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Overview of germplasm collecting activities for plant genetic resources for food and agriculture in Sudan from 2002 to 2022

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Abstract: From 2002 to 2022, the Agricultural Plant Genetic Resources Conservation and Research Centre (APGRC) in Sudan conducted 56 collecting missions for plant genetic resources for food and agriculture (PGRFA) in Sudan. These missions aimed to conserve the country's crop genetic diversity and covered different states and almost all ecological zones within the country, from the desert in the north to the high-rainfall savannah in the far south. Different farming systems were included, such as rain-fed, irrigated and flood-irrigated systems. The most covered states were West Darfur in the far west followed by South Kordofan in the western-central region. A total of 7,720 PGRFA accessions were collected encompassing diverse crops and plant species within different plant groups. Cultivated varieties made up 90% of the whole collection, while crop wild relatives accounted for 8%, and range plants represented the remaining 2%. Cereals were the most collected group (48%), followed by vegetables (17%). The least represented groups were range plants, medicinal plants and fibre crops. Sorghum was the most represented crop in the collection with 2,481 accessions, followed by pearl millet with 1,022 accessions. Hundreds of accessions of cowpea, okra, sesame and other crops were also collected. A total of 181 accessions of natural range plants were collected from selected states. The materials collected during these germplasm collecting missions will be conserved at the APGRC genebank, characterized and evaluated for different traits. Further germplasm collection activities may be carried out in the future to address any identified gaps.

Keywords: PGRFA, collecting missions, conservation, cultivated varieties, crop wild relatives, range plants, South Kordofan

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Introduction

Sudan is the third largest country in Africa, after Algeria and the Democratic Republic of Congo, with an area of 1.88 million km^2 (UNEP and HCENR, 2020). It is located between latitudes 10° and 22° North, and longitudes 22° and 38° East. Sudan is ecologically divided into five vegetation zones according to rainfall patterns from north to south (Figure 1). These are: 1) Desert (0–75mm), 2) Semi-desert (75–300mm), 3) Low-rainfall savannah on clay or sand (300–800mm), 4) High-rainfall savannah (800–1500mm) and 5) Mountain vegetation (300–1000mm) (HCENR, 2015).

According to the Ministry of Agriculture and Forestry (2015), Sudan's cultivable arable land is estimated at 86 million hectares. However, less than 20% of the potential area is utilized in three major farming subsectors (Ministry of Agriculture and Forestry, 2015):

- The irrigated system subsector, estimated at 5 million hectares, where 100% of wheat and 25% of sorghum are produced, in addition to others including vegetables and fruit trees, oil crops such as groundnut, and cotton as a cash crop;
- The semi-mechanized rain-fed subsector, estimated at 6 million hectares, where the two main

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crops are sorghum and sesame, in addition to sunflower;
- The agro-pastoral traditional rain-fed subsector, of about nine million hectares, where main crops produced are sorghum, pearl millet, sesame and groundnut, as well as seed watermelon and roselle.

Sudan is endowed with different ecosystems making it rich in biodiversity, including plant genetic resources for food and agriculture (PGRFA). Sudan is part of the East African Primary Region of crop genetic diversity, with high diversity for coffee, cotton, cowpeas, melons, millets, olives, peas, sesame and sorghum (Khoury *et al*, 2016). Wild relatives of crops such as sorghum, pearl millet, okra, watermelon and melon are known in the country (Mahmoud *et al*, 1995). Old introduced cultivars for crops such as maize, faba bean and tomato are still existing and utilized by some farmers. In addition, rangelands encompass different ecological zones extending from desert and semi-desert in the north to low and high rainfall savannah to the southern border and include a wealth of natural range plant species (HCENR, 2013).

Factors threatening the genetic diversity of PGRFA in Sudan include several natural and man-made factors. The most important ones are drought spells and seasonal rain fluctuations, expansion in modern agriculture and use of advanced improved cultivars, expansion in new constructions and activities other than crop cultivation, and disturbance of normal traditional systems of life, including agricultural activities due to civil strives and wars in several regions within the country (HCENR, 2015).

