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EDITED BY
Hale Tufan,
Cornell University, United States

REVIEWED BY
Pablo Torres-Lima,
Metropolitan Autonomous University, Mexico
Ndèye Fatou Faye,
Institut Sénégalais de Recherches Agricoles (ISRA), Senegal

*CORRESPONDENCE
Krista Isaacs
✉ isaacskr@msu.edu

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Increasing sorghum yields for smallholder farmers in Mali: the evolution towards a context-driven, on-farm, gender-responsive sorghum breeding program

Krista Isaacs[1]*, Eva Weltzien[2], Hermann Some[3], Abdoulaye Diallo[4], Bocar Diallo[4], Mamourou Sidibé[5], Kirsten vom Brocke[6,7], Bakary Samake[8], Baloua Nebié[9] and Fred W. Rattunde[2]

[1]Department of Plant, Soil, and Microbial Sciences, Michigan State University, East Lansing, MI, United States, [2]Agronomy Department, University of Wisconsin-Madison, Madison, WI, United States, [3]Integrated Plant Breeding, CGIAR, Dakar, Senegal, [4]Programme Sorgho, Institut d'Economie Rurale, Bamako, Mali, [5]Sorghum Program, International Crops Research Institute for the Semi-Arid Tropics, Bamako, Mali, [6]CIRAD, UMR AGAP Institut, F-34398, Montpellier, France, [7]UMR AGAP Institut, Univ Montpellier, CIRAD, INRAE, Institut Agro, Montpellier, France, [8]Centre CABIA (Centre d'Appui à la Biodiversité et aux Initiatives Agrosylvopastorales), Borokoro/Yanfolila, Region de Bougouni, Mali, [9]International Maize and Wheat Improvement Center (CIMMYT), Dakar, Senegal

This case study explores a decades long evolution towards a gender-responsive sorghum breeding program in Mali. With known disparities in men and women's access to the resources that improve agricultural productivity and evidence that gender roles and responsibilities shape knowledge and preferences about varieties, there is need for methods that support gender-responsive processes in plant breeding programs. Gender-sensitive and gender-responsive approaches in plant breeding may increase varietal options available to diverse end-users, increase adoption, and limit negative impacts on vulnerable populations. We assess a participatory plant breeding program in Mali to identify determinants of gender-responsive breeding programs. The analysis uses a case study methodology that draws upon project reports, theses, articles, and experiential knowledge to understand how the sorghum breeding program transitioned over time. This case study details (a) more than a decade of sorghum breeding activities and research that led to (b) the inclusion of women in participatory plant breeding, culinary tests, and large-scale participatory selection in on-farm trials, reaching hundreds of women each year and (c) iterative co-learning processes to develop preferred sorghum varieties and increase sorghum yields on men and women's fields. Analyses indicated that collaborations among many institutions on-farm with community actors, research across various disciplines such as agronomy and social sciences, context-specific breeding, and long-term funding were essential to increasing gender sensitivity and responsive in the breeding efforts.

KEYWORDS

gender, participatory plant breeding, sorghum, gender-responsive, seed

1 Introduction

Family run and small-scale agricultural production systems are vital to the food and livelihood sovereignty of rural populations, who produce 80 and 35%, respectively, of the world's food (Lowder et al., 2021). Rural women contribute substantial knowledge and labor towards farming (Doss, 2014), in addition to their responsibilities for the household and childcare and their income generation roles. Despite their significant roles in growing, harvesting, selling, and preparing these crops for family consumption or sale, plant breeding programs have made limited efforts towards positively impacting rural women's livelihood options. Even the understanding and thus inclusion of women's knowledge, preferences, and livelihood strategies has been limited over the past 50 years. Patriarchal tendencies in western science, socio-cultural traditions in rural societies, intersectional-based biases on who holds knowledge, and the corporatization of public breeding, have all contributed to neglecting a potent avenue for increasing agriculture production and well-being of smallholder farm families.

Crop improvement has been extremely successful in homogenous environments, or at least environments where other inputs and management can generate relatively homogenous growing conditions, such as in the Midwest, United States, the Indo-Gangetic Plains, or the fertile Chernozem soils of Ukraine. Selection pressure to generate high-yielding varieties that perform well across homogenous conditions has had less success in stress-prone, less predictable environments (Annicchiarico, 2002) and on the heterogenous small-scale farms (Dawson et al., 2008) that are essential to local and regional food systems. Low adoption rates of improved varieties are due, in part to, their lack of adaptation to the predominant production environments, farmers' limited access and income for purchasing seed and requisite inputs, risk-aversion to new varieties, and exclusion of farmers, especially women, from the trait selection process (Camara et al., 2005; Meijer et al., 2015; Sissoko et al., 2019; Weltzien et al., 2019a; Acevedo et al., 2020; Magnan et al., 2020; Dessalegn et al., 2022). Successful crop improvement that respects food and livelihood sovereignty in these contexts requires a deeper understanding of the intersectional strategies and environmental factors that shape small scale livelihoods.

1.1 Gender in plant breeding

Women farmers face disproportionate obstacles to achieving food security and well-being compared to men. They own less land, have less access to inputs, credit, education, information networks, and resources in households are often allocated unequally. Even in many measures of agricultural productivity gaps, the rectifying of which is purported as a means to improve economic outcomes and well-being, women's livelihood strategies, intentional choices, and the hidden work of reproductive and household care, are often unaccounted for. With known disparities in men and women's access to the resources that improve agricultural productivity (Doss, 2018), including new varieties and seed, and evidence that gender roles and responsibilities shape knowledge and preferences about varieties (Diallo et al., 2018; Weltzien et al., 2019a), processes and methods to create responsive plant breeding programs are needed.

There are efforts in plant breeding to collect gender-sensitive data and understand how and when gender differentiated research on plant traits is necessary. Commonly, trait preference studies use direct ranking (Jinbaani et al., 2023) or choice experiments (Waldman et al., 2014) but these methods give little attention to the social structures and roles and responsibilities within households that shape those preferences (Teeken et al., 2021). Furthermore, a recent review of gender and plant breeding research showed that even when gender-differentiated data were collected for assessing farmers' preferences for plant traits, gender differentiated analyses were rare (Weltzien et al., 2019a). Recent efforts have focused on interdisciplinary research that examines how roles and responsibilities in crop and seed production, processing, cooking, and marketing influences these trait preferences (Diallo et al., 2018; Marimo et al., 2020; Isaacs et al., 2023). Teeken et al. (2021) examined how intersectional identities shaped cassava trait preferences, finding that food product quality traits were more important to food insecure households, and women and men's preferences varied by region, wealth, and household characteristics. Collection of disaggregated data is not enough—having interventions or next steps in research that respond to the challenges discovered in the initial gender analysis and trait preference discovery are essential for meaningful programming that supports women and men in their pursuit of well-being and sustainable agricultural livelihoods. These efforts should also seek to ensure that research and development activities do not increase burdens on women in terms of drudgery, lack of access to new varieties, or through the creation of varieties that shift who is responsible for the production and subsequent profits (Ashby and Polar, 2019). The previous decade's pioneers in gender-responsive plant breeding can provide useful insights for increasing the gender-responsiveness of other plant breeding programs. Here we use a case study to describe the evolution towards a gender-responsive sorghum breeding program in Mali, to address the research question: What are the determinants of gender-responsive breeding programs?

1.2 Setting the stage

Over more than two decades, sorghum breeders, scientists, farmer associations, and practitioners in Mali have created a farmer-driven crop improvement program engaged in participatory plant breeding (PPB) and interdisciplinarity (Rattunde et al., 2021). The objectives of this sorghum breeding team were to characterize an ever-changing production environment, farmer needs, and gender factors related to sorghum, with the purpose of improving food security (Orr et al., 2022) and farmer well-being by increasing the availability and access to preferred, quality sorghum varieties, diverse variety types, and seed. This program transitioned over time from gender-sensitive (men produce sorghum; women are engaged in sorghum production activities) to actively engaging with women and changing programming to respond to a more nuanced, contextual appreciation of the roles and responsibilities of men and women as sorghum producers and actors. We examine this transition in detail to identify determinants of gender-responsive breeding programs.

