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Dual-Purpose Sorghum: A Targeted Sustainable Crop-Livestock Intervention for the Smallholder Subsistence Farming Communities of Adilabad, India

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Sorghum plays an important role in the mixed crop–livestock system of tribal farming communities in Adilabad District, a high climate risk-prone region in India. Currently, the local seed system is limited to landraces and hybrids that are primarily used for domestic grain and fodder purposes. This study aimed to understand the farmers' needs and context, and use this knowledge to deliver relevant, adoptable climate-smart sorghum crop technologies through farmer-participatory approaches (FPAs). We conducted an *ex-ante* survey with 103 farmer households to understand their preferences and constraints concerning sorghum, their staple food-crop. Farmers expressed taste as the most important characteristic, followed by stover yield, grain yield, drought adaptation, and pest resistance. They identified fodder deficit, loss of seed purity in landraces, and lack of diverse sorghum seed options as critical constraints. Therefore, we chose dual-purpose, open-pollinated sorghum varieties suitable for postrainy/*rabi* cultivation as the study site's entry point. Accordingly, sixteen popular *rabi* sorghum varieties were tested at ICRISAT station (2017–18 and 2018–19) for agronomic performance in field conditions under a range of treatments (irrigation and fertilization). The standing crop was also scored by farmer representatives. Additionally, the detailed lysifield study elucidated the plant functions underlying the crop agronomic performance under water stress (plant water use and stay-green score) and an important trait of farmer's interest (relation between stay-green score and *in-vitro* stover digestibility and relation between grain fat and protein content) The selected varieties– Phule Chitra, CSV22, M35-1 and preferred landrace (*Sevata jonna*)–were further tested with 21 farmers at Adilabad (2018–20). Participating farmers from both the trials and focus group discussions voiced their preference and willingness to adopt Phule Chitra and CSV22. This article summarizes how system-relevant crop options were selected for subsistence farmers of Adilabad and deployed using participatory approaches. While varieties are developed for wider adoption, farmers adopt only those suitable for their farm, household, and accessible market. Therefore, we strongly advocate FPA for developing and delivering farmer relevant crop technologies as a vehicle to systematically break crop adoption barriers and create a positive impact on household diets, well-being, and livelihoods, especially for smallholder subsistence farmers.

Keywords: dual-purpose sorghum, farmer-participatory varietal selection, India, landraces, seed production, stover quality, tribal farming community

INTRODUCTION

Sorghum is the world's fifth most important cereal crop, after maize, rice, wheat, and barley (FAOSTAT, 2020). Compared to other major cereals, sorghum requires less water, less external inputs, is more resistant to pests and diseases, and can withstand harsh climatic circumstances (Nagaraj et al., 2013; Balakrishna et al., 2019). The multi-purpose C4 crop plays an essential role in food, feed, and fodder security in dryland agriculture (Upadhyaya et al., 2016; Chapke and Tonapi, 2019). Apart from food, it is also a valuable source of bio-fuel (Appiah-Nkansah et al., 2019). To more than 500 million people in Africa and Asia, sorghum is an integral and irreplaceable dietary staple food (Kumar et al., 2011; Kumar, 2016).

In Asia, India is the main producer of sorghum despite the crop being mostly cultivated by small and marginal farmers in the stress-prone semi-arid regions (Chapke and Tonapi, 2019). In 2019, the country's area under sorghum cultivation was 4.1 million hectares, with a production of 3.5 million tons and a productivity of 849 kg ha^{-1} (Sridhara et al., 2020). Compared to the global average (∼1,481 kg ha^{-1}), sorghum productivity in India is rather low, mostly because the crop is often cultivated under rainfed conditions (Yadav et al., 2011; DACNET, 2016; FAOSTAT, 2020). Additionally, heat, water stress (Assefa et al., 2010) and lack of crop management options accessible and affordable to the farmers (Rao et al., 2010; Srivastava et al., 2010) contribute significantly to lower the crop productivity. *Kharif* (rainy) sorghum is primarily used for poultry feed, animal feed industries and alcohol (Patil et al., 2014), whereas *rabi* (postrainy) sorghum is grown for household consumption, fodder purposes, fiber, and fuel (Kumara et al., 2014). In areas where market linkages for sorghum are poor or limited, it is mostly a subsistence crop.

Adilabad district, in Telangana, is one of the areas in India inhabited by a high number of tribal people (**Figures 1A–C**). More than 75% of the district's population lives in rural areas and 35% of the people belong to tribal (farmer) communities (Poshadri et al., 2019). For these farmers, sorghum is the staple food and the primary source of animal fodder (Pandravada et al., 2013). The current regional system offers hybrids that, though cultivated, tend to have poor grain quality and are therefore less preferred for human consumption. The local and improved landraces however, are appreciated for their superior grain quality (bold, white, and with sweeter taste) and hence preferred for household consumption (Nagaraj et al., 2013). These farmer-conserved landraces (Pandravada et al., 2008, 2013), though best suited for human consumption, are not accessible to all, due to lack of formal seed banks and its undetermined seed purity. However, these landraces link closely to their culture, cultivation system, and diet of farming communities and are, thus, of high value (Pandravada et al., 2013; Sivaraj et al., 2016). Unfortunately, the Indian Government's food policies favoring consumption of rice and wheat, together with cultivation of cash crops, has impacted the country's sorghum area under cultivation, crop management (inputs given) and consumption (Srivastava et al., 2010; Pandravada et al., 2013). The decline in sorghum consumption and other coarse cereals, such as pearl millet and finger millet, has substantially reduced the population's iron intake without compensation from other food groups. This is particularly the case in areas where rice replaced the coarse cereals (DeFries et al., 2018). This gradual alteration in dietary habits and cultivation patterns (**Figure 1E**) has resulted in poorer health status among the people (NFHS, 2016; DeFries et al., 2018) and fodder scarcity in the region (Hall et al., 2007). Over 65% of Adilabad's women and children below 5 years are anemic, and more than 35% of the children of that age group are underweight (weight for age) and stunted (height for age) (NFHS, 2016; Poshadri et al., 2019). Several studies have shown that increased consumption of sorghum and millets could reduce anemia and improve the diets of Indian households (Prasad et al., 2016; Phuke et al., 2017; DeFries et al., 2018). Nutritional status of the population in subsistence farming systems is often the outcome of farmers' choices and/or options available and affordable within the socio-economic context. The quality of food consumed directly influences physical health and cognitive abilities, which impact the ability to earn. This further leads to economic losses that impact gross domestic price (GDP) (de la Peña et al., 2018). Besides these health and dietary challenges, the farmers of Adilabad live in an area of India that is prone to high or very high climate risk (Kumar et al., 2018; **Figure 1B**). The district faces major temperature fluctuations, heat, and cold waves and irregular rainfall, which is affecting the crops and threatening the livelihood security of the tribal farming communities. Therefore, cultivation of sustainable climate-smart agro-technologies (e.g., suitable crops), that meet the local farmers' needs and preferences, will be a valuable solution for the communities.

Nagaraj et al. (2013) highlighted the possible changes in policies that would impact the current demand–supply status and food and nutritional security positively, considering sorghum's

