A multi-dimensional assessment of sustainable foods and the influence of stakeholder perceptions during nutrition interventions

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ABSTRACT

In addressing the growing challenge of malnutrition, many governments, donors, and international organizations have committed to supporting large-scale programs to speed up global nutrition targets. However, food systems differ in size and structure from one country to another and between rural and urban areas, which might affect nutrition program success, especially in developing countries. In this study, we developed and tested an integrated field and model-based framework to assess nutrition, health, environment, and time burden to support the sustainable implementation of interventions within a local food system. Then, we examined the influence of stakeholder priorities in harmony with SDGs 2 and 12 on contextual drivers for selecting an optimal food processing method to introduce into meal preparation. The framework was designed considering nutrient profiling, environmental impact assessment, and multicriteria modeling and executed on the "Strengthening Capacity of Local Actors in the Nutrition-Sensitive Agri-food Value Chain" project in Zambia and Malawi. The results suggest that stakeholders' priorities substantially influence the method adopted in a local food system. Additionally, there are inevitable trade-offs, such as time burden/gain, fuel and water consumption, and lower/greater micronutrient levels during food processing and meal preparation that compete with nutrition program objectives; nonetheless, these trade-offs must be embraced to achieve sustainable food systems. Furthermore, nutrient leakages observed due to varying local processing and preparation raise concerns about the sustained efforts by international organizations. If confirmed in other regions, implies that investments during nutrition programs are wasted somewhere in the system due to inefficiencies at the household level.

1. Introduction

In recent years, there has been worldwide recognition of the problems associated with nutrition and environmental sustainability. As a result, they have become prominent parts of global discussions on a sustainable future. However, the global statistics are alarming: one in every three people is malnourished (Cederholm et al., 2019; van der Merwe et al., 2022); in adults, approximately 1.9 billion are overweight, while an estimated 462 million are underweight (Lelieveldt, 2023; Li et al., 2020; Okunogbe et al., 2022); in children, this challenge is escalated; malnutrition contributes to 45 % of deaths in children below five years and 21 % of disability-adjusted life years (Black et al., 2008; Black et al., 2013). Additionally, the current food production and consumption patterns contribute to approximately 70 % of freshwater consumption, more than a quarter of global greenhouse gas emissions, and over 60 %

of biodiversity loss (Agyemang and Kwofie, 2021; Mancosu et al., 2015; Potapov et al., 2017). Fighting malnutrition while addressing environmental sustainability-related issues requires multisectoral and multistakeholder interventions as well as coordination between researchers, funders, and policymakers. To this end, nutrition-sensitive agriculture programs such as livestock transfer, irrigation programs, homestead food production systems, large-scale food fortification, and biofortification have been designed and implemented to improve diets and promote human health while meeting global nutrition targets (Khalid et al., 2019; Miller and Welch, 2013; Sharma et al., 2016). To date, several large-scale biofortified crops, such as iron-fortified beans, rice and millet, vitamin A orange, cassava, maize, and sweet potato programs, have been implemented in Rwanda, Mozambique, Uganda, India, Nepal, and Bolivia with widespread endorsement across Africa, South Asia and Latin and South America (Blakstad et al., 2022; Huey et al.,

2022; Pandey et al., 2016). Additionally, sustained efforts by international organizations such as HarvestPlus, Scaling Up Nutrition (SUN) Movement, and their respective partners have continuously supplied enriched, stable crops that are cost-effective and scalable to improve micronutrient intake (Douthwaite et al., 2022; Foley et al., 2021). At the same time, food assistance programs have increased to improve the quality or quantity of food beneficiaries consume while addressing nutritional and health needs (Lentz and Barrett, 2013). For example, the World Food Program, an agency of the United Nations, currently purchased over $1.6 billion worth of food in 2018, from which 420 million school-age children in middle and low-income countries across the globe received meals (Program, 2023). Also, nutrition-sensitive programs have been implemented at the country level, with specific attention to sub-national and local actors to improve access to sustainable healthy foods for target populations (Rosenberg et al., 2018; Warren and Frongillo, 2017).

Often, nutrition program implementers and evaluators have differing priorities, with the former focused more on delivering targets set out in the proposed plan and the latter on auditing (Di Prima et al., 2022). Bezabih et al. (2022) discussed contextual barriers that have hindered the joint planning, monitoring, and evaluation of nutrition programs among different sectors in Ethiopia. Additionally, Olney et al. (2017) reported that critical factors such as poor targeting of beneficiaries, and suboptimal evaluation designs and implementations hindered the effectiveness, reach, and generation of evidence of nutrition-sensitive programs. Johnston et al. (2018) highlighted that time constraints and potential trade-offs for household members influenced nutritional outcomes in various complex ways in low and middle-income countries. Moreover, Mashingaidze et al. (2020) emphasized insufficient knowledge of food preparation practices and habits within local food systems[1] as a barrier to achieving nutritional security in African countries. Other studies by Alonso et al. (2018) and Makate (2020) discussed integrating local culture and the local food environment to increase the adoption of solutions for beneficiary groups during nutrition interventions. Mosha et al. (2018) also investigated integrated homestead food production, food consumption, and women empowerment interventions using a multisectoral approach to women and child health and nutrition. The study demonstrated that an integrated agriculture and nutrition intervention among rural households could significantly reduce the undernutrition and disease burden among target beneficiaries in developing countries.

Despite these efforts to eradicate all levels of hunger, nutritious foods have not necessarily led to a sustainable food system and vice versa (Scott, 2018; Willett et al., 2019). A sustainable food system requires that nutritional issues, climate-related challenges, and other critical drivers within a local food system be addressed in parallel. Furthermore, food systems differ in size and structure from one country to another and between rural and urban areas, which might affect nutrition program success, especially in developing countries. Additionally, the local food system environment ultimately influences the choices made by individuals. Consequently, an approach designed from local food systems considering all inherent trade-offs could yield cobenefits during nutrition programs. Therefore, stakeholders, international organizations, and donors must consider critical drivers such as environmental sustainability, nutrition, meal preparation pathways, local culture, time burden, and resource utilization within local food systems during the design and implementation of nutrition programs. Aligning these critical drivers in the context of different stakeholder priorities is necessary for achieving a more sustainable and healthier outcome while addressing the combined nutrition and environmental crises our food system presents.

Based on the above premises, the objective of the study was to develop and test an integrated field and model-based evaluation framework to assess the nutrition, health, environmental sustainability, and time burden components that support the successful implementation of nutrition interventions. We explored the dynamics and influence of stakeholder priorities in harmony with SDGs 2 and 12 for selecting an optimal softening and food processing method and the associated nutrition, environmental sustainability, and resource consumption trade-offs during implementation. We hypothesized that stakeholder preferences could substantially influence the pathways to address the nutrition needs of target communities in the broader context of sustainability. In demonstrating the validity of the framework and testing the hypothesis, we present a case study that examines the changing nature of intervention pathways under the "Strengthening Capacity of Local Actors in the Nutrition-Sensitive Agri-Food Value Chain" (SCLANSA-FVC) project in Zambia and Malawi. Understanding such interactions between the drivers provided invaluable insights that enabled the intervention program designers to map appropriate and timely interventions that accounted for relevant contextual drivers at different spatiotemporal levels within the target regions. The overall structure of the study takes the form of four sections, including the introduction. Section 2 presents the proposed integrated methodological framework for evaluating the intervention pathways during execution. Section 3 presents the case study of employing the framework for nutrition intervention and the inevitable trade-offs and implications. The final section draws together the essential findings and standouts of this study.

2. Method framework development and implementation

2.1. Literature review

Within the last 20 years, several global, regional, and national efforts to eradicate hunger and all determinants of malnutrition have increased through nutrition-sensitive interventions. For the case of the target countries and other neighboring countries, numerous nutrition programs have been implemented. For example, Rosenberg et al. (2018) reported on Realigning Agriculture to Improve Nutrition in Zambia, which focused on increasing household access to diverse food groups, which consequently had no improvement in diet diversity. Girard et al. (2017) investigated the impact of improving nutrition knowledge, diets, and nutritional status of pregnant and lactating mothers during the Mama SASHA (Sweetpotato Action for Security and Health in Africa) nutrition program in Kenya. The study showed that promoting orange-fleshed sweet potatoes to pregnant and lactating mothers was a feasible strategy for improving maternal knowledge and Vitamin A intake. Brugh et al. (2018) studied the impact of the Malawian Government's cash transfer programs on 3920 households to improve diet quality and economic vulnerability during lean seasons. The study showed that after a year of implementing this program, there was little improvement in the diet quality and economic vulnerability of target households to food insecurity. In another study supported by the Norwegian and Chinese Development Aid to conserve agriculture and cotton production in Zambia (Umar et al., 2020), it was reported that gender mainstreaming in developing aid programs might not yield substantial benefits as opposed to those that require contributions from smallholder farmers. Also, Kaminski et al. (2022) reported on using pond polyculture intervention (tilapia farms) as a complementary source of micronutrient supply for households in Northern Zambia in addressing food and nutrition insecurity during fisheries management restrictions. The lessons from the above studies and the proliferation of literature on nutrition interventions, such as the work of Margolies (2019), Corbett (2018), Kakunta (2017), and Ruel et al. (2018) within the target regions, served as the foundation work to improve the nutrition outcomes in the context of sustainability.

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[1] A local food system is one that shortens the distance between food producers and consumers, both literally and figuratively. Source: (Enthoven and Van den Broeck, 2021).

2.2. Method framework

The proposed method framework was designed based on the relevant sustainability dimensions to support the assessment of components necessary for a successful and sustainable nutrition intervention. Building on the work of Pandey et al. (2016) and Michaud-Létourneau and Pelletier (2017), who designed a multisectoral framework for nutrition coordination, Fig. 1 presents the proposed method framework that incorporates nutrition, environmental sustainability, and the integration of stakeholders' opinions in alignment with the SDGs to promote sustainable nutrition-sensitive programs. The method framework comprised four project phases categorized into field and model-based components. The field-based component consisted of project phases one and two, executed to evaluate the intervention zone and investigate the local processing pathways that could be adopted to address the nutrition challenges. Project phase one was executed in the first nine months, while phase two was executed from the seventh to eighteenth months (with a three-month overlap with phase one) of the SCLANSA-FVC project. At the same time, the model-based components, which consisted of project phases three and four, were applied to investigate the environmental, nutrition, and health impacts and the influence of stakeholder preference on the food processing pathway within the local food system. Activities within phase three were conducted within the same timeframe as phase two. Phase four was conducted intermittently

across years two and three of the project timeline. The optimal identified pathway (Project Phase Four 4.4) was then introduced into the local meal preparation to address the nutritional needs of the target population. This took place in the third year of the project timeline. Subsequent activities involved information, communication, training, and knowledge transfer within the selected local communities.