This case study uses a mixed methods analysis to understand how multiple factors, including personnel, funding, and participatory processes with many partners, led to increasingly gender-responsive breeding efforts. We present key milestones in the first 15 years of this program, insights into relevant methodologies for future programs, and specific research findings on gender that led to innovations in the breeding program.

1.3 A gender-responsive evaluation framework for long-term participatory plant breeding programs

Efforts towards meaningful inclusion of women in the agricultural development process has had many iterations with varying degrees of alignment with feminist scholarship (Farhall and Rickards, 2021). Nonetheless, recent design and evaluation categories in agricultural research and development, gender-sensitive and gender-responsive, are intended to better operationalize gender-inclusion. Gender-sensitive work recognizes the different needs of women and men (and boys and girls) and acknowledges there are gender power dynamics (UN Women, 2020) while ensuring no-harm such as increased labor or exacerbation of power dynamics in the household. Gender-responsive programming and research calls for understanding the complex interactions of gender and the biophysical environments that shape women and men's needs, priorities, and opportunities (Meinzen-Dick et al., 2011; Mangheni et al., 2021), and respond to them. Programs that are gender-responsive engage with interdisciplinary teams, are intentionally designed to benefit men and women, and consider gender and power relations at the local level as well as within research teams, research and program topics, and institutions (Menghani et al., 2021). Such approaches aim to reduce gender inequities *in situ* (rather than structurally) (Farhall and Rickards, 2021) and use participatory processes that are inclusive and respectful of all stakeholders (UN Women, 2020).

To evaluate the gender-responsiveness of a PPB research and development program, multiple frameworks necessarily come together. Here we briefly examine these disciplinary elements. Evaluations of gender-responsive research and programs have used different parameters. UN Women use two broad categories for evaluations across diverse program types: the first assesses the "degree to which gender and power relationships…change as a result of an intervention" and secondly, it "entails a process that is inclusive, participatory and respectful of all stakeholders," including women's voices and the prevalence of different groups (UN Women, 2020). To test the gender-responsiveness of 14 agricultural research projects, Mangheni et al. (2021) developed a monitoring and evaluation (M&E) framework that considered gender parameters at each stage of research: planning and priority setting, research process, research products, institutional environment, and M&E. This framework lends itself to the research portion of the sorghum program activities but requires amendments for a long-term program that includes capacity building and project-oriented programming.

In ideal PPB programs, all the stages of the crop improvement cycle are in close collaboration between farmers and researchers and there are iterative cycles of discovery, learning, and action through dialogue with farmers, sharing knowledge and characterizing the context, priority setting, planning, and developing seed distribution strategies (Christinck et al., 2005). This participation can take the form of consultation, in which local opinions are asked and research teams make decisions; collaboration, in which priorities are determined together with farmers but project responsibilities remain with the research team; or co-learning, in which farmers and researchers share knowledge, shape priorities, and project responsibilities may be joint (Christinck et al., 2005). Furthermore, farmers and researchers iteratively inform each stage of the breeding cycle, which are: set breeding objectives, generate or assemble new variability for relevant traits, select in segregating populations and experimental lines, test and evaluate experimental varieties, and produce and distribute seed (Christinck et al., 2005). Historically, even with PPB, in which participation is the driving principle, the depth of women's engagement and the response to those findings may be varied. In other words, PPB is not an inherently gender-responsive process. The research components of the iterative cycle of PPB matches, to extent, the research process described by Mangheni et al. (2021). In order to identify determinants of a gender-responsive breeding program, we will use a case study approach analysing the PPB sorghum breeding program in Mali and identifying how and when it transitioned from gender-sensitive to gender-responsive. Finally, we will use these findings to make recommendations for future work and for streamlining the process.

2 Methods and data used

A mixed methods case study review was utilized to analyze when, how, and to what effect gender was integrated into the sorghum breeding program in Mali and to identify critical intervention features that led to a gender-responsive program. An explanatory and descriptive case study approach (Baxter and Jack, 2008) allows for the rich analysis of a process or program in context, using various data sources and exploration of the relationships and communities that shape the phenomenon (Yin, 2003). The process that led towards a gender-responsive program is the unit of analysis (Baxter and Jack, 2008; Miles et al., 2014), in other words we considered the decision-making, research findings, serendipity, and opportunities in the specific context of sorghum breeding in Mali.

The sorghum breeding program that we describe here consisted of the sorghum teams of the Malian Institut d'Economie Rurale (IER) and of the International Crops Research Institute of the Semi-Arid Tropics (ICRISAT), several national non-governmental organizations (NGOs), and farmer cooperatives. The analysis spans from 1997 to 2013, encompassing multiple partners, various funding sources, iterative research objectives, and different stakeholders. This case study focuses on efforts in Mali, although the sorghum team worked with National Agricultural Research Station (NARS) partners in Burkina Faso and Niger as well (vom Brocke et al., 2020). Data for the case study include peer reviewed journal articles, interviews, technical reports, book chapters, dissertations, masters' theses, evidence from informal stakeholder engagement, and grey literature. Documentation from workplans and technical reports provided evidence of how the program responded to research findings over time. We include in-depth descriptions of findings from these resources to fully illustrate the case, to show the subsequent responses to the findings, and because many of these resources are reports or theses that are difficult to access. We also developed a timeline to connect various phases of the program and demonstrate if and how the results of the first learning phase informed the activities of the second implementation phase (Hong et al., 2020). This case study complements a parallel case study on sorghum in Mali that demonstrated how creating a collaborative framework and local level decision-making opened pathways for resilient farming and food systems (Rattunde et al., 2021). Here, we expand on these learnings to understand how gender research was integrated into the same program.

3 Results

Activities, learning, and partnerships in the evolution to a gender-responsive sorghum breeding program.

3.1 Early agricultural research institutions in Mali

The Sudan-Savanna belt across West Africa is a major rainfed sorghum production area. Sorghum production in West Africa is primarily by small farmers for food security purposes, such as home consumption and sale at local markets. There are few large-scale or commercial operations, and the breeding program targeted the small farm production environment. In 1979, ICRISAT and IER began a bilateral collaboration on sorghum and millet research, and later groundnut, funded by USAID. They have worked in partnership since, with goals of strengthening the national research programs, crop improvement, and cropping systems research (Shetty et al., 1991). Earlier documents indicated that exotic germplasm was used to develop improved varieties but low adoption and interest from farmers pushed activities to on-farm trials to test the varieties under farmer conditions. On-farm results showed low productivity and researchers suggested returning to local germplasm as it was more familiar to the farmers and had sufficient yield (Shetty et al., 1991). The same report indicated that women were largely left out of changes in technologies, crops and productivity and that labor for women and other groups limited their ability to participate effectively in outreach activities and make gains in agricultural productivity (Shetty et al., 1991).

3.2 Production in Malian households

Within a Malinke or Bambara village in Mali, family units are called *du* and are composed of extended family members including a male household head, married sons and their families, and/or brothers, and multiple wives (Smale et al., 2019). The *du* are the unit of agricultural production (UAP). The various family units in the *du* have collective plots in which production decisions and planning are controlled by the male household head (Becker, 1989), with labor contributions from all able members of the extended family. The collective plots are used to produce the household supply of staple crops, such as millets, sorghum, and maize, and cash crops, such as cotton.