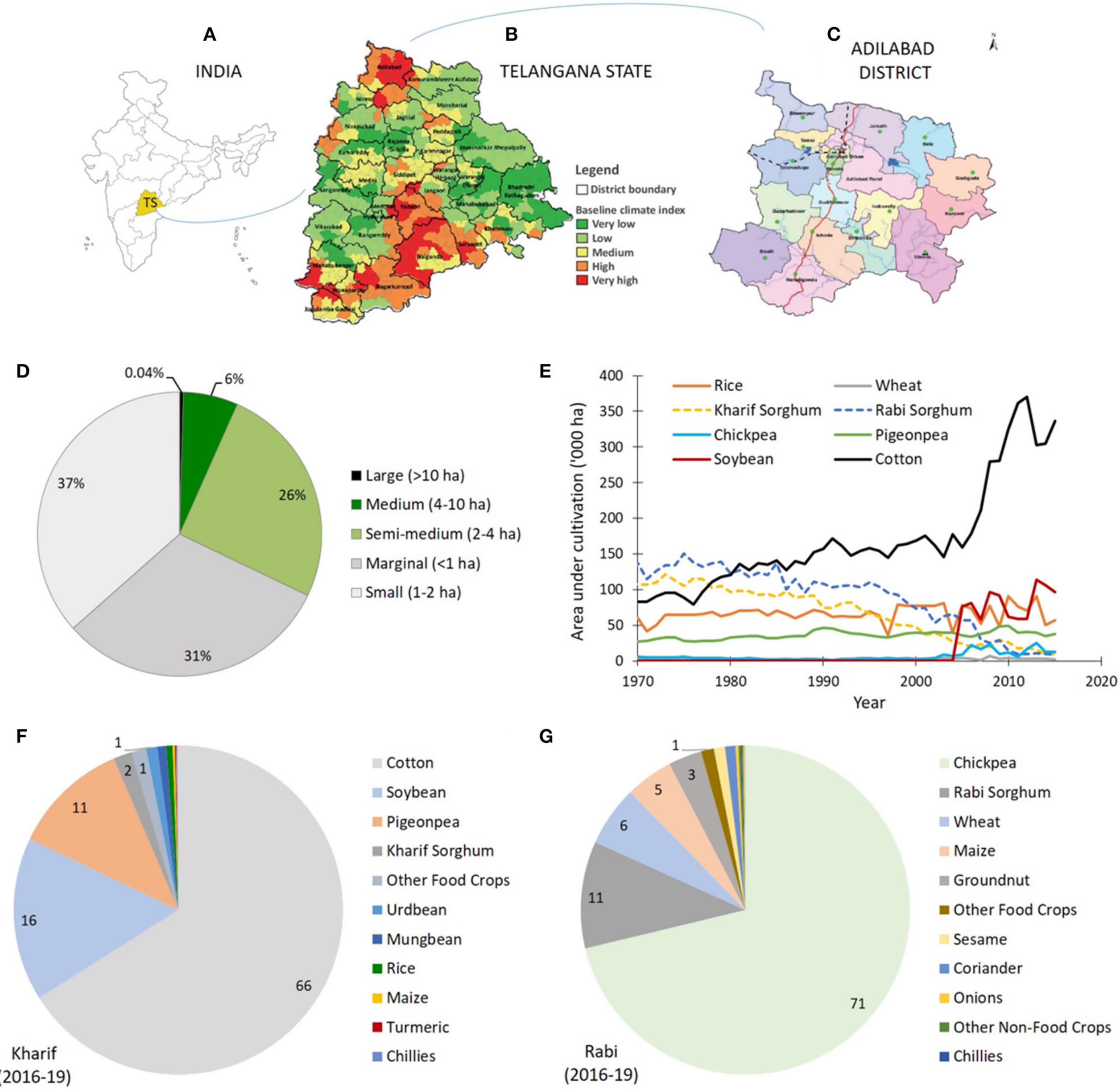

FIGURE 1 | Matrix of figures related to Adilabad district. **(A)** Telangana state in India (Source: https://www.vectorstock.com/royalty-free-vector/telangana-vector-3170092); **(B)** Climate-exposure index for Telangana state (Source: Kumar et al., 2018); **(C)** Mandals in Adilabad district; **(D)** Composition of farmers based on landholding in Adilabad district (2016 data, http://adilabad.telangana.gov.in/keystatistics/); **(E)** Trend of area under cultivation of major crops cultivated in Adilabad (1967–2015 data, http://data.icrisat.org/dld/src/crops.html); **(F)** Major crops being cultivated in Adilabad across rainy (*kharif*); **(G)** Postrainy (*rabi*) cropping seasons (2016–19 data, https://data.telangana.gov.in/dataset/adilabad-district-mandal-wise-crop-areas).

nutritive value (Blümmel et al., 2003; Kumar et al., 2010, 2011) and climate resilience (Kholová et al., 2013; Singh et al., 2014). The renewed global recognition of millets for their nutritional quality and introduction of a minimum support price for sorghum creates a new opportunity to revive sorghum as a competitive cereal crop in India. The Indian Government has committed to double the farmer's income by 2022 (Chand, 2017). For this, a number of policies and programs have been initiated (Paroda, 2018), such as the National Food Security Mission (NFSM), Pradhan Mantri Fasal Bima Yojana (PMFBY) and the National Mission on Sustainable Agriculture (NMSA). Additionally, many state governments (e.g., Odisha, Karnataka, Andhra Pradesh, Tamil Nadu, Sikkim, and Himachal Pradesh) are actively promoting consumption of nutritive coarse grains and legumes through the public distribution system[1] and programs aiming to improve school mid-day meals (https://epds.nic.in/; (Anitha et al., 2019b, 2022)). The Governments are also encouraging the establishment of farmer cooperatives, agri-business setups, and small ventures that create and support value chains for traditional crops (crops other than major cereals, such as rice, maize, or wheat). However, for sorghum to be part of the public distribution system and integrated into school meals, increasing crop yield is necessary (Anitha et al., 2019a,b). Currently, sorghum production in Adilabad District (**Figure 1E**) is insufficient to meet these goals.

To be able to support Adilabad's farmer communities in sustainable sorghum cultivation, it is crucial to see "the bigger picture" and have a systemic approach. Many crop improvement programs mainly focus on productivity gains (Barnes, 2002). Yet, it is widely recognized that adoption of new varieties is still a major problem (Alary et al., 2020), especially among small and marginal farmers. This is often due to a poor definition of the farmers' requirements and not including the socio-economic context (Thiele et al., 2020; Kholová et al., 2021). In that context, farmer participatory variety selection (FPVS) has been demonstrated to be a valuable tool (Ceccarelli, 2015). FPVS actively involves farmers in the selection process which creates a valuable knowledge exchange between all stakeholders and increases the chance of variety adoption (Humphries et al., 2015; Fadda and Van Etten, 2019; Kholová et al., 2021). Also, FPVS offers farmers and researchers the opportunity to detect potential and suitability of the variety in an earlier stage than formal breeding and agricultural extension (Wale and Yalew, 2007; Jiménez et al., 2016).

With this aim in mind, a targeted farmer-participatory study initiated at Adilabad focused on identifying sustainable sorghum options and test its relevance (Schematic diagram shown in **Figure 2**). The objectives of this study encompassed (i) defining the socio-economic context of the existing cropping systems in Adilabad District; (ii) assessing local farmers' preferences and selecting suitable sorghum varieties; and (iii) designing farmer participatory approaches (FPAs) to enable successful transfer of improved sorghum varieties to overcome crop adoption barriers.

METHODOLOGY

An Overview of the Methodology Is Shown in **Figure 3** Describing the Stages of the Study.

Understanding Crop–Livestock System of Adilabad

To understand the farming system in Adilabad, secondary district- and mandal-level data from Central and State Government reports, peer-reviewed publications, and publicly available documents were extracted for collating statistics related to demography, agricultural status and socio-economic metrics (Kumar, 2010; NAIP Project Report, 2012; Sivaraj et al., 2012; Pandravada et al., 2013; Adilabad District Report, 2016; Reddy et al., 2017; Kumar et al., 2018; NITI Aayog Report, 2018; Telangana Districts Profile Report, 2018; Task Force Report, 2019). In addition, an *ex-ante* household survey was conducted with tribal farmer families in Utnoor mandal[2] in the years 2018–20. A total of 103 interviews and a few focus group discussions were conducted with the support of the local Non-Governmental Organization, Centre for Collective Development (NGO, CCD) (**Figure 3**). The survey/interviews covered questions related to demography, socio-economic variables, landholding, livestock management, crop cultivation with an emphasis on sorghum, and dietary patterns.

Selecting Relevant Sorghum Varieties for Post-rainy Cultivation

Two field experiments during postrainy (or *rabi*, Oct–Feb) seasons of 2017–18 (Year 1) and 2018–19 (Year 2) were conducted at ICRISAT research station located in Patancheru, Telangana (latitude 17°30′N; longitude 78°16′E; altitude 549 m). The experimental site with Vertisol (or black soil) of medium depth (∼150 cm) was prepared according to the recommended sorghum cultivation practice (Trivedi, 2008). The experimental layout was a randomized complete block design with irrigation- and nitrogen-based multifactorial treatment as the main factor and genotype as sub-factor, randomized three times in blocks of each factor. The arrangement allowed a density of 15–16 plants m^{-2}. Weather data was recorded using TinyTag Ultra 2® TGU-4500 data loggers (Gemini Dataloggers Ltd, Chichester, UK) placed at the canopy level of the crop.

Sixteen varieties of sorghum were subjected to three agronomic treatments as described in Blümmel et al. (2015): well-watered with high nitrogen input (WWHN); water stressed with high nitrogen input (WSHN); and water stressed with low nitrogen input (WSLN) (**Figure 2**). The well-watered (WW) plots were irrigated every 15 days, whereas water-stressed (WS) plots were irrigated only thrice during the vegetative stage. Plants under high nitrogen (HN) treatment (i.e., WWHN and WSHN) received a basal dosage of ammonium phosphate fertilizer at the rate of 200 kg ha^{-1} and an additional top-dressing of urea at vegetative stage (∼30–40 days after sowing). In contrast, the plants under low nitrogen (LN) treatment (i.e., WSLN) did not receive any fertilizer application throughout the experimentation. They had access to only the residual Nitrogen in the soil. Of the several agronomic traits measured, this article focuses only on stover and grain yield (SY and GY, respectively). Twelve plants per treatment were harvested at physiological maturity for recording yield parameter. Panicle and stover were separated after harvest and dried at 60°C for 72 h.

For selection of varieties for the FPVS, farmers' representatives were invited to score the standing crop in the 2017–18 *rabi* trial. Based on their feedback, SY, and GY, varieties from each treatment were ranked using a selection index with 80% weightage given to GY and 60% weightage to SY for capturing

[1]Public Distribution System (PDS) portal of India. Ministry of Consumer Affairs, Food and Public Distribution. Available online at: https://epds.nic.in/ [Accessed on March 8, 2022].

[2]Administrative unit of a district.