2.3. Implementation of the framework

2.3.1. Phase one

In project phase one, we sought to evaluate the intervention zones and their local food systems. The studies of van den Bold et al. (2015) and Hodge et al. (2015) highlighted the critical role and social responsibility of stakeholders from different levels, from national to local, in addressing and monitoring nutrition-sensitive activities for long-term improvement outcomes. Given this, in activity 1.1 of phase one, the nutrition program designers, in collaboration with stakeholders and local partners, identified selected sites/intervention zones within Zambia and Malawi based on a framework that captured the (a) level of malnutrition (b) availability of resources, (c) potential for partnership and local partner capacity, and (d) potential for impact and scale (See Figs. S7 and S8 of the supplementary document for site selection frameworks). The stakeholders engaged during this exercise comprised project partners from Canada, Italy, Zambia, and Malawi. Other key
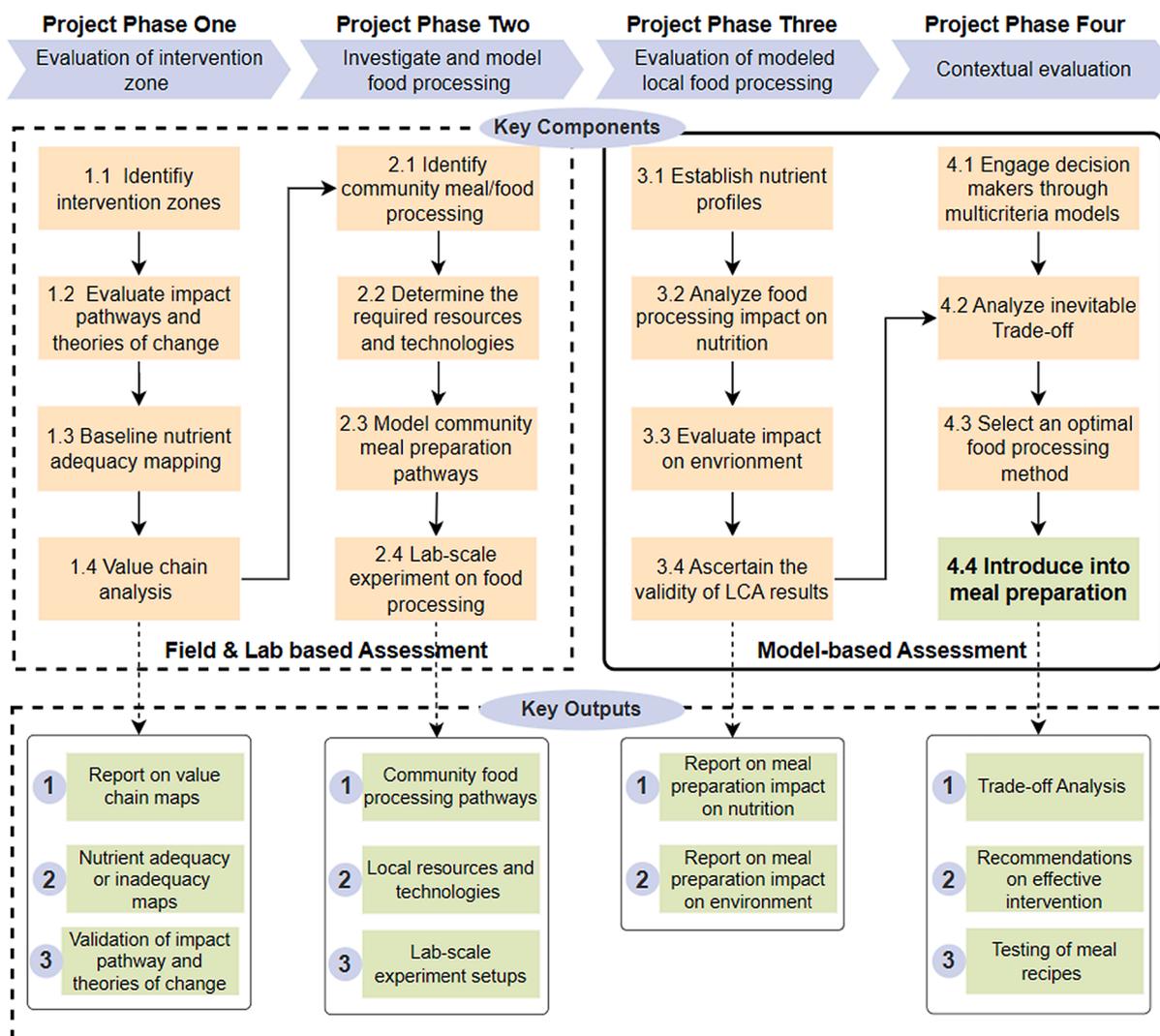

Fig. 1. The proposed integrated framework for assessing relevant components for sustainable nutrition program implementation.

stakeholders included WorldFish, Bioversity International, Self-Help Africa (SHA), the Food Science Department at the University of Zambia, the Small Producers Development and Transporters Association (SPRODETA) in Malawi, and Lilongwe University of Natural Science and Research (LUANAR), Malawi. Then, in activity 1.2, the impact pathways and associated theories of change designed during the nutrition project development were assessed. The impact pathways included (a) actions to be undertaken by intervention designers, (b) goods and services, (c) target beneficiaries, and (d) capacity and expected behavior change. Furthermore, the assumptions linked to the anticipated change in each pathway were validated in harmony with the local food system. Through the impact pathway analysis, intervention program designers determined key beneficiaries and agricultural commodities to meet the intervention objectives.

Next, in activity 1.3 of Fig. 1, a baseline evaluation of the nutrition status of the target intervention zone was conducted to ascertain the challenges of consumption of sustainable healthy diets[2]. The dietary intake and nutrient adequacy information was estimated using two indicators based on ten food groups: the individual dietary diversity score (IDDS) (Habte and Krawinkel, 2016) and minimum dietary diversity -Women (MDDW) (Fung et al., 2018). In the intervention zones within the target countries, 40 clusters were selected for random sampling, with a total sample size of 640 households investigated. This enabled the intervention program designers to develop nutrient adequacy or inadequacy maps and value chain maps, according to the work of Rosenberg et al. (2018), to understand, identify and locate significant challenges behind the target zones' insufficient and unbalanced diet. Then focus group discussions were held, which included 20 individuals from each target region. Four focus group discussions were held to understand the local food system, determine food groups and their seasonality, and highlight periods of food insecurity and the potential of adopting local foods to address nutritional challenges. In the final activity of project phase one, a value chain analysis of the local food system, was conducted to identify resource utilization, agricultural commodity flow, knowledge exchange or technologies, baseline agricultural practices, postharvest losses/analysis, and critical actors within the value chains (Wesana et al., 2018). This involved 1,200 participants from Zambia and Malawi in understanding the value chain dynamics, bottlenecks, and constraints from harvest to consumption in the target zones.

2.3.2. Phase two

The components of project phase two in the method framework focused on investigating and modeling the target district's food processing and meal preparation. First, in Activity 2.1 and 2.2, we identified community-level food processing and meal preparation methods and resources applied for selected agricultural products. Next, further investigation was made into the local perception of food processing, meal preparation, storage, and consumption. From here, bean softening techniques were designed to reduce the cooking time and energy requirements during processing. Table S3 presents the different softening and cooking pathways explored before the intervention execution. Then, in Activity 2.3 and 2.4, the different food processing methods were modeled at a laboratory scale to investigate their impact on nutrition and environmental sustainability.

2.3.3. Phase three

In project phase three, we evaluated the impact of different food processing methods from an environmental-nutrition and time burden perspective. In Activities 3.1 and 3.2, we nutrient-profiled unprocessed

and processed commodity samples. Then, we analyzed the impact of food processing with a critical focus on nutrient retention, increase, and leakages for the different processing methods identified in Activity 2.1. The extent of loss, gain, or retention of relevant nutritional components was based on the selected relevant nutrients, which included macro and micronutrients. All mineral, proximate, and ultimate analyses were conducted according to the recommendations of Kwofie et al. (2019). The statistical analyses of the mineral composition were performed with the JMP Pro (version 16.1.0) software package for Windows (SAS Institute Inc., Cary, NC, 1989–2016). The statistically significant differences among samples were separated using the least significant difference (LSD) at a 5 % probability level. A comparison of means was made using the Turkey-Kramer HSD model. In Activity 3.3, an environmental impact of food processing method leveraging the established life cycle assessment (LCA) framework designed according to ISO standards (ISO 14000:2006 and ISO 14044:2006) to incorporate environmental sustainability during the intervention execution (ISO, 2006). The environmental impact of each food processing method was modeled using the Ecoinvent 3.7.1 database (Wernet et al., 2016) and OpenLCA software v1.11.1 (GreenDelta, 2020). The LCA is summarized into four steps: defining the goal and scope, life cycle inventory, conducting the life cycle impact assessment, and interpreting the results.

The credibility of the conclusion of the LCA study depended on the rigorous status of the uncertainty analysis carried out. Hence, the data quality and variability associated with the parameters used in the assessment were also conducted using the OpenLCA pedigree matrix (Muller et al., 2016; Yu et al., 2018). The pedigree matrix was used to derive an uncertain standard deviation associated with each process stream in the inventory. Unfortunately, this approach was adopted due to the absence of empirical measurement data for the underlying parameters' distribution range. This pedigree method translated the qualitative uncertainty characteristics of the data using five criteria (reliability, completeness, temporal correlation, geographic correlation, and other technological correlation) into the estimated geometric standard deviation of a lognormal distribution (Prado-Lopez et al., 2014; Wernet et al., 2016).

Finally, the Monte Carlo simulation approach was implemented to quantify uncertainty in the OpenLCA software. In addition, pure statistical methods such as the coefficient of variation were employed to validate the quantitative results. The coefficient of variation (CV) measured the degree of dispersion of the probability distribution and demonstrated the extent of uncertainty (Eq.·(1)) (Venkatesh et al., 2011). The lower the CV, the more precise the estimated impact score.

$$CV = \frac{sd(A_i)}{m((A_i)} i = 1 \cdots .N \tag{1}$$

where sd is the standard deviation, m is the mean and A_i is the ordered sample. Fig. 2 illustrates the interdependence and relationship between the components of phases two, three, and four.

2.3.4. Phase four

Finally, in phase four activities 4.1 and 4.2, we applied a decision modeling approach to guide intervention designers in selecting the optimal food processing method while embracing the inevitable trade-offs during the intervention execution. The analysis was performed by applying the integrated Judgement Matrix (JM)- Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) model, which considered stakeholder preferences and priorities in harmony with SDGs 2 and 12 against a set of criteria (Bai et al., 2017; Papathanasiou and Ploskas, 2018). In this context, Fig. 3 demonstrates the different criteria levels adopted. This approach was applied to eliminate confusion for stakeholders. Overall, the criteria aggregation framework for the sustainability evaluation comprised three levels. The first criteria included nutrition targets, environmental sustainability, and time burden during food processing.

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[2] Sustainable Healthy Diets are dietary patterns that promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe, and equitable; and are culturally acceptable. Sources: (Aidoo et al., 2023; Hachem et al., 2020).
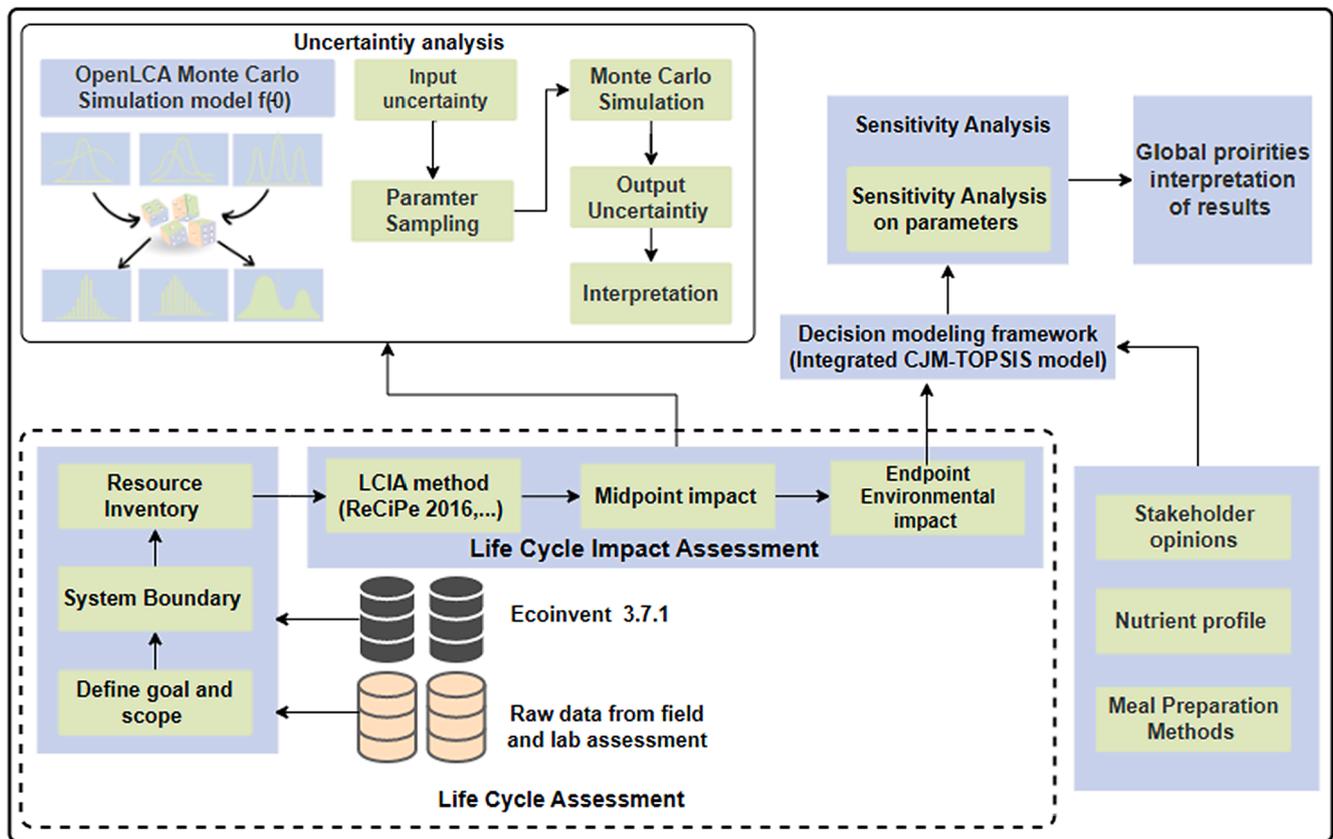
Fig. 2. Method framework for the dependencies between phases two, three, and four.