Minor family members, including brothers, sons, and wives (unmarried women do not have a right to use land) are allocated plots of land to cultivate each year after the collective fields are allocated (Wooten, 2003). Women are allocated plots last, which generally means they receive the plots that have poorer soil quality. Women are responsible for planting crops that contribute to the sauce for the family meal (Wooten, 2003): mainly cowpea and groundnuts; and they grow cash crops to provide for the ingredients in the sauce. It was not understood until later that most women produced sorghum on their plots too, often in intercrops, as an additional household food security crop. The production of sorghum by women on their own plots only became clear through dedicated partnerships with communities and through gender-sensitive inquiry with social scientists (Van den Broek, 2007). These revelations led to multiple changes in the sorghum breeding program that was already an advanced form of participatory plant breeding (PPB).

3.3 Organizations and actors involved in sorghum breeding

The two institutions leading agricultural research in Mali, ICRISAT-Mali and IER, have had collaborating sorghum breeding programs for many decades. In the late 1990's ICRISAT transferred two plant breeders to Mali who had previously started a participatory plant breeding program in India on millets. One of this pair was a woman, who brought with her awareness of women's roles in agricultural livelihoods from previous work, had a keen sense of engaging with local actors, and had previously engaged with women producers in India. Gender-responsive evaluations have indicated the importance of including female investigators (Meinzen-Dick et al., 2011; Elias and International, 2013) because it is more acceptable, according to certain socio-cultural contexts, for women farmers to engage with other women (Njuguna-Mungai et al., 2016). In addition, the female plant breeder was likely an appealing mentor for aspiring female scientists that later participated in activities. Together, the plant breeders brought with them a philosophy of participatory engagement and partnerships with national research institutes and local actors. This approach led to the development of strong, long-term partnerships with farmer cooperatives, associations, and national NGOs, in addition to strengthening engagement with scientists and technicians at IER. The partnership of IER with ICRISAT led to continuous "learning by doing" and training of many staff in PPB and gender-sensitive processes. Partnerships with farmer organizations like ULPC and AOPP, often organized and maintained by dedicated Malian technicians, and national non-profits such as AMEDD and AMASSA, that work directly with farmers, proved to be a formidable approach to develop a network of communities engaged in the participatory activities. These organizations not only supported in logistics and organizing community activities, but also served as a cultural bridge for scientists and technicians to engage with farmers in a meaningful and reciprocal way.

3.3.1 Key personnel

The two plant breeders hired in 1998 that led the full-scale development of a gender-responsive sorghum breeding program at ICRISAT were supported by technicians (many of them were women), animators, graduate students, and committed staff who were essential for communication and connections within villages. The plant breeders continued to shift the program towards developing and conserving varieties based on local germplasm (guinea race rather than caudatum and kafir races) and in collaboration with farmers. Their appointment, among other things, was based on learnings from earlier data collected by an agricultural economist in 1995–1996. That dataset showed new varieties developed from exotic cultivars (caudatum race) were poorly adapted to the production environment and unfamiliar to farmers (Yapi et al., 2000) in the region.

Building on the existing bilateral collaboration between IER and ICRISAT, plant breeders worked with the sorghum breeding program at IER; collectively they are all referred to in this paper as the sorghum team. In addition, various graduate students contributed to the program, with added value from visiting social scientists who periodically sought out research opportunities with the sorghum team and who studied the roles and responsibilities of women in sorghum producing households. For example, in 2007 a social scientist did a study that provided the first insight into the quantities of sorghum women were growing on their fields.

3.4 Key activities

The plant breeders implemented various forms of farmer participatory engagement and partnered with academics and practitioners with diverse backgrounds. The iterative learning over the years in collaboration with these partners and the communities led to new approaches and the creation of a gender-sensitive and then gender-responsive breeding program that incorporated various practical innovations to increase relevance to men and women (Figure 1). As the program grew, roughly 300 women per season evaluated on-farm sorghum lines, more than 50 women conducted the cooking trials per season, and at least 100 women per season conducting the sensory evaluations. In addition to the large number of participatory on-farm trials, and the ensuing discussions and observations, a critical entry point was the detailed understanding of farmers' seed management practices and norms that came later (Siart, 2008).

3.5 Description of breeding activities and engagement with men and women sorghum producers

The learning and subsequent shifts (Table 1) that changed how women were engaged in the PPB sorghum program are described below to illustrate the process of becoming a gender-responsive breeding program. The PPB sorghum, started in 1998, provided the foundation for this learning and evolution, and to this day integrates many of the trial types and evaluations detailed below. The program considers farmer and breeder selection criteria on an on-going basis (Christinck et al., 2005); utilizes a Diversified Guinea Race population, and guinea race core collection for the development of hybrids and varieties with increased resilience; and conducts annual on-farm farmer selection of lines and varieties (Christinck et al., 2019; Weltzien et al., 2019b). Many different forms of participatory processes and farmer-led activities were used (Figure 1) and we highlight several below.

3.5.1 Women in selection

The breeding team (IER and ICRISAT) included women farmers in their outreach and engagement early on with the purpose of developing varieties suitable for the whole household. From previous research, the team knew that sorghum was grown on collective family plots in which management decisions were made by the male household head, men and women labored in the fields with specific roles, e.g., weeding was women's task, harvesting was men's task, and that women were responsible for processing sorghum for meals. Thus, they included both men and women in identifying breeding priorities through participatory variety evaluations and over time adjusted these methodologies to (a) include farmers earlier on in the breeding process through farmers' selection among and within segregating lines (Rattunde et al., 2016), (b) re-define breeding priorities based on the expressed visions of farmers on the future development of their production systems, and (c) ensure that women comfortably shared their opinions and observations.

Looking back, it is clear involving women as participants provided some information as to their preferences, but the structure of the group activities may have limited the information they shared. Their engagement in varietal selections did not necessarily lead to the same level of insight as provided by social and gender analysis, nor into social differences that underpin varietal preferences and affect adoption of new varieties. This is similar to a recent evaluation of gender-responsiveness across agricultural research cycles in which the authors found that few projects conducted a complete gender analysis (Mangheni et al., 2021). Still, women were a part of the activities from the beginning and efforts were made to adjust how preferences and information was collected from women that contributed to shifting towards a gender-sensitive program.

In 2003, the sorghum team initiated more extensive field trials to advance multi-location testing of new breeding lines, involve farmers in selection decisions, and understand farmers' selection criteria in more detail. These trials started in 2003 and included 32 entries, e.g., lines or varieties, that were grown in multiple villages across the region for evaluation by men and women. The trials were typically planted in 4 farmer's fields in a village that had sufficient interest and area to support these larger trials. These trials included newly developed breeding lines and experimental hybrids available from the Diversified Guinea populations, the IER selection program, and local checks (Kante et al., 2017). Having farmers evaluate early breeding lines and incorporating their criteria in the selection process shifted the sorghum program towards a partnership with the farmers, and their organizations (vom Brocke et al., 2010). The farmers chose the varieties that would advance in the breeding program, get released, and enter into seed production and dissemination.