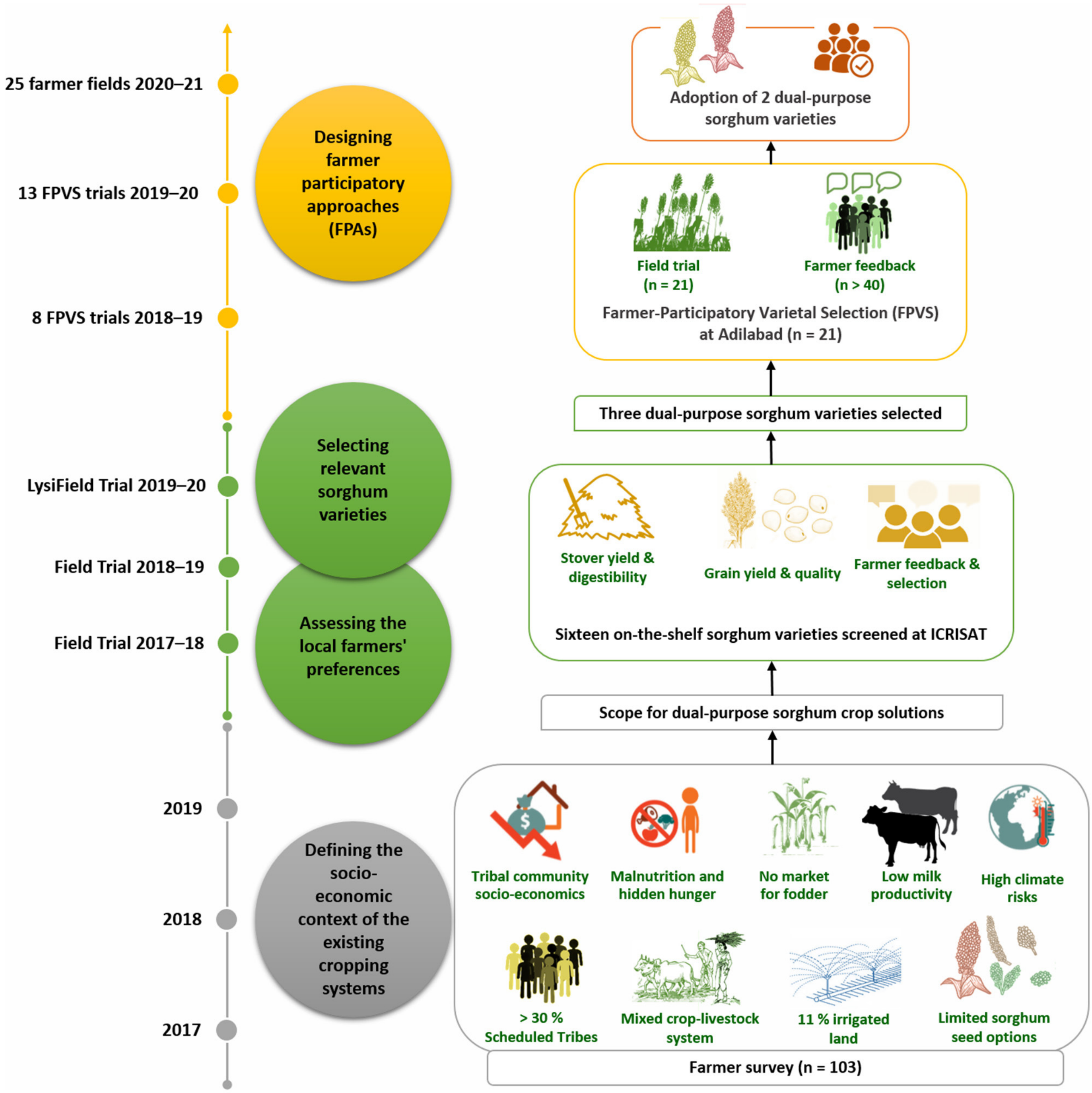

FIGURE 2 | Schematic diagram representing the project objectives, activities, observations and progress across the years.

the dual-purpose functionality of the varieties:

$$Ranking = (0.8 \times SY) + (0.6 \times GY)$$

Assessing Traits Relevant to Crop–Livestock Systems

Based on ranking from the on-station field trial (described above), three dual-purpose varieties– Phule Chitra (IC 523095; Gadakh et al., 2013), CSV22 (IC 552490; Gadakh et al., 2013), and improved landrace M35-1 (IC 552490; Reddy et al., 2009) were selected. These genotypes were tested along with the local landrace, *Sevata jonna*, for agronomic traits under WW and terminal WS conditions during the postrainy season of 2018–19 using high-throughput plant phenotyping platform, LysiField[3] (Vadez et al., 2011) (**Figure 3**). Eight replicates of each genotype were maintained per water treatment in a completely randomized block design factorized for genotypes. The plants were scored for leaf senescence visually from the bottom leaves to the top at 80

[3]http://gems.icrisat.org/lysimetric-facility/

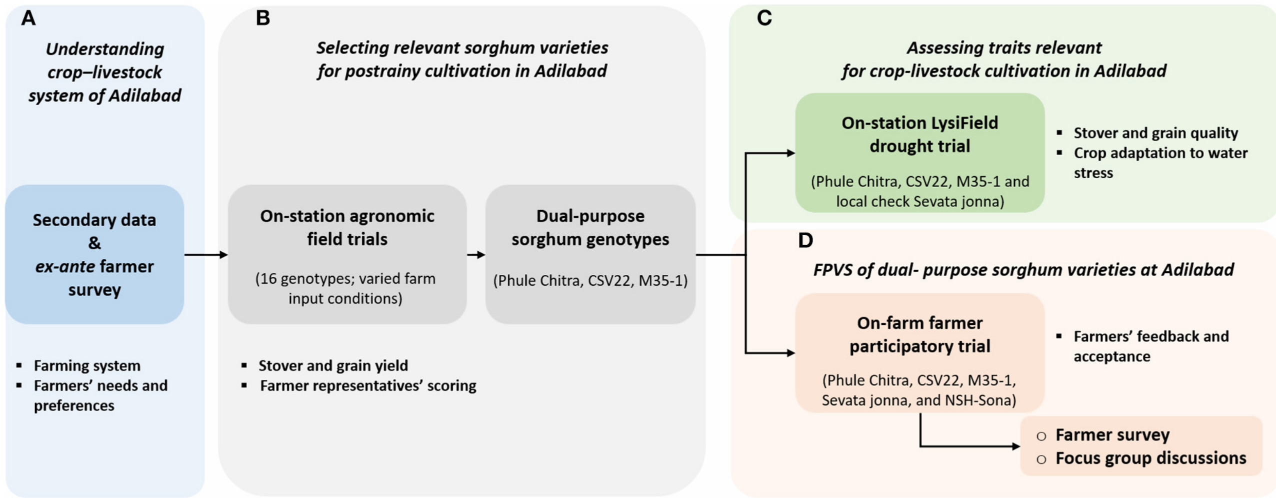

FIGURE 3 | Defined stages of project activities **(A)** Understanding crop–livestock system of Adilabad; **(B)** Selecting relevant sorghum varieties for postrainy cultivation; **(C)** Assessing traits relevant for crop-livestock cultivation; **(D)** FPVS of dual- purpose sorghum varieties at Adilabad.

and 87 days after sowing (DAS) in WS plants. The senescence scores ranged from 10 to 100%. Furthermore, the grain and fodder samples of the four varieties from the LysiField trial were processed for quantifying percentage of protein, fat and *in vitro* digestibility using near-infrared spectroscopy (NIRS; Instrument FOSS® DS2500 with WINSI II software package) and existing robust calibration models (Choudhary et al., 2010; Blümmel et al., 2015).

FPVS of Dual-Purpose Sorghum Varieties

On-farm trials were conducted at Utnoor mandal with the farmers linked to a local NGO (Centre for Collective Development) and farmer producer organization (FPO; Praja Mithra Rythu Federation). The experimental layout had genotypes in adjacent plots of 2.4 × 6 m dimension, i.e., each genotype in four rows of six-meter-long plots with 10 × 60 cm spacing. Farmers were asked to follow their usual management practice. During *rabi* 2018–19, Phule Chitra, CSV22, and M35-1 were cultivated by eight farmers. Based on their feedback, genotypes Phule Chitra and CSV22 were cultivated in trial plots of thirteen farmers in *rabi* 2019–20, along with *Sevata jonna* and local hybrid NSH-Sona for testing suitability of the open-pollinated genotypes compared to local seed options (**Figure 3**). Farmers' willingness to explore seed options and feedback on introduced genotypes (such as grain taste, grain and fodder quality and quantity, disease infestations, bird damage, crop management) were documented through interviews and focus group discussions (**Figure 3**). In addition, farmers were trained for selfing panicles to produce quality seeds using basic bags, thereby lowering their dependence on the market for seed.

Data Analysis

Numeric data from interviews were converted into percentage metrics to assess the preference and distribution of a parameter across the farming community. Quantitative agronomic data were analyzed using unbalanced ANOVA in GenStat® 18th edition (VSN International, Hemel Hempstead, UK) and comparison of means within treatment and across treatments was done using Fisher's unprotected Least Significance Difference (LSD, $P < 0.05$) comparison. As there was a poor plant stand of *Sevata jonna* in the 2018 field trial, the genotype was excluded from the analysis. Grain quality spectral data from FOSS DS2500 were converted to amount of protein and fat per 100 g of seed using winISI software and predefined sorghum model. Narrative analysis method was used for documenting qualitative data from farmer feedback through interviews and focus group discussions.