The impact of time burden was regarded as the time commitment during food processing. Each dimension was divided into subcriteria of unique characteristics at the second level. The environmental sustainability dimension was characterized by human health damage, ecosystem damage, and resource loss criteria. Likewise, the subcriteria nutrition characterized micro/macronutrient loss or gain. At the same time, the food processing time dimension reflected the time burden/gained in minutes.

In activity 4.3, where we explored the optimal processing method, the quantitative outputs of the second level were input to the integrated JM-TOPSIS framework at the decision modeling level. Within the JM-TOPSIS framework, each global priority on sustainable healthy diets was translated and compared at a pairwise and triplet comparison scale. On a pairwise comparison scale, i was considered more important or better than j, whereas, on the triplet scale, i was regarded as a little more important/better than j and k (Agyemang et al., 2022a, 2022b; Kadziński et al., 2021). The linear statements corresponded to comparison values of [0.7,0.3] and [0.6,0.3,0.1].[3] For a comparative assessment of the sustainability performance of the different food processing methods, a practical insignificance threshold of 1 % was set according to the recommendation of Kruschke (2013). Thus in this study, we considered two processing strategies practically equivalent if their difference in performance score lies within (−0.01, 0.01). Furthermore, a series of sensitivity analyses were conducted to examine the influence of variable changes on the choice of implementation pathway. Based on their original value, we assumed decision variables to change within ±10 %. An interpretation and influence of the changes were achieved using the integrated JM-TOPSIS model. It is important to highlight that resources such as fuel and water were not isolated at a criteria level since they were accounted for during the LCA.

Finally, in Activity 4.4, the optimal food processing method was introduced into meal preparation through new recipes designed within the local communities. Additional sensory and evaluation tests were conducted to determine their acceptability. The sensory tests were conducted on pregnant and lactating women, children aged 6–24 months, and caretakers, including men. Furthermore, a cooking demonstration of the formulated meals was made. However, the amount of ingredients differed in the recipes in each community where sensory testing was made—participants judged by taste, odor, texture, and appearance. From here, training, knowledge transfer, and communication of the different meals were made within the selected communities in Zambia and Malawi.

3. Results and discussion-Case study

This section presents the results of applying the method framework in section 2.0 to the SCLANSA-FVC project. The SCLANSA-FVC project was a three-year project that provided support through knowledge development, skill training, and technology transfer to national institutions and local actors such as farmers, processors, extension officers, and policymakers within the food value chain in the targeted countries. This project addressed food processing, handling, storage, marketing, and consumption. The overarching project goal was to sustainably improve the nutritional status of farming households in Malawi and Zambia. The paragraphs below provide the output of following through with the proposed method framework for selecting an optimal local food processing method to improve household meal preparation and nutritional status.

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[3] For a detailed description of the mathematical formulations entailed in the JM-TOPIS model, readers can refer to the following studies (Agyemang, 2022; Agyemang et al., 2022; Huo et al., 2011; Payne; et al., 2023).
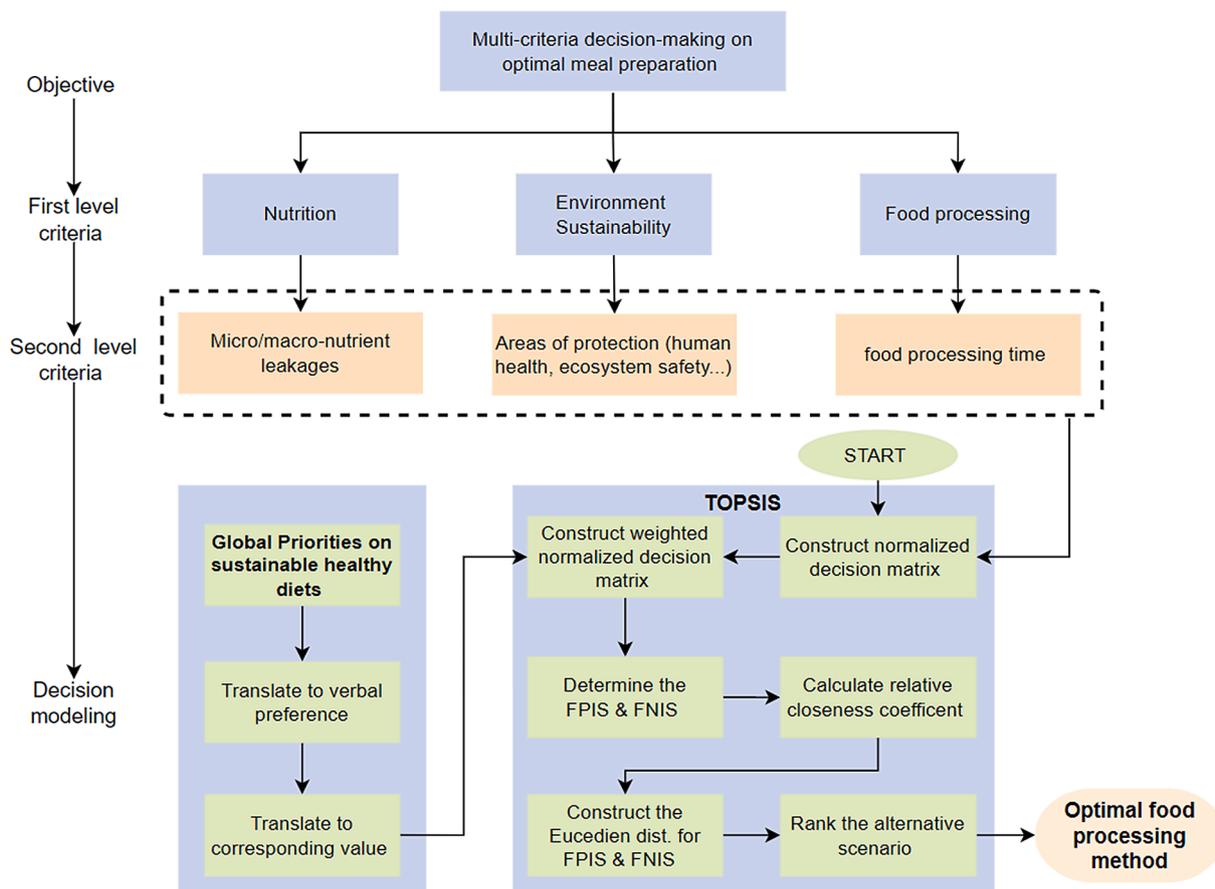
Fig. 3. An integrated JM-TOPSIS decision modeling framework.

3.1. Evaluation of intervention zone (results of phase one)

3.1.1. Selected intervention zones

Based on the completed site selection framework results, the potential districts selected in Zambia were Mbala and Luwingu, while Chitipa and Mzimba were selected in Malawi. The two districts in Zambia were in the Northern province, where the Smallholder Productivity Promotion Programme (SP3) and the Sustainable Agricultural Production Programme (SAPP) were underway. At the same time, the Sustainable Agricultural Production Programme (SAPP) and Rural Livelihoods and Economic Enhancement Programme (RLEEP) projects were ongoing in the Chitipa district in Malawi.

3.1.2. Validated impact pathways and theories of change

Through inception meetings with 45 stakeholders, women's empowerment and household food processing were determined as the pathways to address the nutrition challenges of the target districts. Hence, the target beneficiaries identified were (a) households with women of reproductive age (15–49 years), (b) impoverished households, and (c) households headed by a female.

3.1.3. Baseline survey and nutrient inadequacy maps

In Zambia and Malawi, the baseline survey showed that, on average, 3.42 ± 1.10 and 4.10 ± 0.01 (IDDS) food groups were consumed by all women. Additionally, starchy staple foods were consumed by 99 % of women in Zambia and 100 % in Malawi. 87 % and 86 % of the women surveyed in Zambia and Malawi consumed dark green leafy vegetables. Only 18 % (95 % CI [15.2, 21.6]) of women in Zambia and 37 % in Malawi achieved the threshold of consuming five or more out of ten food groups the day before the interview and are therefore more likely to have more adequate micronutrient intakes. The consumption of animal

products was generally low in selected districts in both countries. Table S1 of the Supplementary Document (SD) shows the food consumption percentage from various groups of women in selected districts. The diet consumed in both countries reflected the typical Malawian and Zambian diets, characterized by large portions of energy-dense foods and low diversity. The results corroborate the work of Fatch et al. (2023), who reported a low agricultural diversity index (mean index of 28 % with a standard deviation of 19 %) from cross-design surveys targeting women, children, and men in 424 households in Lilongwe districts in Malawi.

3.1.4. Value chain analysis

Based on the results of the focus group discussions, three foods (beans, fish, and leafy vegetables) were identified to provide the relevant nutrients, especially for pregnant and lactating women and children. A broader value chain assessment, including processing parameters and analysis, material resource use, and waste generation, was performed on beans, fish, and leafy vegetable value chains and their extent of use within the target regions. For brevity, the rest of the paper will focus on beans. Kabulangeti and Maine varieties were selected due to their availability in both countries. Table 1 shows the mineral comparison of different varieties of beans against other staple foods consumed within the local food system of the target districts. From Table 1, we observe the relative abundance of the target minerals in the Kabulangeti and Maine varieties compared to other available agricultural commodities. Fig. 4 (a) summarizes the targeted regions' bean value chain processes and plant utilization mechanisms. The value chain analysis was extended to include these components to offer a broader understanding of their influence on the project goal while providing realistic solutions. Figs. S1 and S2 of the SD present the material flow analysis, and the process flows for bean production and consumption,

Table 1

Mineral comparison of selected food items against widely consumed food commodities in the target intervention zones (mg/100 g) (Mineral content before processing; **Standard error was not provided in the study).

S/N	Food items	Nutrient			
		Calcium	Iron	Zinc	Reference
1	Kabulangeti beans	154 ± 8.5	8.22 ± 0.9	3.84 ± 0.3	Present study
2	Maine beans	218 ± 14	12.19 ± 1.3	4.48 ± 0.7	
3	Pinto beans	117 ± 28	8.62 ± 0.2	2.48 ± 0.2	Di Bella et al. (2016)
4	Red Kidney beans	84 ± 4.0	10.96 ± 0.1	2.88 ± 0.4	
5	Black eye beans	101 ± 1	8.65 ± 0.9	2.53 ± 0.1	
6	Mung beans	48.29 ± 1.6	10.52 ± 0.2	4.72 ± 0.2	Anwar et al. (2007)
7	Cowpeas (Mtilane variety)	26.0 ± 0.02	2.0 ± 0.02	0.7 ± 0.0	Gondwe et al. (2019)
8	Groundnut (peanuts)	13.4 ± 1.4	1.64 ± 00	1.75 ± 0.0	Belete and Bayissa (2020)
9	Rice	5.19 ± 1.8	2.35 ± 0.3	1.14 ± 0.0	Vunain et al. (2020)
10	Corn	7±**	2.71 ±**	2.21 ±**	Nuss and Tanumihardjo (2010)
11	Wheat (Triticum turgidum)	6.1 ± 0.2	4.5 ± 0.0	5.6 ± 0.1	Ciudad-Mulero et al. (2021)
12	Okra	266 ± 20	1.6 ± 0.2	2.0 ± 0.2	Romdhane et al. (2020)

considering relevant inputs. Additionally, Fig. 4 (b) presents the knowledge flow, type of information, and strength of trust among stakeholders within the value chain.

3.2. Investigation and modeling of local food processing (results of phase two)

3.2.1. Local food processing methods and required resources

The selected bean varieties were classified as hard to cook in nature; hence were subjected to various softening techniques to reduce the time and energy required for cooking. Within the selected districts across the two countries, a preliminary survey showed that 64 % of households processed beans in one form or another. Furthermore, 12.4 % of households reported adding ash (potash) to soften beans during processing. In addition, 25 % soaked beans overnight while 63 % added chemicals (sodium chloride (NaCl)) before processing. Thus, NaCl, potash, water, and wood as fuel source were identified as resources for processing beans within the local food system.