Even in the early stages of the program, when it wasn't clear to the team that women produced their own sorghum, women's experience as farmers contributing knowledge and labor in the collective fields was recognized. This recognition extended into the PPB field days, in which methods evolved over the years to ensure women were comfortable and able to contribute their ideas. One way of doing this was to have women technicians from the sorghum team and/or animators in the communities lead the discussions with women separately from men. Another important feature of these activities was awareness of the different levels of literacy in the groups. After recommendations from social scientists, the sorghum team tried different approaches and the methodology evolved such that a female technician accompanied several women in the field, guided them through the different lines, and helped collect their evaluations of each variety by recording the information. Women who could do their own assessments did so. At the end of the field day, the results were

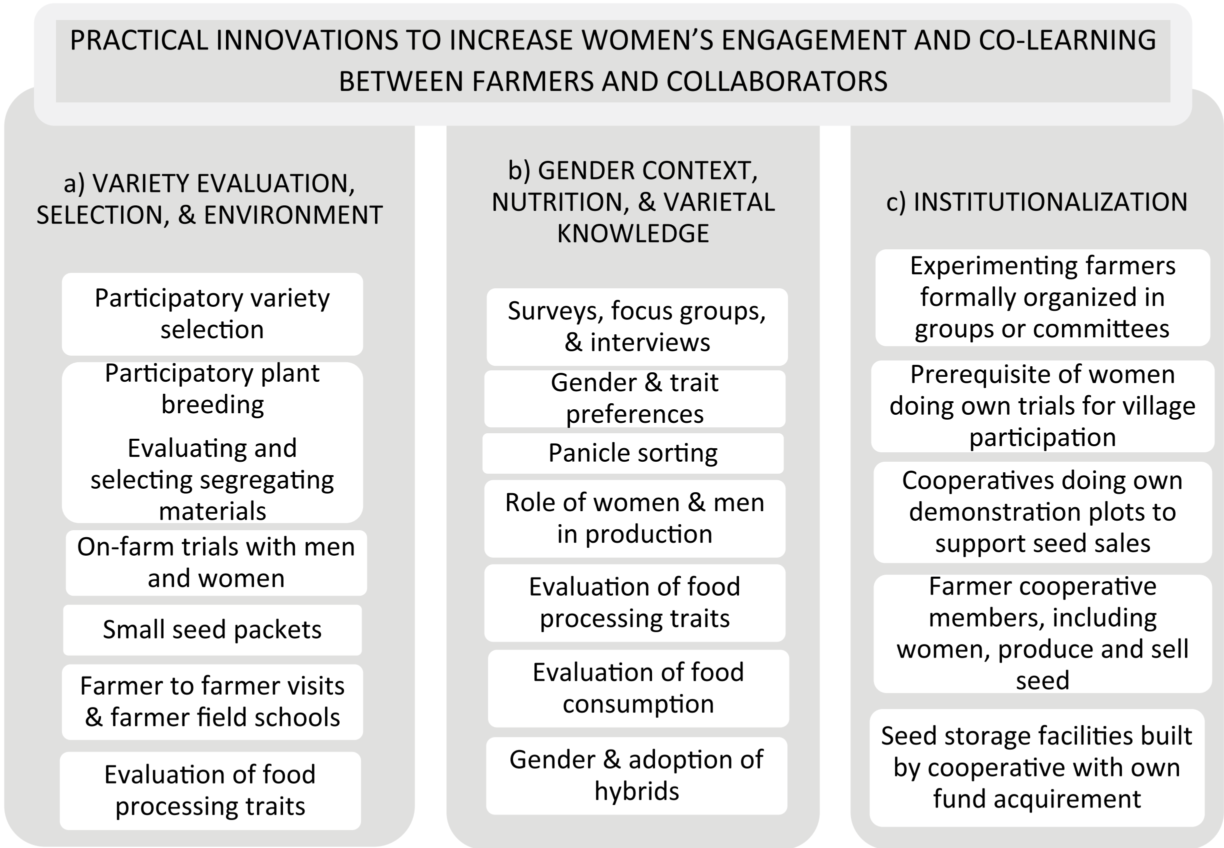

FIGURE 1
Activities used by the sorghum breeding program to engage with farmers through **(A)** biophysical and participatory studies with men and women, **(B)** gender analysis, and **(C)** the methods for institutionalizing local level experimentation and seed production with men and women; and informed by **(A,B)**.

presented back to the plenary of all farmer groups, women contributed to the reflections, and also reflected on the results of the male group.

In 2004, the sorghum team started to formalize participatory, 5-entry on-farm trials with individual farmers. The on-farm trials included entries selected by farmers from the 32-entry trials; the farmers chose 4 varieties to grow in comparison with a local check. The 4 entries were selected based on the results of the 32 entry trials presented to farmer groups during the planning and feedback meetings, held every year in each trial region. Farmers selected entries targeting specific growing conditions, e.g., early sowing dates, fields infested by Striga, intercropping with maize, of low soil fertility. Several sets of such trials were co-designed this way, and village groups of at least 4 farmers chose one of these sets for testing. These 5-entry on-farm trials by individuals allowed the farmers to see how the new varieties (lines) performed in their specific growing environments and they were able to compare performance with their local variety, also by visiting the fields of their group members. It wasn't until later, after understanding the extent that women grew sorghum, that women were specifically included in the 5-entry on-farm trials. Because women grew sorghum mostly as an intercrop in groundnut fields, and thus more space was required, the design was changed, such that women only tested 2 new entries in comparison with their checks. Men farmer groups were given these trials sets only if a group of at least 4 women from their village was interested to conduct their own trials. Male farmers often encouraged their wives to participate.

3.6 Interdisciplinary collaborations over the years

3.6.1 Women's knowledge on grain quality, decortication yield, and culinary attributes

The sorghum team was developing ways to learn more about the grain quality attributes that women, as the processors of the sorghum grain at household level, preferred, starting with the first large scale farmer managed trials, in 2001. Previously, Shetty et al. (1991) evaluated grain quality in the laboratory with detailed observations and analysis of the biochemical attributes important for processing and sensory qualities (Fliedel, 1994). However, these results were not systematically included in selection decisions. Grain quality evaluations moved to the villages, where women could be included, and the whole process of post-harvest management and processing could be considered by the users. Evaluations of grain color, hardness, and other qualities grew into culinary tests conducted in the villages using the varieties (lines) selected from the 32-entry trials. An

TABLE 1 Timeline of gender research and key breeding decisions in the case of PPB with sorghum producers.

Year	Activities and learning	Program response and breeding decisions
Gender-aware stage		
1998–continuous	Identified and examined farmers' selection criteria for sorghum varieties, compared these criteria with the breeder's agronomic observations. Germplasm from local/regional farmers collected. Social survey research not sex-disaggregated Gender-aware approach: Women included as participants in PPB and PVS.	Integrate farmer and breeder criteria into the early stages of the breeding program. Decision to focus breeding program specifically on 900–1,200 mm rainfall environment. Decision to focus on guinea-race germplasm improvement.
1999	Start of 'big trial' with 24 variety trials in Siby and Dioila areas, learning about farmers' seed management practices. Gender-aware approach: Women included as participants in PPB and PVS.	Started the development of breeding lines from "Diversified Guinea Race population," tall and short versions. Breeders leant something about farmers' preferred varieties and trait preferences but not much insight about gender differences.
2001	Breeders expand collaboration to include development partners, such as World Vision.	Breeders initiate collaboration with the IER Food technology Lab on methodology for evaluating processing and sensory grain qualities. Breeders experiment with methodology for fully farmer managed variety trials.
Gender-sensitive stage Definition: programming that recognizes and acknowledges gender power dynamics but does not address these other than try to integrate an understanding into the programming		
2002	Very high demand for test packets for on-farm testing of different varieties; small seed packs made testing feasible for men and women farmers with small plots of land and have unique growing conditions, and provided access to new varietal diversity in the absence.	First sale of 100 g seed packets, from the extension office in Dioila.
2003	Start of 32 entry variety trials, with two plant height groups, as newly developed breeding lines became available from Diversified Guinea populations. Yearly evaluations of 32 entry variety trials in men's fields. Women evaluated same trials separately and in discussion groups, providing new insights into gender differences.	Data on varietal appreciation was always collected from women and men farmers, and presented separately.
2004–now	Start of participatory 5-entry trials with entries selected by farmers from on-farm 32-entry trials from the IER/ICRISAT breeding program: farmers grew 4 varieties and a local check on their farms for evaluations. Greater awareness of need to assess processing traits. Introduction of grain quality assessment and culinary trials.	A standardized protocol for these trials was developed. Specific trial sets targeted specific objectives, and regions; varieties for early or late sowing, for Striga infested fields, for intercropping with maize, etc.
Gender-responsive stage Definition: programming which includes specific action to try and reduce gender inequalities within communities		
2002–2005	Initiated women's assessment of grain, processing, and culinary qualities using cultivars selected from the 32 entry-trials. Learned: the importance of decortication yield, food yield, and the women's skills at evaluating grain visually.	Hired experienced older women regularly to score the seed of selected progenies for grain quality—and throw out the bad ones.
2006	Systematic testing of culinary test method: Validation of decortication and food yield concepts; Different decortication yields of varieties indicated need to consider varietal differences for grain quality on women's work loads.	Continuation of grain quality, processing, and culinary tests. Farmers' local varieties included in tests here forward to provide appropriate reference points for setting targets for major, independent traits.
2007	Master's student in rural sociology studied the production of sorghum in women's fields and assessment of women's potential to engage in the seed supply of sorghum. First realization of the extent that women grew sorghum and how they used it: sold at market for small household goods like salt and maggi for sauce; kept a portion for the lean season; extra meals for younger children. Sorghum production contributed to their food and nutrition security.	Started to participate in Harvest Plus, selection for high Fe because of what they learned about women's use of sorghum for food and nutrition security.