RESULTS

Secondary Data and *ex-ante* Household Survey

In Adilabad, livelihood of farming communities depends predominantly on mixed crop-livestock systems. Long-term climate analysis shows that all mandals of Adilabad are prone to high or very high climatic risk threatening the livelihood and food security of tribal farming communities (Kumar et al., 2018; **Figure 1B**). About 94% of the farmers own <4 hectares of land. In this group, about 62% of the farmers own <2 hectares of land (i.e., are small and marginal farmers) (**Figure 1D**). Despite the small landholding, the farmers seem to be responsive to market prices and cultivate multiple crops accordingly in both rainy (*kharif*, Jun–Oct) and postrainy (*rabi*, Oct/Nov-Feb/Mar) seasons to meet their domestic and economic needs (**Figures 1F,G**). With strong regional market linkages and stable minimum support price[4] farmers have adopted cash crops (cotton, soybean, pigeonpea, and chickpea) positively over the decades. Consequently, a strong downward trend in the area under cultivation of the region's staple dietary crop, sorghum,

[4]https://farmer.gov.in/mspstatements.aspx

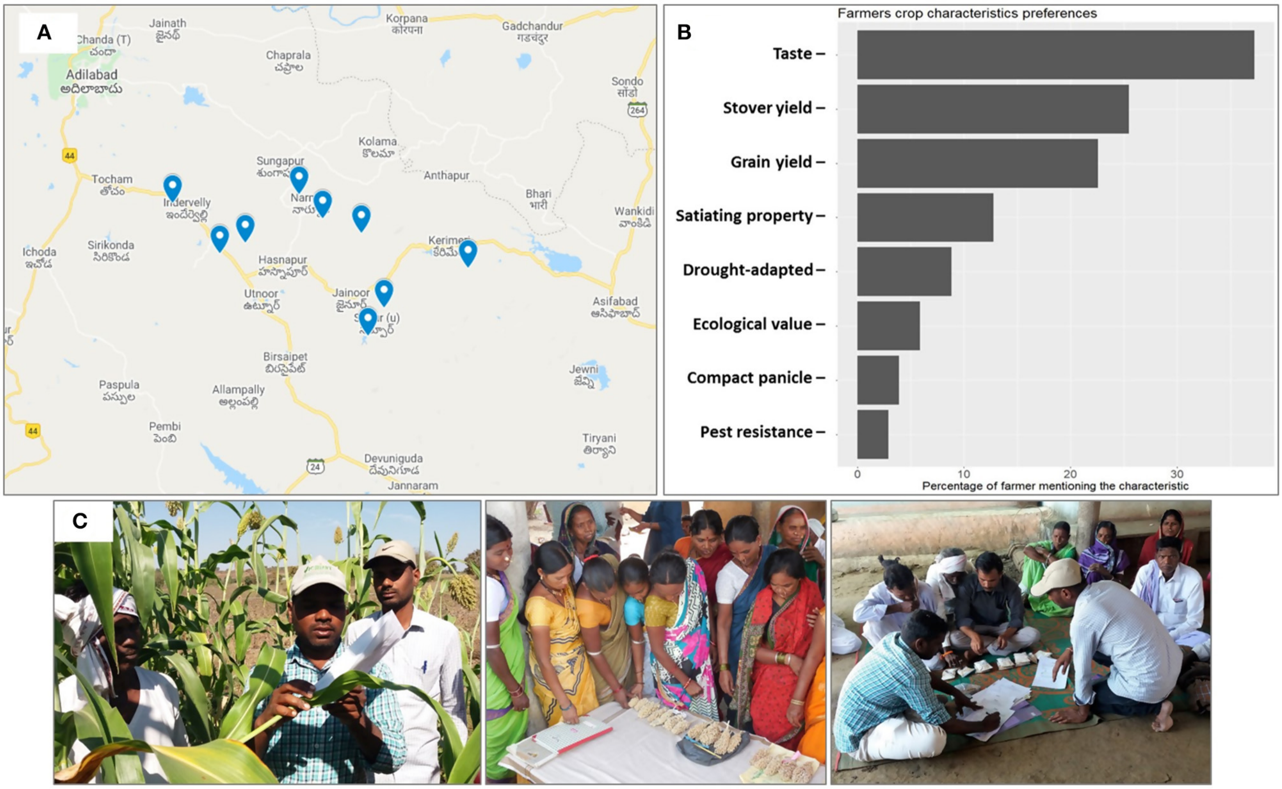

FIGURE 4 | (A) Geo-tagged positions of the villages in Adilabad district where ex ante survey and farmer-participatory varietal selection trials were conducted during 2017–18 and 2018–19; **(B)** Farmers' preferences collated from the 103 farmer interviews and focus group discussions conducted in the years 2018–20; **(C)** Collage of pictures from our participatory work at study site.

is seen from 1975 (0.15 m ha) to 2015 (0.008 m ha) (Adilabad District Report, 2016) (**Figure 1E**).

A total of 103 farm household interviews were conducted in the Utnoor region (**Figures 4A,C**). The farmers expressed that sorghum is an indispensable crop as it is cultivated for both grain and fodder in both *kharif* and *rabi* seasons. Both men and women of the community mentioned that their diets have gradually changed to include rice and wheat over the last 2–3 decades. However, they make an effort to have sorghum in at least one meal per day as it is considered to be more satiating and healthier than rice and wheat. Upon enquiring about farmers' preference for sorghum, taste was the most mentioned trait followed by stover yield, grain yield, drought adaptation, inputs requirements and pest resistance (**Figure 4B**). During the *rabi* cultivation, some farmers grew sorghum in high density to meet their fodder requirement for summer season at the expense of grain.

On-Station Selection of *rabi* Sorghum Varieties for Low Input Systems: Agronomic Trials

Based on the *ex-ante* survey, dual-purpose open-pollinated varieties (OPVs) of sorghum seemed to be a promising entry-point to address both the grain and fodder needs of the region. For testing this hypothesis, fourteen of well-characterized Government released sorghum varieties were tested along with widely popular improved landrace (M35-1) and local landrace (*Sevata jonna*) in the postrainy/*rabi* seasons of 2017–19 in ICRISAT. The on-station field trials at ICRISAT focused on screening the varieties in response to multifactorial treatments of irrigation and nitrogen: WWHN (high-input), WSHN, and WSLN (low-input) conditions. Farmer representatives scored the standing crop for traits such as stover, panicle type, presence of awns, and the taste of grain. They emphasized on varieties coping well-under low input (water stressed, low nitrogen) conditions. **Table 1** summarizes the stover and grain yield along with the metric of ranking recorded in the varieties tested under high-input (WWHN) and low input (WSLN) conditions in *rabi* 2017–18 (data from *rabi* 2018–19 not shown, unpublished).

Consequently, sorghum varieties M35-1, CSV22, and Phule Chitra were selected for further detailed trials on-station and on-field at Adilabad. The on-station trials at ICRISAT focused on screening the quantity and quality traits of the varieties in response to WW and WS conditions. Whereas, the on-farm farmer-participatory varietal selection (FPVS) trials at Utnoor were conducted to assess farmers' willingness to explore seed options and engage with the farming community to understand their preferences and the regional production conditions.

TABLE 1 | Selection of sorghum varieties based on grain and stover yield (g plant^{-1}) tested under low-input (water stressed with low nitrogen input, WSLN) and high-input (well-watered with high nitrogen, WWHN) conditions in postrainy (*rabi)* trial of 2017–18.

Genotypes	Grain yield (g plant^{-1})		Stover yield (g plant^{-1})		Ranking	
	WS LN	WW HN	WS LN	WW HN	WS LN	WW HN
M35-1	20.4	31.1	37.3	46.9	**38.7**	53.0
Phule Revati	18.9	38.7	36.5	55.0	**37.3**	63.9
CSV 22	17.6	31.6	38.1	55.1	**37.0**	58.3
Phule Chitra	16.2	30.5	39.8	50.6	**36.8**	54.8
Phule Vasudha	17.9	29.0	35.6	47.4	**35.7**	51.6
Sevata jonna	15.5	31.1	38.4	46.9	35.4	53.1
CSV 26	17.6	35.1	35.0	55.5	34.7	61.4
Phule Suchitra	16.6	38.9	35.2	53.8	34.4	63.4
Parbhani Moti	13.8	32.5	37.7	52.9	33.9	57.8
CSV 216R	16.2	33.9	32.0	53.7	32.1	59.4
CSV 18	14.4	38.0	32.3	56.7	31.0	64.4
CSV 29R	15.3	31.7	30.5	53.1	30.5	57.2
AKSV 13R	14.0	40.4	31.8	55.7	30.4	65.8
Phule Maulee	14.5	35.6	30.5	48.8	29.9	57.7
CSV 14R	15.4	34.9	28.8	50.0	29.4	57.9
Phule Anuradha	12.9	39.7	26.2	49.3	26.0	61.3
LSD ($P < 0.05$)	*5.4*	*8.4*	*7.8*	*10.0*	-	-
G	*0.318*	*0.129*	*0.020*	*0.543*		
G	*0.325*		*0.107*		-	-
E	*<0.001*		*<0.001*			
G × E	*0.032*		*0.163*		-	-

Ranking was calculated with 80% weightage prescribed to grain yield and 60% weightage to stover yield. Output of unbalanced ANOVA and Fisher's unprotected Least Significance Difference (LSD; $P < 0.05$) comparison of means within and across treatments for SY and GY is presented in the table.
LN, low Nitrogen; HN, high Nitrogen; WS, water stressed; WW, well-watered conditions.
Top five ranking varieties suitable for low-input conditions are highlighted in bold font.

Critical Assessment of Traits Relevant to Crop–Livestock Systems: LysiField Drought Trial

The LysiField trial conducted on-station in 2019–20 aimed to dissect the impact of drought on agronomic and quality traits (SY, GY, leaf senescence, protein and fat content of grains, and *in vitro* organic matter digestibility of stover) (**Figures 5–7**). Harvest index, an important criterion in crop selection representing the percentage of grain yield to total aerial biomass ranged from 10–34 to 24–47% in WS and WW plants, respectively (**Supplementary Figure 1A**). A very tight relationship between grain yield and HI was observed in WS plants ($r^2 = 0.90$, $n = 18$), unlike the WW plants ($r^2 = 0.42$, $n = 17$) (**Supplementary Figure 1A**). In WW plants, the residual of seed weight not explained by HI, correlated significantly with stover weight ($r^2 = 0.89$; $n = 17$; **Supplementary Figure 1B**). Leaf senescence in WS plants was scored at 80 DAS and 87 DAS. As most of WS plants had 100% leaf senescence by 87 DAS, we depended on the 80 DAS score for analysis. SY and GY showed contrasting relationship trends with leaf senescence (r^2 SY $= 0.17$; r^2 GY $= -0.41$) (GY; **Figure 5**). The inverse of leaf senescence was interpreted as stay-green score. Among the 4 genotypes, M35-1 had the highest stay-green score at 80 DAS (51%) followed by CSV22 (30%), Sevata jonna (26%), and Phule Chitra (19%) (data not shown).