3.2.2. Lab-scale models of local food processing methods

Moving on, we leveraged the results from Section 3.2.1 to design six softening and processing scenarios (see Table S3 of SD). For scenarios 2–5, bean seeds were soaked in 200 ml of water for 8, 12, and 16 h before processing. In scenarios 5 and 6, two commonly used salts, thus 5 % of sodium salt and carbonate of potash, were used to process bean samples. The beans were considered cooked when the predetermined cooked bean hardness (softness) for a cultivar was attained. 100 g of raw Kabulangeti and Maine varieties were processed in all the experiments. Additionally, the cooking time was determined as the time taken to reach the predetermined average compression force of 3.75 ± 0.88 N. Changes in bean hardness were monitored using the TA-HD Plus texture analyzer. The steps followed in this activity were in accordance with the study of Di Prima et al. (2022) and Bezabih et al. (2022).

3.3. Evaluation of modeled local food processing scenarios (results of phase three)

3.3.1. Baseline nutrient profiles

Once the beans had reached the desired hardness to be considered cooked, they were nutrient profiled and compared against the baseline values, thus, unprocessed beans. A comparison was made to measure and monitor the influence of the softening and processing methods on nutrients. Table 2 shows the proximate and nutrient analysis of the unprocessed bean varieties. The average protein, ash, fat, and carbohydrate contents of the two varieties were 27.66 ± 0.2 % dw, 3.41 ± 0.0 % dw, 1.37 ± 0.1 %, and 58.17 ± 0.2 % dw, respectively. The gross energy varied between 1484.2 ± 5.9 and 1485.48 ± 5.2 kJ/100 g for the Kabulangeti and Maine varieties. Additionally, a mean comparison using Tukey-Kramer HSD showed that all proximate components except fats were not significantly different ($p < 0.05$) for both varieties. The proximate content agrees with Joshi et al. (2010) findings which showed protein, fat, and ash contents of 26.73 ± 0.14, 1.01 ± 0.16 and 2.44 ± 0.02 %, respectively, for the Boomer variety of lentils. Nonetheless, the results are contrary to previous studies by de Almeida Costa et al. (2006), who reported protein, ash, moisture, lipid, and carbohydrate content to be 21.9 ± 1.53, 3.00 ± 0.03, 9.88 ± 0.84, 2.34 ± 0.01, and 52.5 ± 0.04 for peas respectively. Similarly, the mineral content measured for both varieties showed no statistically significant difference except for copper, which varied between 1.09 ± 0.1 mg/100 g and 1.67 ± 0.1 mg/100 g for Kabulangeti and Maine, respectively. The results imply that either variety could be chosen to address the nutrition needs of the target districts in Zambia and Malawi. Overall, the Maine variety showed a greater mineral content across nine mineral categories when compared to Kabulangeti. With the baseline mineral contents established, the following section presents the impact of processing on the mineral content.

3.3.2. Impact of food processing method and time on nutrient levels

The impact of softening and processing (cooking) on the nutrient level was completed for fifteen samples of beans from Malawi and Zambia. Fig. 5 presents the nutrient loss profile for the Kabulangeti and Maine beans varieties compared to the results in Table 2. The nutrient losses were estimated as a percent of available mineral content in the beans, while the processing time was represented as time gain. From Fig. 5, four distinct quadrants were observed, namely: >10 % nutrient loss and > 90 min cooking time gain (Q1), <10 % nutrient loss and > 90 min cooking time gain (Q2), <10 % nutrient loss and < 90 min cooking time gain (Q3), and > 10 % nutrient loss < 90 min cooking time gain (Q4). Again, it was observed that the lower the cooking time gains, the lesser the nutrient loss. A notable example was a case of (the Kabulangeti variety), where we observed a 20- 25-minute cooking time gain, for SK_12 and SK_16, as opposed to SK08.

However, this time gain was associated with (8.75 %, 11.68 %), (5.57 %,10.42 %), and (0.98 %,5.26 %) nutrient loss for Ca, Fe, and Zn when compared to SK_08. Perhaps the most interesting aspect of Fig. 5 was that the potash preprocessing increased the beans' mineral content. Thus, we observed a 5.37 % and 2.92 % increase in Ca concentration for the Maine and Kabulangeti varieties, respectively. In contrast, we observed conflicting results for Fe concentration, with an 8.57 % loss for Kabulangeti and a surprising 10.68 % increase in the Maine variety. The results implied that potash processing used <50 % of cooking time while minimizing significant nutrient loss. The results presented here corroborate the findings of a great deal of previous studies by Johnston et al. (2018) and Seymour et al. (2020) on the effect of time on nutritional outcomes. Audu and Aremu (2011) reported reduced mineral content when red kidney beans were boiled, roasted, fermented, and cooked. On average, when boiled and roasted, the Mg and Ca contents were reduced by 4.7–10.3 % and 13.8–93.11 % for the red kidney beans. In contrast, Olika et al. (2019) reported an increase in Zn, Fe, and Ca content of improved chickpea varieties upon processing, while there was
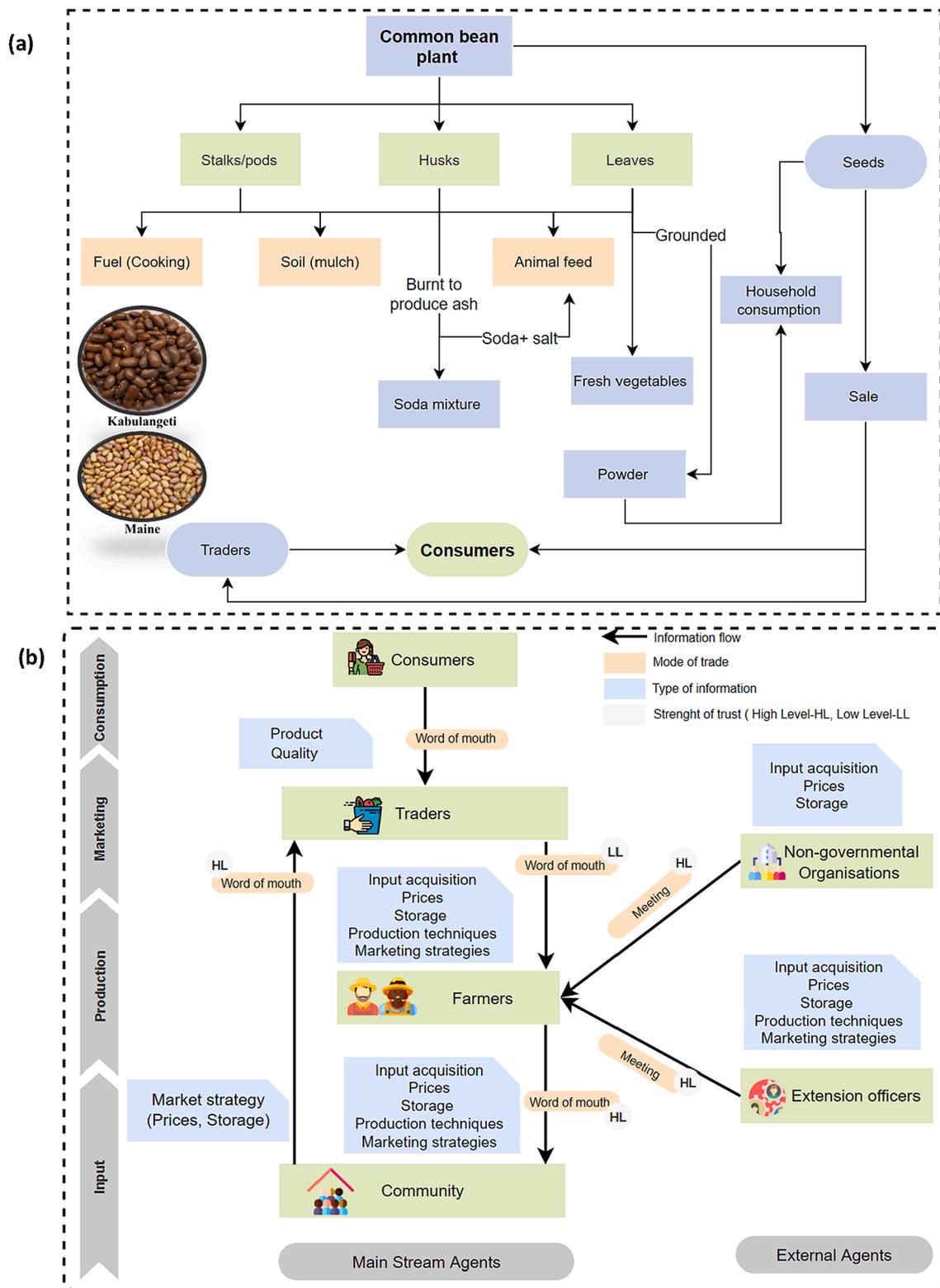
Fig. 4. (a) Bean processing and utilization within the target zones; (b) Knowledge flow and strength of trust among key stakeholders.

a corresponding decrease of 25–82.25 % and 5.89–57.35 % for anti-nutritional factors, tannin, and phytic acid components, respectively. The results demonstrated that the time burden, type of reagent, and processing method employed at the household level could influence the nutritional security of household members. Again, households may have access to food; however, the employed household preprocessing practices and processing methods could result in nutrient leakages, resulting in the spatial distribution of food insecurity across a spectrum of daily recommended minerals and nutrients. Considering that individuals consume composite foods and not single foods, the promotion of sustainable foods in target regions could consider ingredients of a meal to address food insecurity with multiple cobenefits.

Table 2
Proximate composition and mineral analysis of the two varieties of beans.

Nutrient	Unit	Kabulangeti	Maine
Proximate components			
Protein	% dw	26.90 ± 1.6^a	28.41 ± 0.1^a
Ash	% dw	3.46 ± 0.1^a	3.35 ± 0.0^a
Moisture	%	9.25 ± 0.0^a	9.56 ± 0.1^a
Fat	%	1.26 ± 0.0^a	1.48 ± 0.0^b
Carbohydrate	%	59.13 ± 1.2^a	57.2 ± 1.5^a
Gross Energy	kJ/100 g	1484.2 ± 5.9^a	1485.48 ± 5.2^a
Macro minerals			
Calcium (Ca)	mg/100 g	154.33 ± 1.1^a	218.49 ± 1.5^a
Phosphorus (P)	mg/100 g	349.06 ± 5.8^a	315.86 ± 2.6^a
Potassium (K)	mg/100 g	1744.77 ± 3.5^a	1578.16 ± 4.8^a
Sodium (Na)	mg/100 g	2.01 ± 0.4^a	2.56 ± 0.3^a
Magnesium	mg/100 g	188.09 ± 2.1^a	206.13 ± 1.8^a
Minor minerals			
Chromium (Cr)	ppb	193.38 ± 1.6^a	127.67 ± 1.0^a
Copper (Cu)	mg/100 g	1.09 ± 0.1^a	1.67 ± 0.1^b
Iron (Fe)	mg/100 g	8.22 ± 0.7^a	12.19 ± 0.3^a
Manganese (Mn)	mg/100 g	2.00 ± 0.2^a	3.34 ± 0.3^a
Selenium (Se)	ppb	42.25 ± 1.8^a	30.61 ± 1.0^a
Zinc (Zn)	mg/100 g	3.84 ± 0.5^a	4.48 ± 0.4^a
Cobalt (Co)	ppb	703.88 ± 1.2^a	1075.70 ± 5.1^a
Nickel (Ni)	mg/100 g	0.15 ± 0.1^a	0.16 ± 0.1^a

**value of mean $\pm$ SD for raw unprocessed bean varieties in the target districts, analyzed individually in duplicate. The mean values in each row with the same superscript demonstrated no significant difference ($p < 0.05$), while the contrary is observed for mean values with different superscripts.

3.3.3. Environmental impact of food processing methods

So far, the evaluation has presented results on the nutrient profiles and loss/gain due to softening and processing methods. This section presents the environmental impact of household bean processing for consumption leveraging the four-step framework of conducting LCA. Six processing scenarios were modeled. The environmental assessment was based on a functional unit of 100 g of processed beans, ready to be added to household meal consumption. Fig. S3 of the SD presents the system boundary for the activities included in the environmental assessment. The specific activities included transporting from farm to household, sorting, storage, preprocessing, and cooking. The primary resources included common beans, water, energy, and waste handling. The assessment was limited to postharvest processing and before household consumption; thus, pre-harvest processes such as planting, fertilizing, and farming practices applications were excluded. The inventory data for the environmental life cycle modeling for the different softening and processing methods are presented in Table S2 of the SD.