(Continued)

TABLE 1 (Continued)

Year	Activities and learning	Program response and breeding decisions
2008	Another master's thesis in sociology with objectives to gain a better understanding of women's specific sorghum cultivation practices, their role in household resource flows, and the impact of ICRISAT's breeding program on women's sorghum variety choice. Nutrition study evaluating dietary diversity and food frequency to understand role of sorghum in diets, women and children nutritional status, and challenges to food security.	Shifted from 5-variety trials to 3 or 5 variety to accommodate women's smaller field size and production constraints and testing in intercropping situation. Assessment of women's sorghum production constraints, triggering soil analysis of men and women's plots leading to the discovery that women's plots were notably lower in P.
2009–2011	While breeders knew there were problems with low-P soils in the region, they also learned from a soil survey that women's fields were much lower in P	Initiated low-P on-station trials, and targeted breeding for low P adaptation; and eventually low-P progeny tested on-farm.
2011–2012	Changed 3–5 entry trials to include the fertilizer treatment. It was required that at least 4 women test the cultivars, for the village to get trials for the men.	Engaged women more explicitly in seed production, also in hybrid seed production.
2012	Methodology for breeding for low P adaptation published, as a basis for proposing a strategy for including low P adaptation as a trait for improvement into the breeding program. Plant breeding for nutrition-sensitive agriculture (NSA) research initiated to generate and identify varieties with high Fe and Zn particularly for women and children, that were well-adapted to low P fields; partnering with HarvestPlus to develop biofortified varieties.	

interdisciplinary team of nutritionists, breeders, and social scientists developed this culinary test methodology in which the women evaluate the grain quality attributes, decorticate the grain, cook the sorghum into a commonly eaten food, tô, and men and women evaluate the sensory qualities of the tô (taste, color, texture, conservation) (Isaacs et al., 2023). After several years, this method was validated in 2006 across different zones and compared with laboratory tests. Results showed clearly that women had important knowledge about decortication yield and grain quality traits that affected their overall appreciation of a variety (Diallo et al., 2018) and importantly, the amount of food obtainable from a variety (Isaacs et al., 2023). Varieties ranged between 68 and 82% in total "food yield," or the amount of useable flour and grits after the bran was separated out. Among other traits, the color of the final dish (tô), the labor required to process a given variety, the adherence of glumes to the grain, and the grain size were all important factors to women (Isaacs et al., 2023). In response to this new information about processing needs and preferences, the sorghum team hired experienced women sorghum producers to visually score on-station selected progenies for grain quality—and discard the lines that did not meet women's criteria. This ensured that progenies with poor grain quality attributes did not advance in the breeding pipeline. The culinary tests also showed that there are specific thresholds for each grain characteristic, that new varieties have to meet to become adoptable. All culinary tests included a farmer local variety to provide an appropriate reference (Isaacs et al., 2023). The culinary tests with the sorghum team are ongoing, with women preparing the lines or varieties selected from the on-farm trials for evaluation every two years, to ensure that only varieties that meet the minimum standards (thresholds) are released and enter seed production. Varieties with specific processing advantages are also thus identified and get released. The collaboration between food technologists, social scientists and breeders were essential for making these changes to the breeding program.

3.6.2 Social scientists expanded the sorghum team's understanding of women's roles and responsibilities in sorghum production in Mali

A series of social science graduate students interested in conducting their thesis research with the sorghum team added invaluable insights into women's use of sorghum and were pivotal in several breeding endeavors. In each of these cases, the social scientists reached out to the sorghum team because they were interested in conducting applied research in an agricultural context. Most of these connections were spontaneous and not linked to outside funding or the sorghum team's network. These collaborations worked well when the student was embedded in the sorghum program which could then provide advice, logistical support, and feedback. Their research findings were grounded in the local context and provided unique insights that led to shifts in the sorghum breeding program. One of the challenges for the students in sociology programs was that they were expected to produce theses focused on theory rather than applied research.

3.6.2.1 Qualitative research revealed nuances about women's sorghum production

In 2007, a rural sociology master's student studied women's production of sorghum and their potential to engage in the sorghum seed supply (Van den Broek, 2007, 2009). Van den Broek interviewed women in Mandé and Diolia districts to learn about their crop management, access to inputs, labor constraints, field allocations, and how they obtained sorghum seeds. Results varied between the two regions, but generally showed that of the women interviewed, 86% grew sorghum on their own fields, which is similar to other findings of more than 80% (Siart, 2008). The mean and median plot size was 1 ha. This was the first full realization of the extent to which women grew sorghum and how they used it. The evidence also indicated women had more control of the production from the sorghum produced on their own plots. They primarily sold it to have cash for small household goods like oil, salt, and other ingredients bouillon) for the sauce (especially in Dioila district) and for extra meals for younger children (Mandé). In Mandé the sorghum produced by women was also used to provide additional meals for young children, especially during the lean period before the next harvest, when all family members may have to reduce the number of meals taken (Van den Broek, 2007). Women reported that they also sometimes provide extra meals for men who are doing heavy field work during this time of year (Van den Broek, 2007). The women interviewed said that in the past there was sufficient food, but this was no longer the case and their sorghum production was needed to fulfill daily food needs (Van den Broek, 2007). While they liked millet, sorghum required less work to transform it to flour and gave higher quantities of flour (Van den Broek, 2007). Thus, women's sorghum production on their own fields heavily supplemented their and their children's food and nutritional security, beyond that of the collective fields of the larger family unit.

Another important finding was how women obtained sorghum seed for their own plots. Van den Broek's (2007) research found that women primarily got their seed from their husbands, by either setting aside small amounts of sorghum that was allotted for meals, or it was provided as seed at the time of sowing to them by their husbands. They rarely obtained seeds from the market because it was mixed varieties. Gifts were another source of seed. Thus, women had limited sources of seeds and, as was found soon after, they did not always have varieties adapted to their field conditions. The report concluded that more specific information on women's sorghum needs, and their roles would be required before understanding if improved sorghum varieties and their commercialization could benefit women.

3.6.2.2 PPB, seed, and gender

With this new information related to women planting sorghum, the plant breeders sought to learn more specifically about how and when women were engaging in the ongoing PPB. In 2008, a second master's student collaborated with the sorghum team and investigated women's roles in household resource flows, the impact of the breeding program on women's sorghum variety choice, and other aspects of seed procurement and saving (Donovan, 2010). The purpose was to develop strategic recommendations for the sorghum program to address women's lack of access to improved seed and participation in PPB programs. Donovan (2010) corroborated Van den Broek's work, finding women in Mandé region planted sorghum in intercrops and that 90% of women's seed originated from their husband (68%) or close relative (22%; 8% of which were female) but that 70% then saved that seed for subsequent years. Furthermore, despite the long-term involvement of the sorghum team in the region, surprisingly few women had heard from their husbands about the new varieties or trials. Men involved in the sorghum team's PPB trials did not necessarily share information with their wives. The household roles and resource flows clearly had very defined gender roles and Donovan (2010) concluded the breeding program could not count on indirect transfer of improved varieties to non-participants. Her recommendations included: increasing the participation of women in the farmer field trials because this was the primary point of acquisition of new varieties in this informal seed system; utilizing specific gender analysis tools that target women's preferences and needs directly; organizing women's only trainings for more open dialogue with breeders; and identifying ways to work with non-literate women (Donovan, 2010).