Under WW and WS conditions, the *in vitro* organic matter digestibility (IVOMD) of stover ranged from 51 to 61%. No significant genotypic variation for IVOMD was observed among the varieties tested. Also, no significant relationship between stover yield and the IVOMD under WW ($r^2 = 0.06$; $n = 11$) and WS ($r^2 = 0.30$, $n = 8$) conditions was observed (**Supplementary Figure 2**). However, a positive relationship between leaf senescence at 80 DAS and IVOMD was found in WS plants ($r^2 = 0.62$, $n = 7$) (**Figure 6**). In WS plants, seeds with higher protein content had lower fat content as opposed to WW plants (WS $r^2 = -0.73$, $n = 8$; WW $r^2 = 0.52$, $n = 6$; **Figure 7**).

Capturing Farmers' Feedback and Knowledge Exchange Through FPVS

The twenty-one farmer-participatory trials conducted during 2018–20 in collaboration with the local NGO offered enriching knowledge exchange between the project partners. The farmers

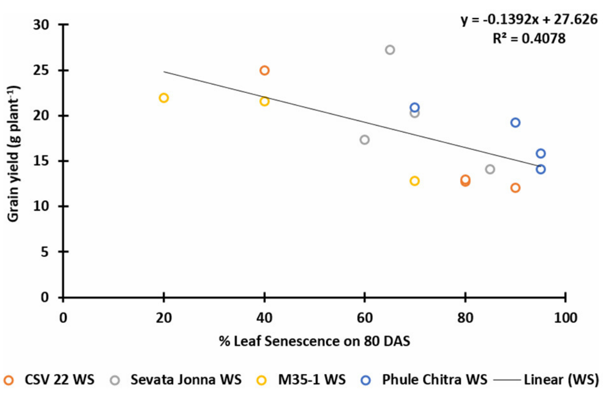

FIGURE 5 | Trait relationship between grain yield (g plant^{-1}) and leaf senescence at 80 DAS in water stressed (WS) plants of four sorghum varieties tested in 2019–20 lysimetric trial. Crop varieties are color coded; Open circles (O) indicate WS plants; solid line (–) indicated relationship between the traits.

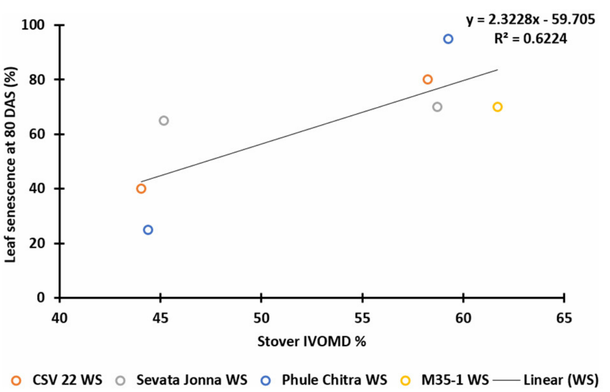

FIGURE 6 | Trait relationship between leaf senescence at 80 DAS and stover quality (*in vitro* organic matter digestibility, IVOMD) in water stressed (WS) plants of four sorghum varieties tested in 2019–20 lysimetric trial. Crop varieties are color coded; Open circles (○) indicate WS plants; solid line (—) indicated relationship between the traits.

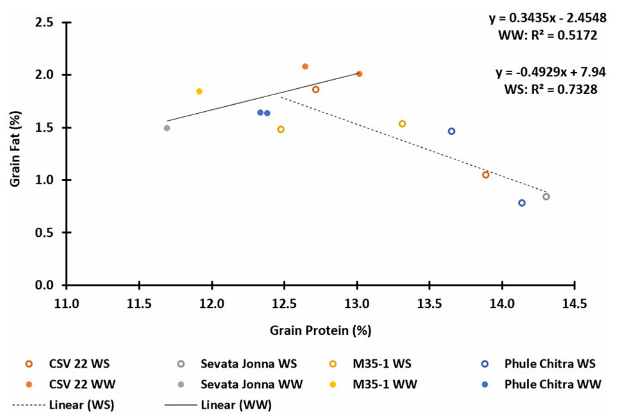

FIGURE 7 | Quality trait relationship between grain fat and protein content in water stressed (WS) and well-watered (WW) plants across four genotypes tested in 2019–20 lysimetric trial. Crop varieties are color coded; Full circles (•) indicate WW plants; Open circles (O) indicate WS plants; solid line (—) indicates relationship in WW plants; dashed line (––) indicates relationship in WS plants.

compared the harvested material for several parameters: morphological traits (e.g., presence of awns, panicle compactness, secondary branching of panicle rachis), agronomic traits (e.g., plant height, stover yield, pest resistance, and water requirement) and quality traits (e.g., hardness and taste of seed, and taste of cooked product (*roti*[5] and *upma*[6]). Focus group discussions with over 40 farmers and results of the FPVS feedback survey showed a high variability in farms, crop management, farmers' preference and willingness of farmers to explore. Most farmers preferred Phule Chitra over CSV22, for its long panicle, thick stems, seed set, and seed boldness.

Several farmers expressed their positive attitude toward the newly introduced varieties and are planning to continue cultivation:

Farmer 1 [F1], male, from Saleguda: "CSV22 and Phule Chitra suit my land. I have saved seeds from the harvest for next sowing."
F2, male, from Narnoor: "I'm planning to grow both varieties. I was surprised by the fodder yield under minimum irrigation."
F3, male, from Keslaguda: "I prefer Phule Chitra, because it has long panicles and gives more seeds. I will keep the harvested seeds, so I can sow them again next season."
F4, male, Soyamguda: "I like Phule Chitra for its long panicles, thick stems and bold seeds. The panicle type and seed set of CSV22 is also good."
F5, male, Narnoor: "I prefer CSV22 over Phule Chitra, because of the type of panicles. The amount of seeds per panicle was good."

According to the participants of the focus group discussions, the taste of the food prepared with Phule Chitra was comparable to that of their local landrace. Some concerns were shown regarding the sweetness of the grains of both varieties, which attracted birds during the seed maturation stage. This required farmers to spend more time in the field and to install bird scaring devices. By contrast, the bent compact panicles of the landraces tend to reduce damage by birds (**Figure 8**).

DISCUSSION

Relevant Sorghum Crop Choices for Adilabad

Adilabad is one of the many underdeveloped districts in India that is tackling poverty, poor health, education, and basic infrastructure deficits (NITI Aayog Report, 2018). The region has a high proportion of indigenous populations (>30%) belonging to Scheduled Castes and Scheduled Tribes that face complex socio-economic and political limitations. The livelihood status of farming communities in this region is further challenged by climate risks. Ceccarelli (2015) stated that crop interventions meeting farmers' needs and preferences are vital for its adoption

[5] Flattened bread.
[6] Thick porridge with seasoning.

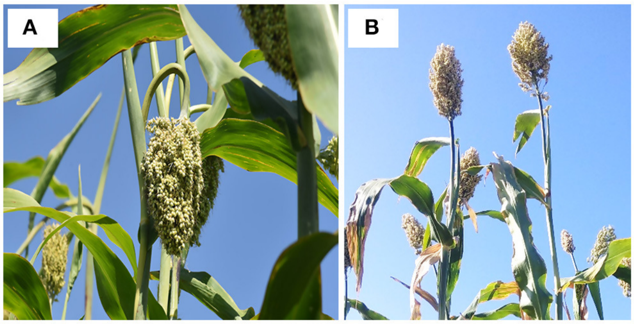

FIGURE 8 | Representative image of the panicle of **(A)** local sorghum landrace *Sevata jonna* and **(B)** open-pollinated dual-purpose sorghum variety Phule Chitra.

and integration in the existing system. During our *ex-ante* survey with the farming community, three key constraints were highlighted: (i) fodder scarcity as one of the important concerns for the farming community; (ii) the limitation of available sorghum seed option to landraces and hybrids; and (iii) the loss of seed purity in landraces over the years. Our initial interactions with the farmers at Utnoor focused on reviving landraces (Rajani, 2018) that hold special cultural and dietary value to the locals (Pandravada et al., 2013; Paltasingh and Paliwal, 2014). These shortcomings indicate that training farmers to maintain purity of seeds and increasing seed options would benefit the sorghum food system among these communities (**Figure 3C**; Voorhaar and Anbazhagan, 2019). In addition, open-pollinated varieties (OPVs) would drastically reduce farmers' dependence on the market for hybrid seeds. Therefore, we explored possible crop options that could fit and benefit the farmers.