Table 3 presents the environmental impact scores for the bean (Kabulangeti) softening and processing scenarios using the ReCiPe 2016 Midpoint(H) method. Similarly, Table S3 of the SD shows the endpoint impact assessment results using the ReCiPe 2016 Endpoint(H) method. Additionally, Fig. 6 compares the impact results for the midpoint and endpoint impact assessment. The midpoint assessment covered 18 impact categories, while the endpoint captured three areas of protection, human health, ecosystem quality, and resource scarcity. Table 3 and Table S3 results were translated to Fig. 6 (a) and (b) to provide an appropriate comparative assessment. From Fig. 6 (a), it was found that, across all impact categories, bean softening and processing with NaCl was associated with the highest impact score. Softening and processing beans with NaCl resulted in a release of 3.46×10^{-2} kg PM2.5 $_{eq}$ of particulate matter, 1.98×10^1 m^{2}a crop eq of land use, and 4.49 kg CO$_2$ $_{eq}$ contribution to global warming.

From the endpoint areas of damage perspective, softening and processing beans using NaCl resulted in 1.51×10^{-1} species disappearing per year, 2.51×10^{-5} disability-adjusted life years, and 2.15×10^{-7} USD loss for three endpoint categories. On the one hand, softening and processing beans using potash salt resulted in the lowest impact scores for eight impact categories and was associated with the release of 1.51×10^{-2} kg PM2.5 $_{eq}$ of particulate matter, 8.67 m^{2}a crop$_{(eq}$ of land use and 2.07 kg CO$_{2eq}$ contribution to global warming. On the other hand, softening and processing using the SK_16 pathway was associated with the lowest impact across nine impact categories. SK_16 resulted in the release of 1.58×10^{-2} kg PM2.5$_{eq}$ of particulate matter, 9.13 m^{2}a crop eq of land use, and 2.07 kg CO$_2$ $_{eq}$ contribution to global warming. From an endpoint perspective, SK_16 contributed to 9.90×10^{-8} species disappearing per year, 1.15×10^{-5} disability-adjusted life years, and 7.33×10^{-2} USD loss for the three endpoint areas of damage. Furthermore, SK_08 resulted in the lowest contribution toward global warming, with 1.19 kg CO$_2$ $_{eq}$.

In summary, the bean processing scenario using potash resulted in the lowest damage to human health (44.25 %) and ecosystem safety,
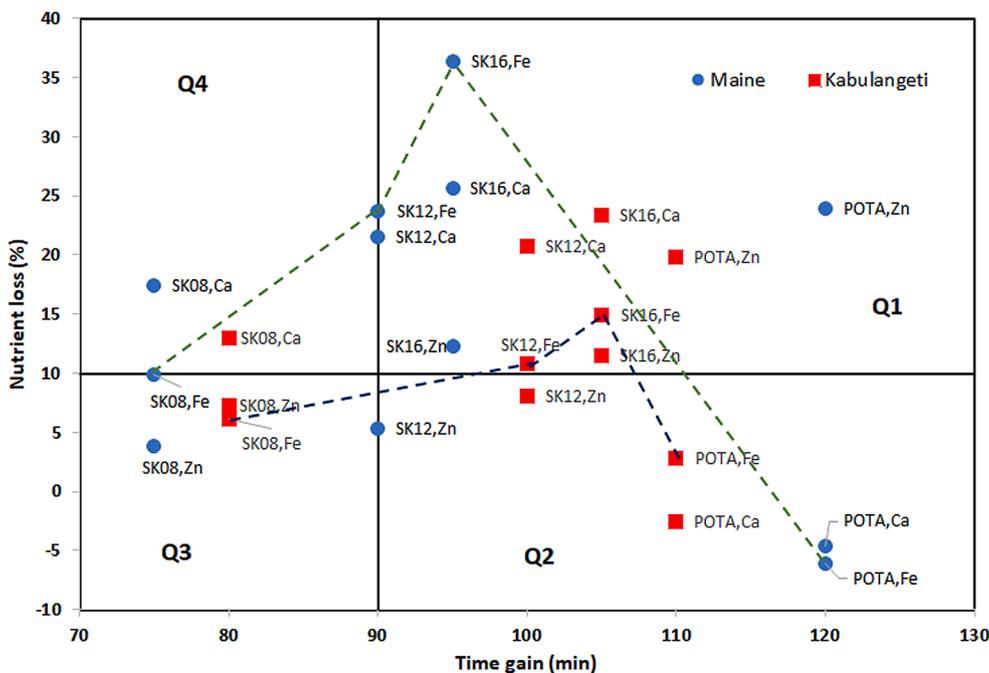

Fig. 5. Nutrient loss against time gain for two varieties of beans.

Table 3

Midpoint environment impact results for the different processing scenarios.

| Indicator	Abb.	SK_08	SK_12	SK_16	NaCl	ODCK	POTA
Fine particulate matter formation, kg PM2.5eq	FPM	2.01E−02	1.66E−02	1.58E−02	3.46E−02	3.30E−02	1.51E−02
Fossil resource scarcity, kg oileq	FRS	3.05E−01	2.12E−01	2.04E−01	4.42E−01	4.21E−01	2.30E−01
Freshwater ecotoxicity, kg 1,4-DCB	FEW	5.00E−02	3.95E−02	3.78E−02	8.20E−02	7.78E−02	3.79E−02
Freshwater eutrophication, kg P eq	FET	1.05E−03	8.68E−04	8.26E−04	1.80E−03	1.72E−03	7.93E−04
Global warming, kg $CO_{2\ eq}$	GW.	1.19E+00	2.17E+00	2.07E+00	4.49E+00	4.28E+00	2.07E+00
Human carcinogenic toxicity, kg 1,4-DCB	HCT	1.23E−01	9.57E−02	9.16E−02	1.99E−01	1.89E−01	9.29E−02
Human noncarcinogenic toxicity, kg 1,4-DCB	HNCT	−3.81E+00	−3.19E+00	−3.02E+00	−7.02E+00	−6.68E+00	−2.78E+00
Ionizing radiation, kBq Co-60eq	I.R.	2.46E−02	1.85E−02	1.77E−02	3.82E−02	3.63E−02	1.86E−02
Land use, m^2a crop eq	LU.	1.15E+01	9.59E+00	9.13E+00	1.98E+01	1.89E+01	8.67E+00
Marine ecotoxicity, kg 1,4-DCB	ME	6.77E−02	5.27E−02	5.04E−02	1.09E−01	1.04E−01	5.12E−02
Marine eutrophication, kg Neq	MET	5.68E−03	4.81E−03	4.59E−03	9.62E−03	9.18E−03	4.37E−03
Mineral resource scarcity, kg Cueq	MRS	8.23E−03	6.66E−03	6.35E−03	1.39E−02	1.32E−02	7.24E−03
Ozone formation, human health, kg NOxeq	OFHH	6.21E−03	4.54E−03	4.41E−03	9.39E−03	8.95E−03	4.71E−03
Ozone formation, Terrestrial ecosystems, kg NOxeq	OFTE	6.34E−03	4.63E−03	4.49E−03	9.58E−03	9.13E−03	4.81E−03
Stratospheric ozone depletion, kg CFC11eq	SOD	7.35E−06	6.36E−06	6.13E−06	1.15E−05	1.10E−05	5.95E−06
Terrestrial acidification, kg SO2eq	TAD	6.47E−02	5.36E−02	5.10E−02	1.11E−01	1.06E−01	4.85E−02
Terrestrial ecotoxicity, kg 1,4-DCB	TET	5.17E+00	2.60E+00	2.52E+00	5.46E+00	5.20E+00	3.89E+00
Water consumption, m^3	WC	7.93E−03	6.39E−03	6.09E−03	1.33E−02	1.27E−02	5.97E−03
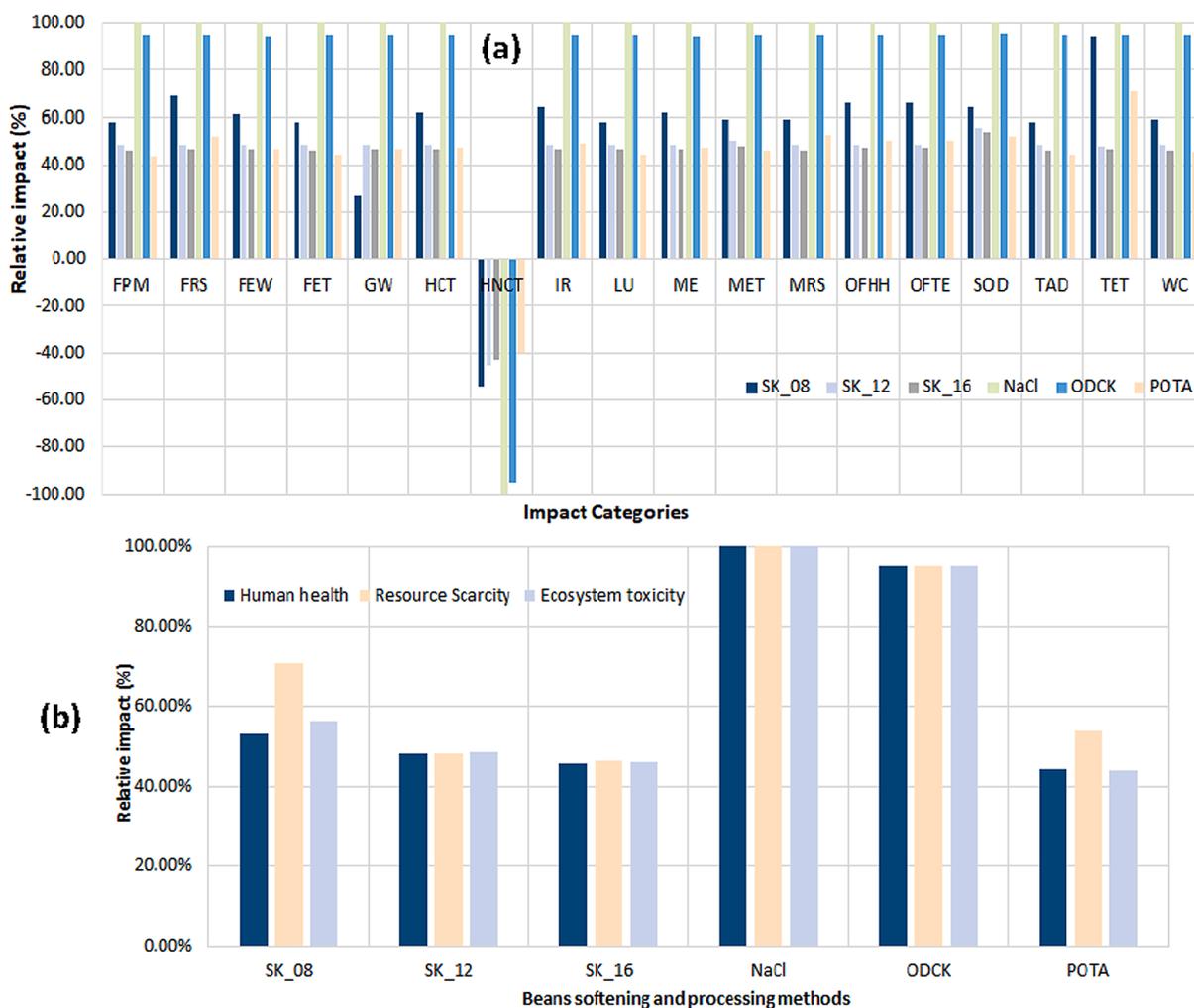
Fig. 6. Relative indicator results of the bean processing scenarios. (a) midpoint results, (b) endpoint results. ** For each indicator, the maximum result is set to 100 % and the results of the other indicators are displayed relative to the maximum.

while processing scenario SK_16 resulted in the lowest damage to resource availability. The NaCl processing strategy contributed the most significant damage in all three endpoint impact categories. Overall, softening and processing beans using NaCl had 2.17 ± 0.0.01 and 2.13 ± 0.02 times more impact on human health, ecosystem damage, and resource loss than SK_08. Considering that the average bean

consumption is 10 kg/capita*year (Sichilima et al., 2016) and 5.47 kg/capita (FAOSTAT, 2017), and the life expectancy is estimated to be 64 and 65 years in Zambia and Malawi (Bank, 2020). In translating the endpoint impact damage on human health, softening and processing using NaCl leads to 25.05 (µ-DALYs) minutes of healthy and productive life lost. On the contrary, softening and processing using POTA results in

11.09 (μ-DALYs) minutes of healthy and productive life lost. On an annual basis, consuming beans processed using NaCl and POTA could result in a loss of 41.75 and 18.49 h of productive and healthy life.