The results of these studies guided developments in the program over the next several years. The first was involvement in HarvestPlus biofortification efforts, with a focus on the selection of high iron and zinc, essential nutrients especially for children and mothers, in sorghum and millets. Second, more research was needed on the soil quality of men and women's fields. Thirdly, "institutionalizing" women's participation in the on-farm variety trials and fourth, more efforts were required to make new varieties more widely accessible by initiating the sale of seed local actors.

3.6.3 Nutrition-sensitive breeding

HarvestPlus was a CGIAR initiative that spanned multiple countries and crops and was focused on traditional breeding to develop and/or identify varieties with naturally high levels of essential nutrients (Bouis and Saltzman, 2017). In the case of Mali, sorghum and millet varieties with high Fe and Zn were the target staple crops considered for biofortification because of their potential impact on children and pregnant women. The McKnight Foundation funded An Bè Jigi ("Hope for all") in Mali from 2006 to 2015 and Helen Keller International (HKI) led the collaboration activities with the sorghum team actors (Bauchspies et al., 2017). The first step, in 2006, was a baseline nutrition study, or quantitative data on food consumption and setting a target level for Fe and Zn biofortification of sorghum (Lugutuah, 2013; Bauchspies et al., 2017). Up to this point, there were no known comprehensive food consumption studies in rural areas of Mali (Smit et al., 2009). Two food consumption studies conducted during the project found cereals (sorghum and millet) provided 69% of total energy intake of children and 75% of intake for mothers (Smit et al., 2009; An Be Jigi, 2010). Cereals provided ±50% of total iron intake, and ± 75% of total zinc intake (An Be Jigi, 2010). Nutritional adequacy ratio for both women and children were low, indicating that there was potential for biofortifying sorghum and millets with Fe and Zn.

This interdisciplinary project wed plant breeding with nutrition and used the strengths of the PPB community networks (Rattunde et al., 2021) to specifically focus on women and children. They identified high Fe and Zn content varieties of millet and sorghum, examined differences in decortication loss for different varieties, explored transformation practices in collective cooking sessions for increased bio-availability including producing whole-grain sorghum flour (Bauchspies et al., 2017), and other activities centered around micronutrient consumption and exclusive breast feeding. Subsequent interviews with 120 women in six villages where the projects were implemented, showed 71% adoption of whole grain processing techniques for children's meals (Bauchspies et al., 2017). At this point, with varietal research and cooking qualities focused on nutritional quality for women and children, it was clear the breeding program was undertaking activities that were gender-responsive by directly selecting lines and varieties that would benefit women and children nutritionally. This long-term funding linked directly with other long-term funding programs from McKnight Foundation, to support uptake and seed dissemination.

3.6.4 Targeted breeding for low P soils

The breeding team knew that there were low-P soils in the region that were problematic. In fact, much of West Africa has soil P content below a threshold of 7–10 ppm plant available soil P (Bray-1P) content for healthy crop production (Doumbia et al., 1993). ICRISAT specifically tested women's fields for P content in 2011, and found that women's fields had even lower P content on-farm ($N = 207$, mean = 7.4, median = 5.5; soil data collected by ICRISAT, Mali in 2011) (Leiser et al., 2012). In response, they initiated targeted breeding for low-P on-station using genetic variation among the Sudanian zone sorghum varieties and breeding lines to enhance adaptation (Leiser et al., 2012). This eventually included low-P progeny testing on-farm in the context of actual farming systems, in other words, testing within the biophysical-environmental and socio-economic context. They also developed management techniques to overcome yield reduction and risk due to P deficiencies. Douaje, a local sorghum variety collected on a CIRAD mission (Sagnard et al., 2011), turned out to be a favorite among women because it was well-adapted to their low-P soil conditions, and it had high Fe and Zn content (Table 2).

3.7 Institutionalization of farmer centered production of sorghum seed

The inclusion of farmer selection criteria and evaluation of environmental factors led the team to make context-responsive changes to the program that benefitted all farmers, including women. 2008 saw the release of the first sorghum hybrids from the Diversified Guinea Race population and the sorghum team expanded sorghum seed production efforts that had already started with farmer cooperatives. Women's cooperatives in Dioila became seed producers of hybrid sorghum varieties in addition to the men's cooperatives that were producing and selling seed. For all seed cooperatives, women became important seed sellers in their areas and small seed packs were an important intervention. Table 2 highlights several preferred varieties released from the program.

3.8 Hybrid varieties and on-farm trials with women

As a result of insight about women's smaller field size and production constraints, the sorghum team shifted the on-farm entry trials to be 3- or 5-entries, in that 3-entry trials required less land, so that testing the varieties was more of an option for women. These trials were conducted on a yearly basis, whereby women and men were planting 2–4 varieties on their own plots and comparing it with their preferred local variety. In 2010, 344 farmers planted these mini-plots (HOPE Team, 2010).

3.8.1 Women conducting their own plot assessments of sorghum varieties, with fertilizer

By 2011, women and men were engaged in the 32-entry trials, grain quality, and culinary tests (women only), sensory evaluations, selection for low-P adapted progeny, hybrid seed production, and 3–5 entry trials on their own farms. The next step was to systematically test how the hybrid sorghum varieties performed on-farm in comparison with local and improved germplasm, and if there were variations in performance on men and women's plots. Researchers hypothesized these varieties have the potential to increase farmer yields but identification of which variety types and management practices increase yield under diverse production conditions was needed. Understanding whether yield advantages are shown in men's or women's fields (with even lower soil-fertility) was needed to make informed decisions in the breeding program.

The network of farmer cooperatives engaged with the sorghum team to conduct a two-year study of on-farm trials comparing fertilizer practices with different sorghum variety types. 186 farmers from three regions across the Sudan-savannah zone of Mali conducted these trials. Men and women participated, with a total of 1,604 sole sorghum plots analyzed, 609 of which were women's plots. Each

TABLE 2 Outcomes of note from the PPB program and 3–5 trial processes.

Variety	Cultivar type	Notes
Bobodje	Local—The variety was given by a farmer to the sorghum program technician, with the request to include it in the trials.	As a result of the 32 entry trial tests, this variety was released. It has white, hard, big grains. It is still being produced as certified seed by some farmers, because there is demand for it.
Douaje	Local—a local variety collected by a collection mission of CIRAD and IER (Sagnard et al.)	Douaje was found to have the highest Fe and Zn concentration and when women tested it in their low P environments, it was well adapted. A very tall variety, this was the women's variety and most demanded by them. 30% grain yield improvements with the application of wood ash.
Lata	Improved	Very successful variety, derived from diversified Guinea race population and parent to Pablo and Fadda, the most popular hybrids.
Fadda Pablo	Hybrid	Pablo, followed by Fadda, were the most successful hybrids. Caufa and Mona hybrid varieties had high yields but were difficult to produce and when stressed, the glumes did not open, reducing the food yield.
Seguifa Soumba (CIRAD 406)	Improved	Varieties previously released when the trials started but mostly unknown by farmers, especially in Koutiala.
Tieble (CSM 335)	Local—variety collected during the first germplasm collections in the 1980s	This variety was included in the first set of on-farm-trials, and was consistently appreciated by farmers for its yield and grain quality. It was released by IER and ICRISAT. It became the long-term local check variety for all breeding trials for the Sudan Savannah zone in Mali.
Kalosabani (Jacumbe, CSM 63E)	Improved	Extra early maturing selection from a local variety.

farmer chose 2 or 4 varieties (depending on field size) from the larger scale 32-entry trials to test and compare with a locally preferred variety of their choice. The test varieties included hybrid and open pollinated bred-and local varieties with varying plant morphologies. The farmers tested each variety under both their normal practice of no fertilizer and under an intensified practice that included thinning the plants and application of a basal dose of fertilizer (100 kg/ha Di-ammonium Phosphate (DAP)) at sowing and topdressing (50 kg/ha Urea) at 45 days after sowing. Farmers were provided sufficient fertilizer and 50 g of seed of each variety (Isaacs et al., manuscript in preparation; in-depth methods available).