Several reports suggest that dual-purpose varieties with superior grain and stover traits can increase overall farm productivity, particularly in (semi)-arid regions with mixed crop-livestock systems where fodder is scarce (Rao and Hall, 2003; Sharma et al., 2010; Erenstein et al., 2011). Ceccarelli (1996) explicitly highlighted the importance of selecting varieties in unfavorable or limited conditions prior to deployment as most of the varieties are bred through cycles of well-managed high input selection trials. In this study, the on-station trials at ICRISAT were conducted under both high- and low-input conditions for quantifying the agronomic traits (stover yield, grain yield, harvest index and stay-green trait) and quality traits (stover digestibility, grain protein and fat) across the dual-purpose varieties–Phule Chitra, CSV22, M35-1 and *Sevata jonna*. Rao and Hall (2003) stated that yield benefits and quality of produce are not the only selection criteria for farmers for varietal adoption. Similarly, the participating farmers ranked taste first followed by stover yield, grain yield, and adaptability to drought, panicle compactness and pest resistance. They also mentioned several morphological and crop traits (as mentioned in results section) that were considered while selecting the varieties from existing the sorghum elite collection.

Of the agronomic traits measured in the on-station trials, we would like to highlight the stay-green trait as it is closely linked with continued photosynthetic capacity of the crop in the post-flowering stage and adaptation to terminal drought (Prasad et al., 2014). Quality traits assessed using near-infrared spectroscopy (NIRS) indicated that stover digestibility, unlike grain protein and fat content, was not severely affected by water stress. As seen in **Figure 6**, a positive relationship ($r^2 = 0.62$) between with stover digestibility (IVOMD) and leaf senescence was observed. This is an important visual trait as every 1% increase in digestibility of sorghum stover can result in 6–8% increase in milk productivity in livestock (Kristjanson and Zerbini, 1999; Zerbini and Thomas, 2003; Hall et al., 2004). Increasing milk production in the region will enhance the nutrition of women and children, and enhance household income through the sale of surplus quantity fodder and milk. Further, NIR-based grain quality analysis showed an inverse relationship between protein and fat content in WS plants (**Figure 7**). Srivastava (2018) documented that smallholder farmers of Adilabad, commonly consume what they cultivated and conserve a portion of their harvested seeds for next season sowing. In the study site, farmers often stored their harvested seeds in jute/plastic bags or earthen pots at home. As sorghum grains tend to get rancid upon storage, seed types that have lower fat and higher protein would be suitable for the smallholder farmer household consumption.

Combining Farmers' and Researchers' Knowledge

Genotype–environment (G × E) interactions are complex and they get further complicated with crop management and resources accessible during cultivation (G × E × M). Farming communities manage these complexities in the best way possible with the options they have access to. Introducing new OPVs through farmer-participatory methods was helpful in testing if the varieties met the farmers' requirements (taste and stover) (Voorhaar and Anbazhagan, 2019). Although our FPVS trials are still ongoing (25 farmers participated in 2020–21 and more to be included in 2021–22), until now, the varieties Phule Chitra and CSV22 have been well-received and adopted by the participating sorghum farmers. In the absence of formal seed banks, the responsibility of conserving seeds lies on the community itself. During our study, farmers were trained to use selfing article bags to maintain seed purity and enable farmers to produce their own seeds (landraces or the OPVs) independently. In addition to the efforts to revive landraces, the participating sorghum farmers' overall response to Phule Chitra and CSV22's was positive. Several farmers informed that they will continue to practice panicle selfing to maintain seed purity, cultivate *Sevata jonna* for household consumption and OPVs Phule Chitra and CSV22 in high density for fodder. A farmer from Chintakara village continued to cultivate CSV22 and Phule Chitra beyond the 2017–18 FPVS, proactively performed selfing and shared the harvested seeds with other farmers of his village. Although this appears as a singular activity, within close-knit communities such as the tribal community in the study area, knowledge transfer through demonstration, experience, and word-of-mouth plays a significant role. Based on the outcome of the study, conservation of landraces and integration of OPVs, can be a valuable short-term solution to strengthen the sorghum seed system in Adilabad.

CONCLUSION

Building further on the farmer participatory approach, a detailed socio-economic analysis along with a scaled-up varietal intervention project with impact assessment is planned for 2021–24. We envision that bringing nutritionally-dense, dual-purpose sorghum into the cultivation system can improve health, wellbeing and livelihood of the tribal farming community. With improved household income and quality of diet, physical health and cognitive development of the community will change for the better. The "Nutri-Food Basket" and "Giri Poshana" projects at Adilabad show that food-based interventions supplementing existing diets, help in reducing underweight among children and tackling anemia in women Padmaja and Kavitha (2017), Padmaja et al. (2018). In addition, by increasing the regional production of sorghum grain and fodder, several crop value chains and market linkages can be created with farmer producer organizations and cooperatives boosting the local economy and farm income. With the support of already existing Government policies/initiatives (such as the National Food Security Mission and National Mission on Sustainable Agriculture), the surplus grain can be channeled into the Government's procurement system. This could be a game-changing market-pull for increasing sorghum cultivation, breaking the threshold of subsistence farming in several households, and replacing rice in the mid-day school meal program and public distribution system.

In conclusion, for increasing the varietal adoption and plant breeding efficiency, we emphasize the importance of (i) FPAs to understand farming community's context and specific needs, (ii) on-station selection methodologies that reflect different cultivation conditions, and (iii) knowledge and technology exchange between farmers and researchers to consider traits beyond yield and productivity gains.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: doi: 10.21421/D2/LBSXTT.

ETHICS STATEMENT

The farmer participants provided written informed consent to participate in this study. Also, a prior informed consent was obtained from the participants, both farmers and researchers, for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

KA and MV: on-field experimentation at Adilabad, designing farmers' survey, interviewing farmers at Adilabad, data collation and analysis, and drafting of manuscript. JK: research ideation, project planning and management, experimentation on-station and on-field, interviewing farmers at Adilabad, and reviewing of manuscript. KC: grain and stover quality assessment and data collation. SC: project planning and management, on-field experimentation and interviewing farmers at Adilabad, data collation and analysis, and reviewing of manuscript. SM: experimentation on-station at ICRISAT and on-field at Adilabad, lysimetric trial on-station, interviewing farmers at Adilabad, and data compilation. SK: lysimetric trial on-station and on-field experimentation and interviewing farmers at Adilabad, and data collation and analysis. VG: on-field experimentation at Adilabad, interviewing farmers, and data analysis. RB: lysimetric trial on-station, on-field experimentation, designing farmers' survey and interviewing farmers at Adilabad, data analysis, and coordinating project activities. KR: networking, organizing on-field farmer-participatory trials, and project activity coordination in Adilabad. SN: designing farmers' survey, Adilabad agri-market insights and strategizing relevant intervention, and reviewing of manuscript. AS: networking on-ground at Adilabad, insights on project operations, and marketable interventions. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.742909/full#supplementary-material

Supplementary Figure 1 | (A) Trait relationship between grain yield (g plant^{-1}) and harvest index (HI); and **(B)** regression plot between the residual of grain yield not explained by HI vs. stover yield (g plant^{-1}) in water stressed (WS) and well-watered (WW) plants across four genotypes tested in 2019–20 lysimetric trial. Crop varieties are color coded; Full circles (•) indicate WW plants; Open circles (◯) indicate WS plants; solid line (−−) indicates relationship in WW plants; dashed line (−−) indicates relationship in WS plants.

Supplementary Figure 2 | Trait relationship between stover quality (IVOMD, %) and stover yield (g plant^{-1}) in water stressed (WS) and well-watered (WW) plants across four genotypes tested in 2019–20 lysimetric trial. Crop varieties are color coded; Full circles (•) indicate WW plants; Open circles (◯) indicate WS plants; solid line (−−) indicates relationship in WW plants; dashed line (−−) indicates relationship in WS plants.

REFERENCES

Adilabad District Report (2016). Available online at: https://adilabad.telangana.gov.in/document-category/district-profile/ (accessed: March 20, 2021).

Alary, V., Yigez, A. Y., and Bassi, F. M. (2020). Participatory farmers-weighted selection (PWS) indices to raise adoption of durum cultivars. *Crop Breed. Genet. Genom.* 2, 1–20. doi: 10.20900/cbgg20200014

Anitha, S., Givens, D. I., Subramaniam, K., Upadhyay, S., Kane-Potaka, J., Vogtschmidt, Y. D., et al. (2022). Can feeding a millet-based diet improve the growth of children?—A systematic review and meta-analysis. *Nutrients* 14:225. doi: 10.3390/nu14010225

Anitha, S., Govindaraj, M., and Kane-Potaka, J. (2019a). Balanced amino acid and higher micronutrients in millets complements legumes for improved human dietary nutrition. *Cereal Chem.* 97, 74–84. doi: 10.1002/cche.10227

Anitha, S., Kane-Potaka, J., Tsusaka, T. W., Tripathi, D., Upadhyay, S., Kavishwar, A., et al. (2019b). Acceptance and impact of millet-based mid-day meal on the nutritional status of adolescent school going children in a peri urban region of Karnataka State in India. *Nutrients* 11:2077. doi: 10.3390/nu11092077

Appiah-Nkansah, N. B., Li, J., Rooney, W., and Wang, D. (2019). A review of sweet sorghum as a viable renewable bioenergy crop and its techno-economic analysis. *Renew. Energy* 143, 1121–1132. doi: 10.1016/j.renene.2019.05.066

Assefa, Y., Staggenborg, S. A., and Prasad, P. V. V. (2010). Grain sorghum water requirement and responses to drought stress: a review. *Crop Manag.* 9, 1–11. doi: 10.1094/CM-2010-1109-01-RV

Balakrishna, D., Vinodh, R., Madhu, P., and Avinash, S. (2019). "Tissue culture and genetic transformation in Sorghum bicolor," in *Breeding Sorghum for Diverse end Uses*, eds C. Aruna, K. B. R. S. Visarada, B. V. Bhat, V. A. Tonapi (Cambridge: Woodhead Publishing, Elsevier), 115–130. doi: 10.1016/B978-0-08-101879-8.00007-3

Barnes, A. P. (2002). Publicly funded UK agricultural R and D and 'social' total factor productivity. *Agric. Econ.* 27, 65–74. doi: 10.1111/j.1574-0862.2002.tb00105.x

Blümmel, M., Deshpande, S., Kholová, J., and Vadez, V. (2015). Introgression of staygreen QTLs for concomitant improvement of food and fodder traits in *Sorghum bicolor*. *Field Crops Res.* 180, 228–237. doi: 10.1016/j.fcr.2015.06.005

Blümmel, M., Zerbini, E., Reddy, B. V. S., Hash, C. T., Bidinger, F. R., and Khan, A. A. (2003). Improving the production and utilization of sorghum and pearl millet as livestock feed: progress towards dual-purpose genotypes. *Field Crops Res.* 84, 143–158 doi: 10.1016/S0378-4290(03)00146-1

Ceccarelli, S. (1996). "Positive interpretation of genotype by environment interactions in relation to sustainability and biodiversity," in *Plant Adaptation and Crop Improvement*, eds M. Cooper, G. L. Hammers (Wallingford/Hyderabad/ Manila: CAB International/ ICRISAT/IRRI), 467–486.