The high healthy life minutes lost were attributed to the high particulate matter, nitrous oxides, and carbon monoxides released from burning wood for bean processing. Furthermore, particulate matter (PM2.5$_{(eq)}$) exposure levels for processing methods (ranging between 66.5 and 68.6 μg/m^3) exceeded the World Health Organization's Air Quality Guidelines for 24-hr mean exposure (15 μg/m^3) (Organization, 2016). The findings were consistent with the work of Bede-Ojimadu and Orisakwe (2020), who reported PM2.5 levels of 26.3 ± 1.48 μg/m^3 to 1574 ± 287 μg/m^3 for the use of wood fuels in domestic cooking in Sub-Saharan Africa. Kocbach Bølling et al. (2009) also reported on the exposure to ambient particulate matter from wood burning and associated adverse health effects, including mortality from pulmonary and cardiovascular diseases. Additionally, the findings broadly support the work of Gakidou et al. (2017), who reported on household air pollution from solid fuels accounting for 2.576 (2.216–2.969) million deaths and 77.16135 (66.08637–88.04887) million disability-adjusted life years (DALYs) in 2016. Despite the detrimental impact of burning wood as a fuel source, which has ramifications contrary to the health pillar of food system sustainability, Morrow et al. (2018) reported on the over-reliance of households in rural areas in Ethiopia on on-farm trees as an energy source. In other rural areas in sub-Saharan Africa, trees are regarded as a critical source of domestic energy, livelihood, and well-being to households (Jagger and Kittner, 2017).

3.3.4. Uncertainty analysis of LCIA results

The Monte Carlo simulation to identify uncertainties in the characterized results for each alternative bean softening and processing method was run for 1000 iterations at a 95 % confidence interval. Fig. 7 illustrates the uncertainty profiles and their respective probability distributions for bean processing scenarios POTA and SK_16 computed for the impact categories with >1 % contribution to the areas of damage. The uncertainty profiles and their respective probability distributions for processing scenarios SK_08, SK_12, ODCK, and NaCl are presented in the SD (Fig. S4). The uncertainty profiles were derived from a hypothesized lognormal distribution. The error bars in Fig. 7 (a) and (b) represented the uncertainty range regarding the ratio of the 5th and 95th percentiles of the upper and lower limits to the mean impact scores. The figures show that a significant degree of uncertainty was introduced into terrestrial acidification and human noncarcinogenic toxicity for processing scenarios presented.

However, a lower uncertainty degree was introduced into the fine particulate matter impact category for processing scenario SK_16. Similarly, global warming impact scores were associated with lower uncertainty for processing scenarios of potash salt. Therefore, the results implied that global warming and other impact categories, except for human noncarcinogenic toxicity, captured a lower level of variability, increasing our confidence in the results presented.

Table 4 presents the 95 % confidence interval for the characterized LCIA results for beans processing using potash salt across all impact categories within the range (upper limit (UL) and lower limit (LL)).

The CV computed for the impact categories described the normalized dispersion for all characterized impact stressors. From Tables S4–S8 of the SD, the CV ranged (6.27–8.49 %), (2.15–6.69 %), (5.58–8.25 %), (6.45–7.27 %), (5.14–68 %), and (4.52–7.00 %) for processing scenarios POTA, ODCK, NaCl salt, SK_08, SK_12, and SK_16 respectively. Surprisingly, human noncarcinogenic toxicity was associated with a negative CV across all processing scenarios, possibly due to the high uncertainty introduced into the impact scores.
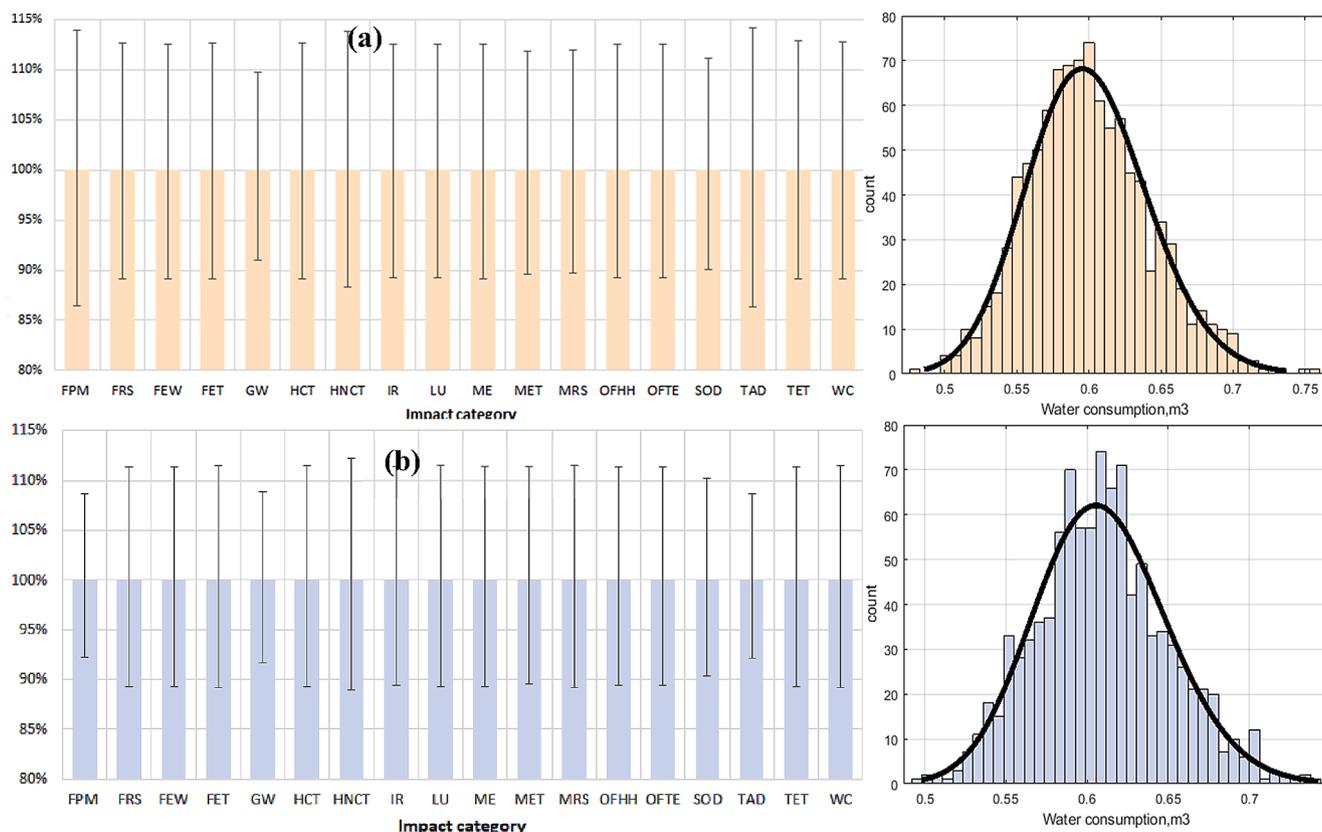

Fig. 7. Uncertainties for characterized LCIA profiles for processing scenarios (a) POTA, and (b) SK_16 and their respective probability distribution profile of characterized water consumption impact category (number of bins = 40)- calculated with 1000-run Monte Carlo analysis in ReCiPe 2016 midpoint.

Table 4
Uncertainty for characterized LCIA profiles of bean processing using potash salt.

Impact category	Mean	SD	CV	LL (5 %)	UL (95 %)
FPM	1.51E+00	1.27E−01	8.40 %	1.31E+00	1.72E+00
FRS	2.31E+01	1.60E+00	6.94 %	2.06E+01	2.60E+01
FEW	3.80E+00	2.63E−01	6.92 %	3.39E+00	4.28E+00
FET	7.97E−02	5.54E−03	6.96 %	7.10E−02	8.97E−02
G.W.	2.08E+02	1.19E+01	5.71 %	1.90E+02	2.28E+02
HCT	9.33E+00	6.48E−01	6.95 %	8.32E+00	1.05E+01
HNCT	−2.80E+02	2.09E+01	−7.47 %	−3.19E+02	−2.47E+02
IR.	1.87E+00	1.29E−01	6.89 %	1.67E+00	2.11E+00
LU.	8.71E+02	6.02E+01	6.91 %	7.77E+02	9.81E+02
ME.	5.15E+00	3.56E−01	6.92 %	4.59E+00	5.79E+00
MET	4.39E−01	2.94E−02	6.70 %	3.93E−01	4.91E−01
MRS	7.28E−01	4.80E−02	6.60 %	6.53E−01	8.15E−01
OFHH	4.74E−01	3.26E−02	6.88 %	4.23E−01	5.33E−01
OFTE	4.83E−01	3.32E−02	6.88 %	4.31E−01	5.43E−01
SOD	5.97E−04	3.71E−05	6.21 %	5.38E−04	6.64E−04
TAD	4.88E+00	4.14E−01	8.49 %	4.21E+00	5.57E+00
TET	3.91E+02	2.74E+01	7.01 %	3.48E+02	4.41E+02
WC.	6.00E−01	4.19E−02	6.98 %	5.35E−01	6.77E−01

3.4. Contextual relevance of sustainability dimensions and inherent trade-offs

This section highlights the influence of relevant stakeholder preferences that can influence the design and adoption of softening and processing methods to introduce into local meal preparation within the target regions. Stakeholder preferences were designed harmoniously with SDGs 2.2 (end all forms of malnutrition) and 12 (sustainable management and efficient use of natural resources). Hence, we explored

stakeholder preferences where nutrition, environment, or processing time were of high priorities. Fig. 8 presents the results from implementing the integrated JM-TOPSIS framework under different stakeholder preferences on the softening and processing strategy for improving meal preparation in the target communities. Two distinct stakeholder preference analyses were conducted, thus a pairwise comparison and a triplet comparison. Fig. 8 (a), (b), and (c) show the results of the pairwise comparison, while Fig. 8 (d), (e), and (f) show the triplet comparison.

3.4.1. The context of nutrition's importance

In the context of a pairwise comparison where nutrition was of utmost interest to stakeholders before introducing into meal preparation at the household level, we observed variations in the choice of softening and processing method to adopt. For example, Fig. 8 (c) showed that if stakeholders viewed nutrition as more important than processing time, bean softening and processing using SK_08 ranked as the optimal processing method. Adopting the SK_08 method resulted in a performance score of 0.683, while using the NaCl processing method ranked as the least desired with a performance of 0.292. Similarly, if nutrition was regarded as more important than environmental sustainability (see Fig. 8a), the SK_12 method ranked as the optimal softening and processing method associated with a performance score of 0.818. In contrast, the SK_16 method ranked the least desired, with a performance score of 0.350.