3.8.2 On-farm results

Combined analysis revealed significant yield differences between the variety types and management practices. Practice had the greatest effect on yield, with intensive practice yielding significantly higher across all variety types for everyone. From the Least Square Means analysis, hybrid-varieties exhibited higher yields than the local varieties in intensive practice for women's trials (1,609 vs. 925 kg/ha, respectively) and men's trials (1,262 vs. 989 kg/ha, respectively). In the farmer practice, although the yields and yield differences were reduced, women hybrid varieties still yielded better than women's local varieties (Figure 2). Otherwise, there were no significant differences in any other category for farmer practice (Figure 2).

Women's yields in the intensive management were higher than men's, this may be directly related to invested interest in success, as they seemed more dedicated to the trials and spent a lot of time managing them (personal communication). Plot-to-plot yield comparisons between hybrid and local varieties in individual farmers' trials varied by zone, with a yield gain from hybrids possible for 75% of farmers in Koutiala (especially women) compared with 55–65% of farmers in the other zones (Figure 3).

An additional 392 test plots were planted in intercrops, important for women, over the two years in Mandé. For these plots, there were few differences in variety type yield between hybrids and local varieties, although men saw a yield boost from hybrids when planted in an intensive practice intercrop. Similar to the pure crop, intensive practice yields in an association increased yields by an average of 500 kg/ha.

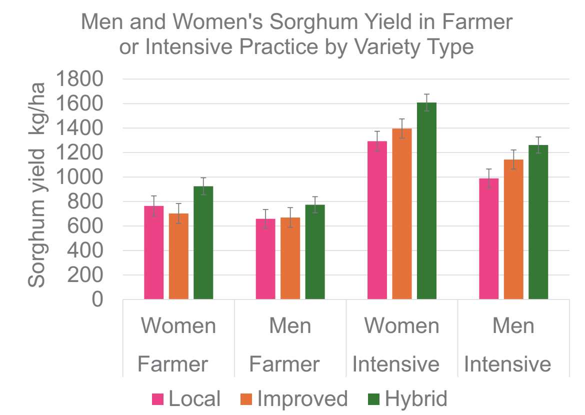

FIGURE 2
Sorghum variety type and management practice mean yields in 2011 and 2012 in Mali. Error bars are standard errors for lsmeans.

The results from this large-scale on-farm study supported the sorghum breeding program strategy of using local germplasm and PPB to generate new hybrid varieties with good adaptation and higher yields for men and women's fields. This superior adaptation of hybrid varieties resulted in women having significant yield gains, even in an intercrop. It also showed that while both men and women may gain from producing hybrid sorghum, there are some environments and conditions in which they are not ideal and improved or local germplasm are better suited. This validated several program strategies including PPB trials each year that engages and exposes diverse farmers to the breeding materials; small seed packs that allow farmers to test new varieties under their own growing conditions with minimal risks (including women's intercrops); diverse variety types available; and activities that support farmer networking to exchange information about different varieties. Finally, the results highlight the importance of fertilizer in improving yields. Although purchase of fertilizer is often out of reach for many farmers, the results showed that if they can access it, men and especially women would maximize the benefit by cultivating hybrid varieties.

4 Discussion

4.1 From gender-sensitive to gender-responsive

The fifteen-year collaboration between ICRISAT and IER sorghum breeding programs in Mali led to improved sorghum production outcomes for both men and women. In the first stage of the program in which women were included as participants in the variety evaluations, the breeding teams were 'gender aware', e.g., aware of gender differences in variety preferences and that improved varieties were not getting traction from farmers. At this stage, no study of gender relations or constraints that underly gender differences in varietal or trait preferences were undertaken.

In the second 'gender-sensitive' stage, breeders realized that sorghum grain quality is important to women. Understanding of trait preferences expanded to include traits that had important implications for the return to women's time invested in grain processing; women were more thoroughly engaged in field and culinary trials and involved in their own discussion groups; but other aspects of gender relations were not investigated systematically. Breeding objectives were more explicitly oriented to address gender-differentiated needs but limited to a post-harvest and culinary perspective.

In the third 'gender-responsive' stage, from 2007 onwards, gender analyses were conducted using methods such as surveys, FGDs, and interviews. In addition, nutrition centered research and breeding was undertaken, focused on women and children's micronutrient deficiencies and methods for increasing Fe and Zn through nutrition field schools. These methods produced data and results that called for breeders' attention because they showed the structural gender inequality that underpinned the different trait preferences—for example, how land was allocated and the quality of that land. This stimulated a cross-disciplinary approach to understanding gendered soil fertility differences. As a result, breeders developed new breeding objectives, including breeding on-station under low P conditions. At this stage, breeding objectives explicitly addressed a structural gender inequality—adaptation to low P availability.

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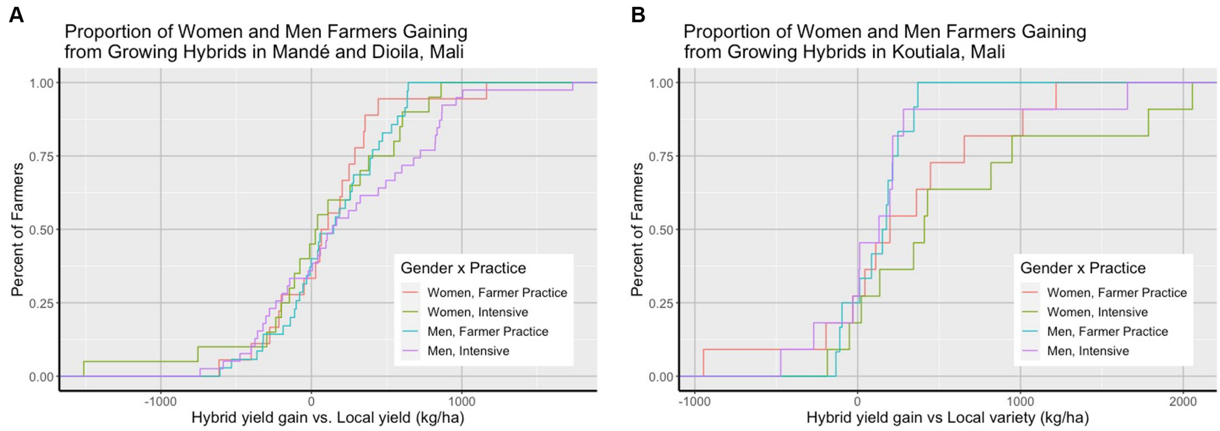

FIGURE 3
Proportion of women and men benefiting from growing sorghum hybrids in **(A)** Mandé and Dioila, and **(B)** Koutiala in 2011 and 2012 in Mali.

Interdisciplinary studies that combined gender analysis with classic agronomic research showed simply focusing on improved varieties and breeding strategies was not sufficient. The two year on-farm trial with men and women not only demonstrated how variable results can be by regional socio-economic differences, but also gender differences in yield that surprisingly, were better for women in several scenarios. Women had the potential to produce as high as men. This suggests gender gaps in productivity may be ameliorated with contextually appropriate resources such as fertilizer and adapted varieties, at least in combination with gender-responsive PPB activities that prioritize local germplasm and farmer selection.