Ceccarelli, S. (2015). Efficiency of plant breeding. *Crop Sci.* 55, 87–97. doi: 10.2135/cropsci2014.02.0158

Chand, R. (2017). *Doubling Farmers' Income: Rationale, Strategy, Prospects and Action Plan*. NITI Policy Paper no.1/2017, National Institution for Transforming India, New Delhi. Available online at: https://www.niti.gov.in/writereaddata/files/document_publication/DOUBLING%20FARMERS%20INCOME.pdf) (accessed: March 20, 2021).

Chapke, R. R., and Tonapi, V. A. (2019). Adoption and socio-economic benefits of improved post-rainy sorghum production technology. *Agric. Res.* 8, 270–278. doi: 10.1007/s40003-018-0359-x

Choudhary, S., Hash, C. T., Sagar, P., Prasad, K. V. S. V., and Blümmel, M. (2010). "Near infrared spectroscopy estimation of pearl millet grain composition and feed quality," in *Proceedings of the 14th International Conference on NIRS Spectroscopy, Bangkok, November*, eds S. Saranwong, S. Kasemsumran, W. Thanapase, P. Williams (Chichester: IM Publications), 87–90.

DACNET (2016). *Department of Agriculture Cooperation*, Government of India. Available online at: https://eands.dacnet.nic.in/PDF/Glance-2016.pdf (accessed: March 20, 2021).

de la Peña, I., Garrett, J., and Gelli, A. (2018). *Nutrition-sensitive value chains from a smallholder perspective: A framework for project design*. Rome: International Fund for Agricultural Development (IFAD). Available online at: https://www.ifad.org/en/web/knowledge/-/publication/research-series-issue-30-nutrition-sensitive-value-chains-from-a-smallholder-perspective-a-framework-for-project-design (accessed on March 20, 2021).

DeFries, R., Chhartre, A., Davis, K. F., Dutta, A., Fanzo, J., Ghosh-Jerath, S., et al. (2018). Impact of historical changes in coarse cereals consumption in India on micronutrient intake and anemia prevalence. *Food Nutr. Bull.* 39, 377–392. doi: 10.1177/0379572118783492

Erenstein, O., Samaddar, A., Teufel, N., and Blümmel, M. (2011). The paradox of limited maize stover use in India's small holder crop-livestock systems. *Exp. Agric.* 47, 677–704. doi: 10.1017/S0014479711000433

Fadda, C., and Van Etten, J. (2019). "Generating farm-validated variety recommendations for climate adaptation," in *The Climate-Smart Agriculture Papers*, eds T. S. Rosenstock, A. Nowak, E. Girvetz (Cham: Springer), 127–138. doi: 10.1007/978-3-319-92798-5_11

FAOSTAT, Food and Agriculture Organization of the United Nations. (2020). Available online at: https://www.fao.org/faostat/en/#data/QCL (accessed on March 20, 2021).

Gadakh, S. R., Shinde, M. S., and Gaikwad, A. R. (2013). Postrainy season sorghum varieties developed at All India Coordinated Sorghum Improvement Project, MPKV, Rahuri. *SAT J.* 11, 1–2.

Hall, A., Blümmel, M., Thorpe, W., Bidinger, F. R., and Hash, C. T. (2004). Sorghum and pearl millet as food-feed-crops in India. *Anim. Nutr. Feed Technol.* 4, 1–15.

Hall, A., Sulaiman, R. V., and Bezkorowajny, J. P. (2007). *Reframing Technical Change: Livestock Fodder Scarcity Revisited as Innovation Capacity Scarcity – A Conceptual Framework*. Nairobi, Kenya: ILRI and UNU/MERIT. Available online at: https://hdl.handle.net/10568/277 (accessed: March 20, 2021).

Humphries, S., Rosas, J. C., Gómez, M., Jiménez, J., Sierra, F., Gallardo, O., et al. (2015). Synergies at the interface of farmer–scientist partnerships: agricultural innovation through participatory research and plant breeding in Honduras. *Agric. Food Secur.* 4:27. doi: 10.1186/s40066-015-0046-0

Jiménez, D., Dorado, H., Cock, J., Prager, S. D., Delerce, S., Grillon, A., et al. (2016). From observation to information: data-driven understanding of on farm yield variation. *PLoS ONE.* 11:e0150015. doi: 10.1371/journal.pone.0150015

Kholová, J., McLean, G., Vadez, V., Craufurd, P., and Hammer, G. L. (2013). Drought stress characterization of post-rainy season (rabi) sorghum in India. *Field Crops Res.* 141, 38–46. doi: 10.1016/j.fcr.2012.10.020

Kholová, J., Oldrich Urban, M., Cock, J., Arcos, J., Arnaud, E., Aytekin, D., et al. (2021). In pursuit of a better world: crop improvement and the CGIAR, *J. Exp. Bot.* 72, 5158–5179. doi: 10.1093/jxb/erab226

Kristjanson, P. M., and Zerbini, E. (1999). *Genetic enhancement of sorghum and millet residues fed to ruminants: An ex-ante assessment of returns to research: ILRI Impact Assessment Series No. 3*. Nairobi: International Livestock Research

Institute. Available online at: https://hdl.handle.net/10568/497 (accessed on March 11, 2021).

Kumar, A. A. (2016). "Botany, taxonomy and breeding," in *The Sorghum Genome: Compendium of Plant Genomes*, eds. S. Rakshit and Y. H. Wang (Cham: Springer), 27–45. doi: 10.1007/978-3-319-47789-3_2

Kumar, A. A., Reddy, B. V. S., Sahrawat, K. L., and Ramaiah, B. (2010). Combating micronutrient malnutrition: Identification of commercial sorghum varieties with high grain iron and zinc. *J. SAT Agric. Res.* 8, 1–5.

Kumar, A. A., Reddy, B. V. S., Sharma, H. C., Hash, C. T., Rao, P. S., Ramaiah, B., et al. (2011). Recent advances in sorghum genetic enhancement research at ICRISAT. *Am.J. Plant Sci.* 2, 589–600. doi: 10.4236/ajps.2011.24070

Kumar, K. A. (2010). *Local Knowledge and Agricultural Sustainability: A Case Study of Pradhan Tribe in Adilabad District (Working Paper No. 81)*. Begumpet: Centre for Economic and Social Studies.

Kumar, S., Murthy, D. K., Gumma, M., Khan, E., Khatri-Chhetri, A., Aggarwal, P., et al. (2018). *Towards climate-smart agricultural policies and investments in Telangana*. Telangana: CGIAR Research Program on Climate Change, Agriculture and Food Security. Available online at: https://hdl.handle.net/10568/90627 (accessed on March 11, 2021).

Kumara, C. D., Bantilan, M. C. S., Rajalaxmi, A., Reddy, B. V. S., Borikar, S. T., Kumar, A. A., et al. (2014). *Development and Diffusion of Sorghum Improved Varieties in India: Impact on Growth and Stability in Yield* (Working Paper Series no. 50). Patancheru: International Crops Research Institute for the Semi-Arid Tropics.

Nagaraj, N., Basavaraj, G., Rao, P. P., Bantilan, M. C. S., and Haldar, S. (2013). Sorghum and pearl millet economy of India: future outlook and options. *Econ. Polit. Wkly.* 48, 74–81.

NAIP Project Report (2012). *Harmonizing Biodiversity Conservation and Agricultural Intensification Through Integration of Plant, Animal and Fish Genetic Resources for Livelihood Security in Fragile Ecosystems*. Available online at: http://www.nbpgr.ernet.in:8080/NAIP-GEF_3/index_naip-gef_3.html (accessed: January 10, 2021).

NFHS (2016). *National Family Health Survey of Adilabad District 2015–16*. Available online at: http://rchiips.org/nfhs/FCTS/TG/TG_FactSheet_532_Adilabad.pdf (accessed: January 10, 2021).

NITI Aayog Report (2018). *Adilabad District Report*. Available online at: https://www.niti.gov.in/niti/hi/best-practices/district-wise-statistics?term_node_tid_depth=188 (accessed: October 10, 2020).