Interestingly, bean softening and processing using SK_08 resulted in a performance score of 0.814. The closeness in performance scores could imply that both processing strategies can be adopted during the intervention, as there is little or no practical significant difference between their performance scores (0.49 %). In addition, both methods resulted in
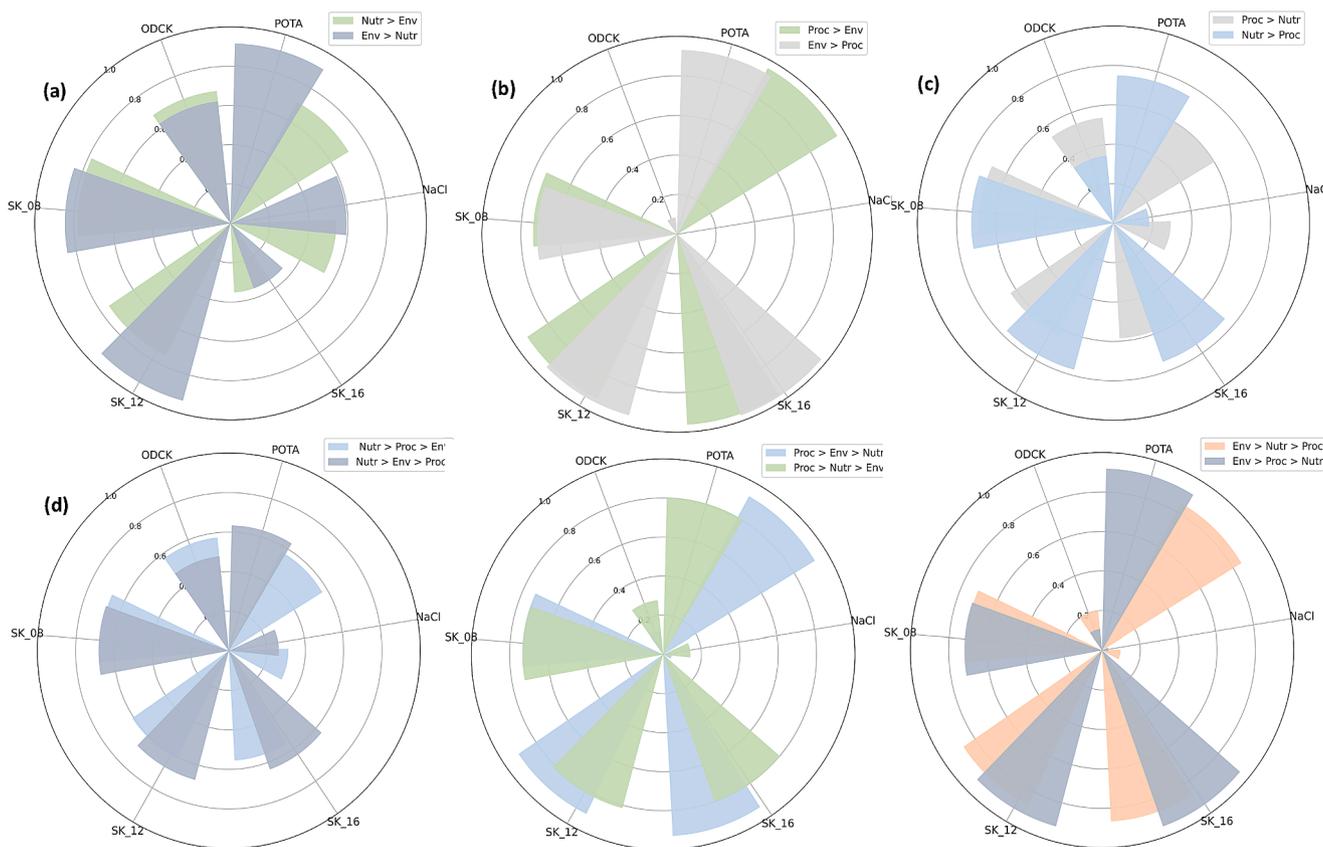

Fig. 8. Contextual variations in the choice of implementation pathway regarding stakeholder interest. Figures (a), (b) and (c) show a pairwise comparison and Figures (e), (f) and (g) show a triplet comparison of different stakeholder preferences for environmental impact, nutrition benefits and processing time dimensions of sustainability. (**Proc is Processing time, **Env is Environmental sustainability, **Nutr is Nutrition.

a relatively good amount of nutrients readily available for consumption.

From a triplet comparison perspective, if stakeholders view nutrition as a little more important than environmental sustainability and processing time, and vice versa, similar observations were made in adopting the optimal softening and processing method. In Fig. 8(d), we can observe that for the case of *nutrition > environment > processing time,* the SK_08 method ranked as the optimal method, while the NaCl method ranked as the least desired. However, the performance scores varied, with SK_08 and NaCl yielding 0.680 and 0.262. Likewise, SK_12 resulted in a performance score of 0.678, which is 0.29 % different from SK_08, which was practically insignificant. Hence, processing strategy SK_12 was considered equivalent to SK_08 in this instance. Furthermore, if we consider the context of *nutrition > processing time > environment,* SK_08 and SK_12 ranked first and second, with performance scores of 0.672 and 0.608, respectively. However, in this case, SK_12 and SK_08 were practically significant. Hence if stakeholder interests were in this direction, then SK_08 would be the more desired method for improving diet.

3.4.2. The context of environmental sustainability importance

Fig. 8 (a) shows that if environmental sustainability was regarded as more important than nutrition, the SK_12 method ranked as the optimal processing strategy with a performance score of 0.934. Interestingly, from the environmental impact assessment results presented above, the softening and processing method POTA ranked the lowest impact across human health (44.25 %) and ecosystem damage areas (43.96 %). Incidentally, SK_12 resulted in a relatively comparable impact contribution of 48.16 % and 44.41 % for the same areas of damage when referenced to the maximum contribution processing method. However, the SK_12 method (7.61×10^{-2} USD2013, equivalent to 48.16 %) resulted in lower resource loss in USD 2013 than POTA (8.49×10^{-2} USD2013, equivalent to 53.65 %). Another possible explanation for this observation was the more significant amount of zinc (2.73 µg/100 g) and iron ((6·11 µg/ 100 g) available in SK_12 than the POTA processing strategy (iron (5.76 µg/100 g) and zinc (2.052 µg/100 g). For the case of environmental sustainability to be more important than processing time (Fig. 8(b)), the SK_16 method ranked as the optimal softening and processing method with a performance score of 0·971. Incidentally, the performance score of SK_12 was 0.946, which was practically significant (2.57 %) compared to the SK_16 and POTA methods.

Similarly, a triplet comparison of environmental sustainability to be a little more important to either nutrition or processing time, Fig. 8(f) revealed that SK_16 ranked as the optimal softening and processing method with a performance score of 0.946 for the case of (*environment > processing time > nutrition*). At the same time, SK_12 yielded a score of 0.872 in the case of (*environment > nutrition > processing time*). However, in pairwise and triplet comparison scenarios, the NaCl softening and processing method resulted in the lowest performance score and hence was undesirable when deciding on the optimal method to introduce in meal preparation.

3.4.3. The context of food processing importance

If we now consider stakeholders regarding processing time as more important than environmental sustainability or nutrition, Fig. 8(b) shows that SK_16 and POTA ranked first and second with performance scores of 0.962 and 0.958, respectively (*processing time > environment*). Regarding (*processing time > nutrition*), SK_12 and POTA ranked first and second with performance scores of 0.770 and 0.750, respectively, which were practically significant. Once again, in both scenarios, the NaCl method yielded the lowest performance scores of 0.182 and 0.000. The triplet comparisons resulted in vastly differing results. In Fig. 8(e), we observed that for *processing time > environment > nutrition*, SK_16, POTA, and SK_12 ranked first, second and third with performance scores of 0.930, 0.924, and 0.909, respectively. In the context of *processing time > nutrition > environment,* SK_12, POTA, and SK_16 yielded performance scores of 0.815, 0.803, and 0.801, respectively. A possible explanation

might be the lower processing time required when employing the POTA, SK_16, and SK_12. The bean softening and processing times required using POTA, SK_16, and SK_12 were 90, 95, and 100 min, respectively. However, differences of 0.66 % and 1.47 % existed between (SK_16, POTA) and (SK_12, POTA), thus making the former practically significant and the latter insignificant. Similarly, in both scenarios, the processing method with NaCl remained the least desired method to adopt for the intervention. Bean processing using NaCl required 200 min, more than twice the time required to process using POTA or SK_16.

Finally, in the context where all sustainability dimensions were equally important to the stakeholders involved prior to the execution of the intervention, SK_12, SK_16, and POTA ranked first, second and third with performance scores of 0.810, 0.793, and 0.783, respectively. Furthermore, the processing strategy with NaCl was the least desired, as has been the case throughout the contextual analysis. In summary, this section has demonstrated that the varying interests of different stakeholders can potentially influence the choice of a food processing method to introduce in household meal preparation during the intervention.

Indeed, the network and gathering of the different stakeholders' opinions to improve the nutrition of selected districts draw similarities to territorial social responsibilities. The rural territories selected in Zambia and Malawi have similar resources and knowledge but unique cultures beyond agricultural production and consumption. Furthermore, the different institutions and stakeholders engaged in this project have responsibilities beyond their legal obligations toward the selected districts through the support of actions that drive sustainability. Therefore, the local food system presented an excellent opportunity to experiment with the response of different stakeholders within different territories while combining different dimensions of sustainability: environment, nutrition, and processing time. For a complete benefit and sustainability of the project beyond the life of the project, it will require the role of community leaders to continue to re-echo and reiterate the knowledge shared for continued benefits. The results and principles presented here corroborate the work of Rusciano et al. (2018), who analyzed surveyed data of Neapolitan farmers, highlighting the environmental, social, and economic features of urban gardens to provide a decision-making pathway. Similarly, Rusciano et al. (2019) investigated stakeholder perspectives under three different sustainability themes (economic, social, and environmental) concerning urban gardens. The study showed that in certain territorial regions of high professional specialization in the farmer's favor, the extreme attention of institutions is toward environmental performance.

3.5. Sensitivity analysis

To ensure confidence in the results presented from the contextual analysis, measuring the approach's robustness was expedient. Hence, a sensitivity analysis was conducted to explore how variations in the sustainability dimensions could influence the final choice of processing method. This was achieved by varying the exact input values of each sustainability dimension and processing method outcomes by ±10 % and then exploring their respective contextual influence. In other words, sustainability components of the top two ranked and the least desired processing methods were varied by ±10 %. Fig. 9 presents the sensitivity analysis performed on the triplet contextual comparison of the sustainability dimension. What was striking about the results in Fig. 9 was that they offered contradictory results to the ones obtained in Section 3.4. For example, in the context of *processing time > nutrition > environment (+10 %)* and *processing time > environment > nutrition (+10 %),* we observed that POTA resulted in the optimal processing pathway to adopt with performance scores of 0.818 and 0.929, respectively, as shown in Fig. 9(a). Howbeit, in the context of *processing time > nutrition > environment (-10 %)* and *processing time > environment > nutrition (-10 %),* SK_12 and SK_16 resulted in the optimal processing strategy with performance scores of 0.830 and 0.938, respectively. In summary, the results indicate that varying sustainability dimensions significantly
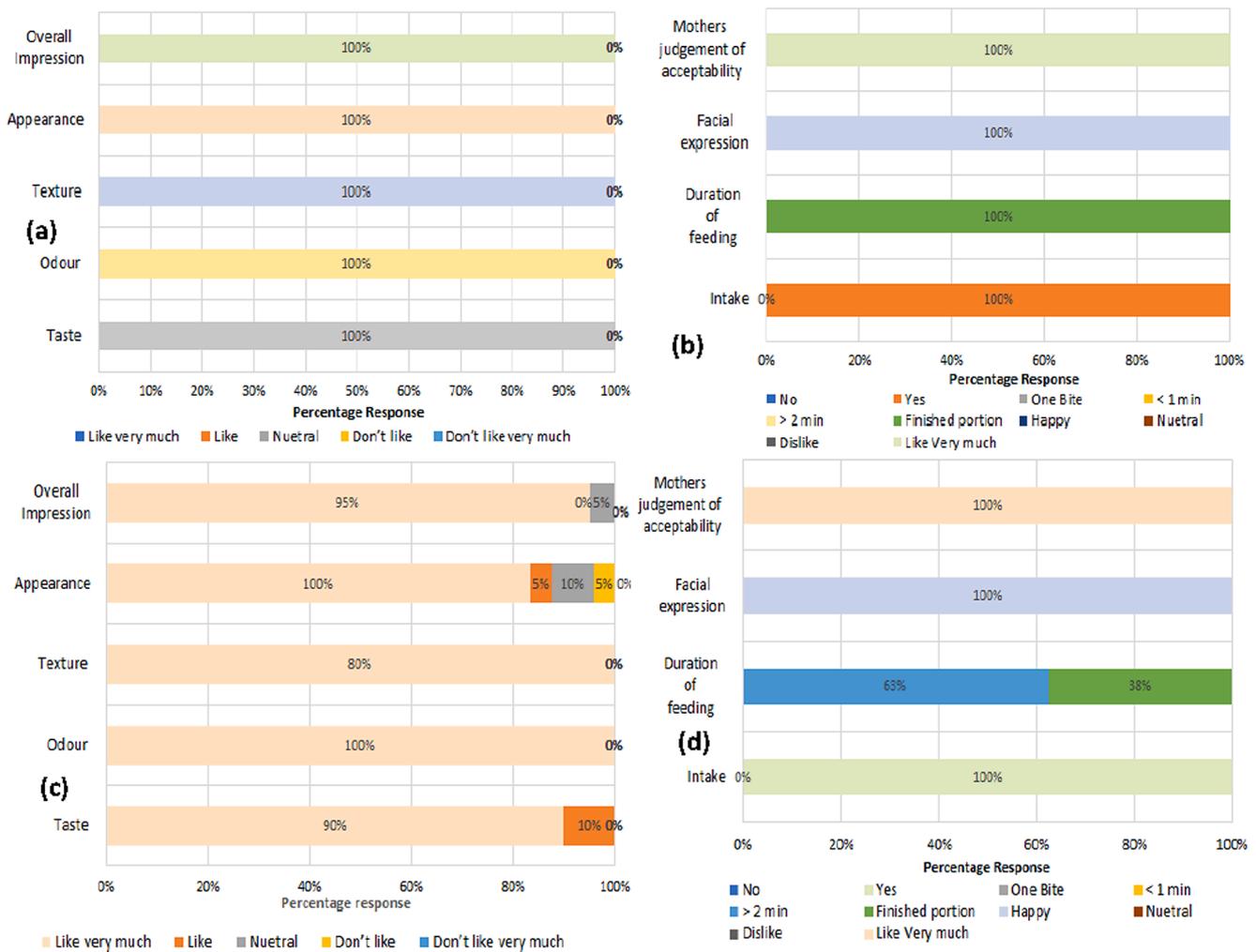
Fig. 9. Sensitivity analysis on the magnitude of each dimension and the influence of stakeholder preferences.

influence the choice of processing strategy. The results in Section 3.4 supported the assertion that contextual factors should be considered before executing nutrition programs.

