018). Despite this strength and the flexibility to accommodate the learning pace of the participants, one challenge to highlight is the significant time commitment to effectively incorporate multiple stakeholder views. While our CLS was run over a 2-week long period, this even proved insufficient at some times, notably at the policy level. This time-related challenge is common in many participatory design efforts (Keen and Mahanty, 2006; Miller Hesed et al., 2020). This can be addressed with an additional level of flexibility when the resources at hand make it possible. Finally, power

management is critical among the CLS participants. In our CLS, a few team members (notably students of different expertise related to WEF issues) tended to dominate on opinions linked to their expertise – instances where facilitation from researchers were critical to balance out dominant voices. Farmers did not shy away from voicing their ideas and felt empowered to seize the space offered for doing so, especially as they were expressing themselves in their local language with translation provided.

The collaborative learning activities generated a lot of benefits from the evaluation reports conducted afterwards. Some of the mentioned benefits included a better understanding of the root causes of the key farmers' challenges, increased trust, knowledge creation, sharing and dissemination, and increased collaboration. The collaborative learning school provided a platform to engage farmers, local government, local leaders, University students, and national policymakers to create and share knowledge in WEF Nexus. Therefore, any development at the local level should begin with methods that build knowledge, capacity, trust, and respect among actors engaged (Hesed et al., 2020; Johnson et al., 2018).

Eaton et al. (2022) outlined five areas of improvement to advance the knowledge and practice of stakeholder engagement efforts. Our CLS experience offers a concrete and solid example of a dialogic process linking research and practice, using innovative, theory-driven designed process and accounting for context to co-create outputs while also allowing evaluation. Besides, it also underscores the importance of equal partnership, which is an ingredient that is often not underscored enough as shaping the quality and success of multi-country, multi-institutional collaborative and interdisciplinary knowledge coproduction efforts.

6. Conclusion

This work demonstrates the intrinsic value of an innovatively designed Collaborative Learning School (CLS) as a stakeholder engagement and participatory learning tool that can be used to advance WEF Nexus solutions across scales in ways that link science, policy, and society. By drawing from principles of design and systems thinking oriented to WEF Nexus framework and using Uganda as a testing site, the CLS enables participatory co-creation of context-driven WEF Nexus pathways to change.

The combined design, implementation, and outputs showcase the potential transformative value of our CLS approach in offering a promising framework for addressing complex WEF Nexus challenges through participatory engagement and solutions coproduction with farmers. First, the design and systems thinking enable iterative problem-solving whereby stakeholders engage in the co-production of actionable knowledge aimed at addressing situated complex WEF challenges. Second, the described implementation process responds to the need for community-engaged, interdisciplinary, cross-sectoral, cross-scalar solutions to address complex WEF Nexus challenges. The integration of cross-scale linkage facilitates engagement/participation of stakeholders across multiple levels of governance. This multi-scalar approach ensures that interventions are responsive to local needs while also aligning with broader policy frameworks and national development agendas. Third, the emphasis on participatory co-creation of actionable outputs ensures that these are not only context-tailored and inclusive of diverse perspectives but also that they are operational at multiple scales with diverse stakeholders, thereby enhancing their relevance and high likelihood of adoption/implementation. Follow-up and continued engagement with stakeholders are critical to ensure momentum is not lost over time.

The CLS serves as a platform for fostering innovation in interdisciplinary collaboration, building consensus, and catalyzing transformative change across scales with collective action toward sustainable development. From the community level to local leadership and national policymakers, the CLS fosters dialogue and enhanced knowledge exchange with critical thinking for both academic and non-academic participants. Building on this experience, future research could investigate the long-term impacts of the CLS, tracking the implementation level of the co-created innovations, technologies, and pathways to change over time and their effectiveness. Continued engagement post-CLS and longitudinal studies can inform on their sustainability.

Authors contributions

INSD, B.D. conceived the paper idea, proposed initial structure, oversaw the analysis, and coordinated write up. JWJ, KA., BKH, PK., VK., EGM, and PN contributed to the analysis and write up. MGJ, AHL, EK, AK, VM, EO, LNS, LSO, CAS, and SUJ contributed to write up, All co-authors reviewed the final version of the manuscript prior to submission

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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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