Padmaja, R., Gebremarium, H., and Kavitha, K. (2018). *Talking nutrition with adolescents in tribal regions of Telangana*. Available online at: http://gldc.cgiar.org/talking-nutrition-with-adolescents-in-tribal-regions-of-telangana/ (accessed on March 7, 2022).

Padmaja, R., and Kavitha, K. (2017). *Food basket of sorghum, millet and legume products to address malnutrition in Telangana, India*. ICRISAT Happenings. Available online at: https://www.icrisat.org/food-basket-of-sorghum-millet-and-legume-products-to-address-malnutrition-in-telangana-india/ (accessed on March 7, 2022).

Paltasingh, T., and Paliwal, G. (2014). Tribal population in India: regional dimensions and imperatives. *J. Reg. Dev. Plan.* 3, 27–36. Available online at: https://ideas.repec.org/a/ris/jrdpin/0032.html (accessed on March 20, 2021).

Pandravada, S. R., Sivaraj, N., Kamala, V., Sunil, N., Sarath Babu, B., and Varaprasad, K. S. (2008). "Agri-biodiversity of Eastern Ghats - Exploration, collection and conservation of crop genetic resources," in Proceedings of the National Seminar on Conservation of Eastern Ghats. (Hyderabad: EPTRI), 11-12. Available online at: http://www.apenvis.nic.in/All%20PDF%20Files/COMMON/Andhra%20Pradesh.pdf (accessed on March 20, 2021).

Pandravada, S. R., Sivaraj, N., Sunil, N., Jairam, R., Prasanthi, Y., Chakrabarty, S. K., et al. (2013). *Sorghum landraces* patronized by tribal communities in Adilabad district, Andhra Pradesh. *Indian J. Tradit. Knowl.* 12, 465–471.

Paroda, R. S. (2018). *Strategy for Doubling Farmers' Income (Strategy Paper).* New Delhi: Trust for Advancement of Agricultural Sciences. doi: 10.1079/9781786395177.0274

Patil, J. V., Reddy, S. P., Prabhakar, A., Umakanth, V., Gomashe, S., and Ganapathy, K. N. (2014). History of post-rainy season sorghum research in India and strategies for breaking the yield plateau. *Indian J. Genet. Plant Breed.* 74, 271–2285. doi: 10.5958/0975-6906.2014.00845.1

Phuke, R. M., Anuradha, K., Radhika, K., Jabeen, F., Anuradha, G., Ramesh, T., et al. (2017). Genetic variability, genotype × environment interaction, correlation, and GGE biplot analysis for grain iron and zinc concentration and other agronomic traits in RIL population of sorghum (*Sorghum bicolor* L. *Moench). Front. Plant Sci.* 8:712. doi: 10.3389/fpls.2017.00712

Poshadri, A., Kumar, P. Y., Kumar, S. M., Charan, S. G., Raghuveer, M., and Devi, R. A. (2019). Backyard kitchen gardening for nutritional security in tribal areas of Adilabad district, India. *Int. J. Chem. Stud.* 7, 4502–4504.

Prasad, R., Benhur, D., Kommi, K., Madhari, R., Rao, V. M., and Patil, J. V. (2016). Impact of sorghum supplementation on growth and micronutrient status of school going children in southern India: a randomized trial. *Indian J. Pediatr.* 83, 9–14. doi: 10.1007/s12098-015-1782-7

Prasad, R., Shivay, Y. S., and Kumar, D. (2014). Agronomic biofortification of cereal grains with iron and zinc. *Adv. Agron.* 125, 55–91. doi: 10.1016/B978-0-12-800137-0.00002-9

Rajani, K. (2018). *Preserving Legacy Grains: The Persa Jonna story*. Agribuzz-ICRISAT Happenings Newsletter. No. 1755, 22 June 2018. Available online at: https://www.icrisat.org/preserving-legacy-grains-the-persa-jonna-story/

Rao, D. B., Seetharama, A., Suresh, A., Sreekanth, M., Reddy Nirmal, K., and Rao, S. V. (2010). *Dynamics of Value and Trade Channels of Sorghum in India.* Rajendranagar: Directorate of Sorghum Research.

Rao, P. P., and Hall, A. (2003). Importance of crop residues in crop-livestock systems in India and farmers' perceptions of fodder quality in coarse cereals. *Field Crop Res.* 84, 189–198. doi: 10.1016/S0378-4290(03)00150-3

Reddy, M. T., Pandravada, S. R., Sivaraj, N., Kamala, V., Sunil, N., and Dikshit, N. (2017). Classification and characterization of landscapes in the territory of Adilabad district, Telangana, Deccan Region, India. *OA Lib. J.* 4:e3745. doi: 10.4236/oalib.1103745

Reddy, S., Reddy, B. V. S., and Kumar, A. (2009). M 35-1 derived sorghum varieties for cultivation during the postrainy season. *J. SAT Agric Res.* 7:4.

Sharma, K., Pattanaik, A. K., Anadan, S., and Blümmel, M. (2010). Food-feed crop research: a synthesis. *Anim. Nutr Feed Technol.* 10, 1–10.

Singh, Y. P., Nayak, A. K., Sharma, D. K., Gautam, R. K., Singh, R. K., Singh, R., et al. (2014). Farmers' participatory variety selection: a suitable crop improvement approach for 21st century. *Agroecol. Sustain. Food Syst.* 38, 427–444. doi: 10.1080/21683565.2013.870101

Sivaraj, N., Elangovan, M., Kamala, V., Pandravada, S. R., Pranusha, P., and Chakrabarty, S. K. (2016). Maximum entropy (Maxent) approach to sorghum landraces distribution modelling. *Indian J. Plant Genet. Resour.* 29, 16–21. doi: 10.5958/0976-1926.2016.00004.8

Sivaraj, N., Pandravada, S. R., Jairam, R., Sunil, N., Varaprasad, K. S., Ramesh, P., et al. (2012). An indigenous cost-effective innovation for bird scares by the Gond tribe in Adilabad district, Andhra Pradesh. *Indian J. Tradit. Knowl.* 11, 714–718.

Sridhara, S., Ramesh, N., Gopakkali, P., Das, B., Venkatappa, S. D., Sanjivaiah, S. H., et al. (2020). Weather-based neural network, stepwise linear and sparse regression approach for rabi sorghum yield forecasting of Karnataka, India. *Agron* 10:1645. doi: 10.3390/agronomy10111645

Srivastava, A., Kumar, N. S., and Aggarwal, P. K. (2010). Assessment on vulnerability of sorghum to climate change in India. *Agric. Ecosyst. Environ.* 138, 160–169. doi: 10.1016/j.agee.2010.04.012

Srivastava, V. K. (2018). The National Committee report on tribal people. *Soc. Change* 48, 120–130. doi: 10.1177/0049085717743843

Task Force Report (2019). *Agriculture Challenges and Way Forward (Submitted to NITI Aayog), Government of Telangana, Agriculture and Cooperation Department, 47.* Available online at: http://niti.gov.in/writereaddata/files/Telangana_Report_1.pdf (accessed: April 11, 2021).

Telangana districts profile report (2018). Available online at: https://data.telangana.gov.in/dataset/adilabad-district-mandal-wise-crop-areas (accessed: March 10, 2021).

Thiele, G., Dufour, D., Vernier, P., Mwanga, R. O. M., Parker, M. L., Schulte Geldermann, E., et al. (2020). A review of varietal change in roots, tubers and bananas: consumer preferences and other drivers of adoption and implications for breeding. *Int. J. Food Sci. Technol.* 56, 1076–1092. doi: 10.1111/ijfs.14684

Trivedi, T. P. (2008). *Handbook of Agriculture*. New Delhi, India: Directorate of Information and Publications of Agriculture, Indian Council of Agricultural Research.

Upadhyaya, H. D., Dwivedi, S. L., Wang, Y. H., Vetriventhan, M., Ciampitti, I., and Prasad, V. (2016). "Sorghum genetic resources", in *Sorghum*, eds I. Ciampitti, V. E. Prasad (Washington, DC: American Society of Agronomy and Crop Science Society of America, Inc.), 1–27. doi: 10.2134/agronmonogr58.2014.0056.5

Vadez, V., Krishnamurthy, L., Hash, C. T., Upadhyaya, H. D., and Borrell, A. K. (2011). Yield, transpiration efficiency, and water-use variations and their interrelationships in the sorghum reference collection. *Crop Pasture Sci.* 62, 645–655. doi: 10.1071/CP11007

Voorhaar, M., and Anbazhagan, K. (2019). *A Farmer's Choice: Tribal Communities in Adilabad Select Their Preferred Sorghum Varieties*. Agribuzz-ICRISAT Happenings. Available online at: https://www.icrisat.org/tribal-communities-in-adilabad-select-their-preferred-sorghum-varieties/ (accessed: March 20, 2021).

Wale, E., and Yalew, A. (2007). Farmers' variety attribute preferences: implications for breeding priority setting and agricultural extension policy in Ethiopia. *Afr. Dev. Rev.* 19, 379–396. doi: 10.1111/j.1467-8268.2007.00167.x

Yadav, J., Ojha, A. K., George, C., Sajeevan, R., Singh, G., Bhargav, H., et al. (2011). *All India Report on Agriculture Census 2010–2011*. Available online at: https://agricoop.nic.in/sites/default/files/air2010-11complete.pdf (accessed: March 20, 2021).

Zerbini, E., and Thomas, D. (2003). Opportunities for improvement of nutritive value in sorghum and pearl millet residues in South Asia through genetic enhancement. *Field Crop Res.* 84, 3–15. doi: 10.1016/S0378-4290(03)00137-0

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