4.1.1 Recognizing and respecting the importance of social scientists

Even with the intentional participatory process the breeding program developed, key factors related to women in sorghum production and household norms would not have been uncovered without the research of social scientists at different junctures. In this case, the breeding program leaders were attuned to the inclusion of women in PPB, but the social scientists had disciplinary theory and methods useful for in-depth inquiry into women's sorghum production and constraints. This interdisciplinary engagement brought new perspectives and skill sets that lent insights into women's involvement in sorghum seed selection and storage, trait preferences, and the breadth of women producing small plots of sorghum. Furthermore, having recognized the significance of gender relations for access to land, the program realized the value of sex-disaggregated analysis of plot fertility, leading to the discovery that women were being allocated plots notably lower in P than plots cultivated by men.

Openness to external researchers, an appreciation of the added insights other disciplines can bring to the table, and close collaboration between actors was essential to the evolution towards gender-responsive breeding. While efforts have been made to increase the role of social and gender studies in biophysical agricultural research and development (Meinzen-Dick et al., 2011; Tufan et al., 2018; van der Burg, 2020), there is still little appreciation for embedding social science research into crop improvement programs, and the depth of training necessary to conduct effective gender and social science research as part of an interdisciplinary team. To ensure gender-sensitive and-responsive research, open-minded teams are required that have a basic understanding and respect the knowledge, methods, and insights that gender and social studies bring (and that *believe* that gender disparities may exist); and vice versa. For example, some engagement with social scientists was less fruitful to the sorghum program because the social scientists were unwilling to engage fully with the sorghum team and create meaningful feedback loops to learn from each other (personal communication), as they saw their role rather as evaluators of the programs and its impacts. Or, applied gender research by graduate students was stymied within their academic units because the work was not appropriately embedded in theory. These theses had to be completely rewritten in order to pass, with the results no longer accessible to the breeding team nor useful to the realities on the ground (Van den Broek, 2007, 2009). This is partially an issue within academia—as western science and funding streams highly value STEM programs, creating hierarchies and doing little to bridge the divides and create shared respect of disciplines. Institutional change is needed in the long-term, and in the short-term, identifying graduate student programs that value applied work and hiring scientists with interdisciplinary sensibilities, and embedding multi-disciplinary teams into crop improvement programs, may be means to overcome these challenges.

4.1.2 Local actors are a cultural bridge between stakeholders

The inclusion of local actors was key to a successful gender-responsive and community engaged breeding program. The team understood the importance of the inclusion of local actors that serve as a cultural bridge between the community, international scientists, and even fellow country people with different backgrounds (urban, status, etc.), language, and cultures. Key personnel with rural experience, community relationships, and technical expertise were the backbone of the program. Key personnel that were women and could comfortably engage with women farmers was essential. One point of reflection is that while researchers and facilitators may be highly educated, they often come from urban backgrounds. This may cause problems in translation due to lack of knowledge regarding terminology and local agricultural vernacular, lack of experience growing crops, different cultural norms, and class differences. Applied research at the community level requires partnerships with local actors to build trust, to bridge language and cultural translators, and ensure culturally appropriate engagement. Finally, while participatory processes are intended to be inclusive, inherent biases of facilitators and organizers can limit participation of different or disadvantaged groups of people. Only through in-depth, intentional, and contextual discovery appropriate to their targets, can they fulfill this goal.

4.1.3 Long-term funding is essential for sustainable outcomes

Long-term or on-going funding, even in small amounts, was vital to the continuation of projects, to learning, and to the subsequent and meaningful adaptations of the program. Long-term funding supported the full-fledged development of the PPB work, the culinary tests, and nutrition-focused research. Initial funding by the CGIAR Program for Participatory Research and Gender Analysis (PRGA) was critical for initiating the farmer participatory research in Mali and providing opportunities for scientific exchange for the development of methodological approaches. The McKnight Foundation provided funds continuously since 2006 that supported PPB embedded in seed systems work in Mali and they supported the iterative process needed to strengthen farmer organizations to produce and disseminate high quality seed (Donovan, 2010). Long-term projects were also vital to learning and implementing new processes that streamlined selection and screening. For example, co-developing the culinary test over several years with various actors and community feedback helped identify key traits that would then be identified early on and "weeded" out of the breeding pipeline. While it took several years to get the culinary test right, there were valuable outcomes and shortcuts were developed. Knowledgeable women from the villages could sort grain from different varieties in the laboratory to quickly exclude varieties without the right traits. This is an example of streamlining a process after the initial investment in learning the nuances of an issue. Funding with commitment to partnerships with local actors, inclusive of women, helped the program nurture these connections over many years.

5 Conclusion

Gender-responsive plant breeding programs require thoughtful and long-term engagement that enables an iterative process of learning with communities. Our analysis indicated that determinants of a gender-responsive PPB program include engagement and gender analysis at each stage of the breeding cycle; in-depth contextual understanding of men and women's roles and motivations in relationship to the crop; men and women team members that have technical and culturally appropriate gender-sensitivity; collaborative, interdisciplinary teams; equitable opportunities for selecting and testing materials; innovations that respond to findings from gender analyses, such as changing breeding priorities, developing new evaluation criteria, or using small seed packs that are more accessible to certain groups; and technologies appropriate for men and women. Such endeavors require rich partnerships across stakeholders and funding cycles that enable trust-building, co-learning, and the flexibility to modify approaches.

Over the course of a decade, a multi-institution sorghum breeding team in Mali transitioned to a gender-responsive program that worked to understand and meet varietal needs across regions with different resources, market needs, and food traditions. Interdisciplinary engagement provided insights to environmental challenges such as low-P conditions on women's fields, women's sorghum production constraints and preferences, and enabled a nutrition program that increased consumption of whole grain sorghum for children. The gender-responsiveness of the team This willingness to engage with other scientists and directly with farmer stakeholders strengthened the program. It also revealed the complex realities of agricultural production and the nuanced socio-cultural factors that inform farmers decisions. The success of the sorghum team and the varieties that were a product of this work was likely because they embraced this complexity, partnered with the community, and focused on empowering a specific region through interdisciplinary programming and variety development. To be sure, this was possible through long-term funding that allowed for sometimes slower progress including the slow timeline of building meaningful community partnerships and systematic yet relevant and appropriate processes. Funders that also understood these complexities on the ground were vital to this program.

In drawing on lessons from established approaches in the sorghum breeding program in Mali, participatory processes can enable the co-creation of knowledge and new technologies between scientists, farmers, and other actors. Diverse processes including large scale regional trials (based on farmer germplasm) in villages, on-farm trials with hundreds of farmers, participatory variety selection, women led processing and culinary tests, and qualitative research, all contributed to the program's understanding about varietal traits for adaptation in various environments and for diverse actors. It also increased the sorghum breeding programs cultural awareness of traits necessary for processing and cooking and the important role of women in the production of sorghum at the household level and in their own plots.

Globally, there are many initiatives, including private and corporate, aimed at increasing farmer access to improved varieties and ensuring this seed gets to the last mile. While increasing farmer productivity is a highly important goal, ensuring that happens sustainably is also vital to our future. Often, the genetic integrity and diversity of these initiatives are unknown, particularly in the case of patented seed. This case study demonstrates methods to apply a more nuanced and inclusive approach to co-development of improved plant varieties that are environmentally and culturally adapted. Furthermore, by relying on local germplasm to develop a diversified sorghum population, the sorghum team increased the likelihood of farmer adoption and environmental adaptation, and they maintained, if not expanded, the varietal diversity necessary to ensure agricultural resilience in the region.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KI: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. EW: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing, Formal analysis. HS: Data curation, Investigation, Methodology, Writing – review & editing. AD: Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. BD: Data curation, Investigation, Methodology, Validation, Writing – review & editing. MS: Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing – review & editing. KV: Investigation, Methodology, Writing – review & editing. BS: Data curation, Investigation, Methodology, Resources, Writing – review & editing. BN: Validation, Writing – review & editing. FR: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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