3.6. Improving nutrition within the local food system

The next step in the intervention focused on incorporating the optimal bean processing method into the local meal preparation to improve nutrition in the target regions. The bean processing method using SK_12 was incorporated into three local recipes and tasted by pregnant and lactating women, children aged 6–24 months, and caretakers, including men. Most participants liked all three local dishes with nutrient-dense agricultural commodities, judging by taste, odor, texture, and appearance. The three recipes were (a) orange juice with dark green leafy vegetable powder, (b) soup made with ground cooked beans, fish powder, tomatoes, and onions, and (c) dark green leafy vegetables with pounded groundnuts and fish powder. Cooking demonstrations were made, and participants' feedback was collected. For each recipe, 20 adult participants and five infants were present for tasting and acceptance evaluation under the supervision of their caretakers in Malawi. In Zambia, 24 adult participants and 8 infants were engaged in the tasting and acceptance evaluation of the formulated meals. Fig. 10 presents the sensory evaluation for both countries using soup made with ground-cooked beans, fish powder, tomatoes, and onions. In Malawi, the caretakers noted that infants ate the soup, seemed happy, and all infants finished their portions. Again, mothers and caretakers expressed a 100 % acceptance rate for the formulated meals. In Zambia, most

respondents ranked the taste, odor, appearance, and overall impression as "5-Like very much".

However, the appearance category scored lower (as five respondents scored appearance ranging from "do not like (2)" to "like (4)"). It was noted that the dark green leafy vegetable powder changed the color of the soup to a dark green, which was not aesthetically pleasing to some respondents. Additionally, caretakers noted that all infants who tried the juice were happy. The mother's judgment of acceptability varied from neutral to very good. The overall impression was "very good" demonstrating that using nutrient-dense powders and ground-cooked beans could be a feasible solution to improving nutrition during the first 1,000 critical days of life in each district where the test was conducted. Nonetheless, the results imply that household nutrition is critical in meeting nutritional goals under the larger umbrella of sustainability. Many studies by Santeramo and Shabnam (2015), Shetty (2018), and Brugh et al. (2018) have highlighted household nutrition as a critical entry point to improving nutritional status and promoting sustainability at the local level, which consequently overflows to national and regional food security targets.

3.7. Implications for policymakers, donors, and intervention designers

3.7.1. Implications for policymakers

For decades now, several policies in research and development have focused on increasing production to address food insecurity. Despite these efforts, the results of the current study imply that local household food processing could be an entry point to meeting food insecurity goals
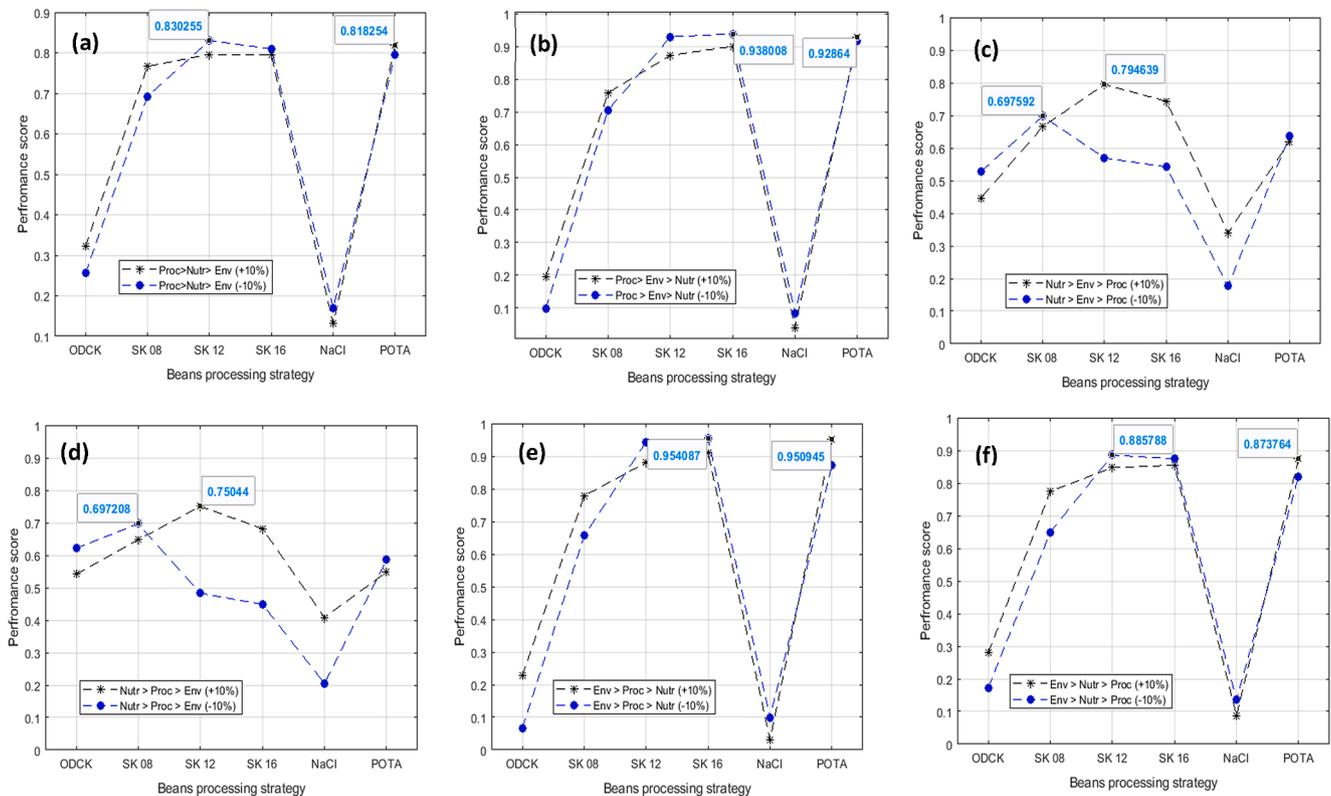
Fig. 10. Sensory evaluation on soup recipe (a) and (c) adult sensory evaluation-100 % represent all participants in Malawi and Zambia; (b) and (d) infant sensory evaluation in Malawi and Zambia.

while promoting sustainable diet cultures. In alignment with the recommendations of Annunziata et al. (2019), the results of the present study suggest the need for well-defined strategies, campaigns, and initiatives to support sustainable food consumption among households in developing countries. In addition, more policies are necessary to promote knowledge sharing of the health implications of different local food processing methods during interventions. Furthermore, existing policies could be redesigned for very popular and most commonly consumed local recipes in harmony with the repurposing of nutrition interventions to better serve the health of people and the planet.

3.7.2. Implications for donors

The study's findings, especially nutritional leakages during bean processing, have raised important questions about global efforts to eradicate malnutrition through nutrition-sensitive interventions. Furthermore, the results could be translated to the context of fortified staple crops such as maize, pearl millet, cassava, sweet potato, and rice that provide higher amounts of vitamins, iron, or zinc in target countries in Africa, Latin America, and Southern Asia. Vaiknoras et al. (2019) reported on the sustained efforts by HarvestPlus to deliver biofortified planting materials and promote iron-fortified bean consumption in Rwandan households since 2012. By the end of 2018, HarvestPlus completed its program and reported that an estimated 20 % of all beans produced in Rwanda were biofortified, with an estimated 420,000 smallholder farming households growing them. Additionally, at the consumption end, the report suggested that iron-fortified beans were consumed regularly by 15 % of the population. However, in 2020, a monitoring and evaluation conducted in Rwanda by Marivoet et al. (2020) demonstrated that the average Rwandan diet looks dismal compared to the recommended levels. Apart from folate and protein, where households reach at least 80 % of the recommended levels, average vitamin B12 adequacy was extremely low (10 %). However, for most other micronutrients, households barely reach half their

recommended intake levels: 48 % for calcium and iron, 50 % for zinc, and 57 % for vitamin A. Furthermore, micronutrient production, market, and household adequacy maps between 2013 and 2017 indicate that (a) neither production nor consumption of iron in Rwanda was yet at the required level, and (b) the ratio of production to consumption is still very high across Rwanda. The results suggest potential iron and other micronutrient leakages from production to consumption. If confirmed, this implies that investments in biofortification during nutrition programs are wasted somewhere in the system because of leakages at the household level. Hence, micronutrient tracking along the value with a critical focus on food processing and household meal preparation nodes within the value chains is needed.

3.7.3. Implications for intervention design

For intervention designers, there is a need to contextualize guidelines and frameworks that integrate other dimensions of sustainability to address health-related issues within target regions. Existing policies that guide intervention implementation could be redesigned to align nutrition intervention with national and regional dietary guidelines. As demonstrated in the present study, stakeholders' preferences could substantially influence a pathway during an intervention. Hence, there is a need for policies that stimulate joint and intersectoral efforts to improve the health and nutrition status of a targeted population through the lens of sustainability.

4. Conclusions

This study developed and tested an integrated field and model-based evaluation framework to assess the nutrition, health, environmental sustainability, and time burden components that support the successful implementation of interventions. Additionally, the influence of stakeholder preference in harmony with SDGs 2 and 12 on choosing an optimal pretreatment and food processing method to introduce into

meal preparation was examined. The findings imply that local food-processing methods may be a leading cause of persistent malnutrition across several regions, despite the efforts of international and government agencies to improve food and nutrition security. Additionally, repurposing nutrition interventions to incorporate other dimensions, such as environmental sustainability, could be critical in promoting a sustainable healthy diet culture that could yield multiple wins. The presented framework can be translated to other food products to promote sustainable healthy diets within local and regional food systems. Additionally, the sensitivity analysis supports the assertion that contextual drivers should be considered to promote sustainable nutrition programs. To many people, food is beyond nutrition and the environment; there are sociocultural (taste preference and traditions), ideological beliefs, and economic drivers that influence food choices and practices. These factors were not captured in the proposed framework. With the ramping demand for sustainability across all sectors, siloed intervention approaches based on single dimensions will no longer suffice. Instead, this calls for incorporating other sustainability dimensions including nutrition and environment into food system intervention design and implementation to significantly close global dietary and macro/micronutrient gaps while operating within a safe planetary space.

CRediT authorship contribution statement

Prince Agyemang: Conceptualization, Methodology, Software, Formal analysis, Validation, Writing – review & editing. **Ebenezer Miezah Kwofie:** Conceptualization, Funding acquisition, Project administration, Methodology, Formal analysis, Validation, Investigation, Data curation, Writing – review & editing. **Aidoo Raphael:** Conceptualization, Writing – review & editing. **Derrick Allotey:** Conceptualization, Writing – review & editing. **Michael Ngadi:** Project administration, Funding acquisition, Writing – review & editing.

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.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodpol.2023.102475.

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