In order to safeguard these important genetic resources, the Agricultural Research Corporation (ARC) of Sudan established the Plant Genetic Resources Programme (PGR Programme). Historically, the PGR Programme dates back to the early 1980s, when activities for collecting and conserving local genetic resources of horticultural crops were conducted by the Horticultural Research Section of the ARC in collaboration with the International Board for Plant Genetic Resources (Hassan *et al*, 1983). In 1995, the programme was mandated for collecting, conserving and enhancing the use of the genetic resources for different agricultural crops under what was by then called the Plant Genetic Resources Unit. Following expansion in the total germplasm holdings and the human and physical capacities of the programme, this unit was upgraded in 2014 into a centre now known as the Agricultural Plant Genetic Resources Conservation and Research Centre (APGRC), which is currently managing the PGR programme. The APGRC headquarters are located in the city of Wad Medani in central Sudan.

During the 1990s and 2000s, the coverage of PGRFA acquired by the PGR Programme expanded to different groups such as cereals, oil crops, grain legumes, in addition to horticultural crops including vegetables, fruit-producing plants and medicinal and aromatic plants. Significant progress in the efforts to collect and acquire PGRFA from different sources occurred from 2003, thanks to the availability of necessary financial resources to conduct germplasm collecting missions from different regions, as well as the improvement in the physical and human capacities of the PGR unit. Funding for the PGR Unit came from the Eastern Africa Plant Genetic Resources Network (EAPGREN) through a project funded by the Swedish International Development Cooperation Agency (Sida), which extended up to 2010, and other funding sources such as the Global Crop Diversity Trust (Crop Trust). Moreover, the budgetary payments to the PGR programme were significantly increased by the national government on an annual basis since 2014.

This paper is intended to provide a general overview of the collecting activities conducted under APGRC, and summarize the results obtained over 20 years from 2002 to 2022 for collecting indigenous PGRFA within Sudan for conservation in the APGRC genebank facilities. Those genebank facilities consist of seedbanks, and field genebanks for vegetatively propagated crops. Information on germplasm collecting activities has been documented within the APGRC genebank documentation system, as well as in the global PGR data platform Genesys (http://www.genesys-pgr.org/wiews/SDN002). This review provides information on the methodologies used to collect PGRFA, the locations visited, the germplasm materials collected as well as the phenotypic variations observed on the collected materials. The results are thoroughly discussed to explain the extent and importance of the geographical coverage and the PGRFA materials collected. The conclusion highlights the major achievements from the germplasm collecting activities and identifies major gaps to be addressed in the future.

Methodology

The germplasm collecting activities followed a structured process, starting with planning and ending with germplasm sampling and data recording on the collected PGRFA from the targeted geographical locations before their conservation at the APGRC genebanks.

Planning

Planning for germplasm collection was conducted through consultative processes involving all APGRC scientific staff during regular programme planning activities within the ARC national research programme planning process. Geographical locations and taxa for collecting were identified and prioritized based on the following:

A. Geographical prioritization

Ecological zones and geographical areas were selected and prioritized based on the following criteria:

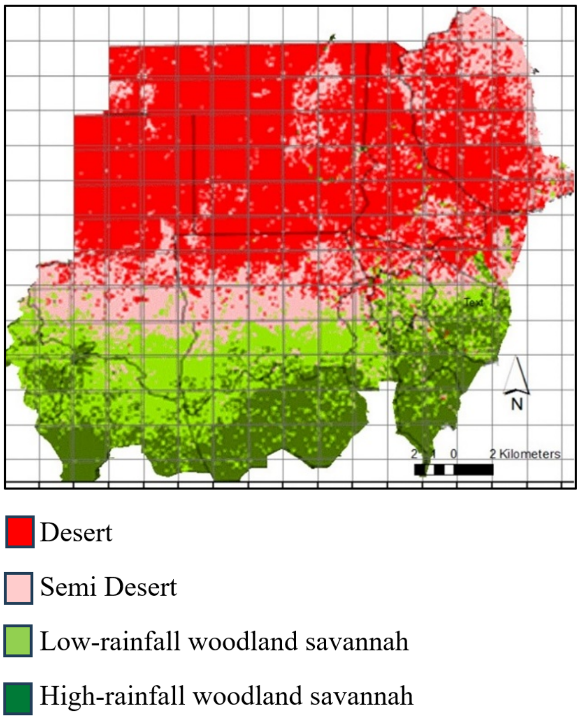

Figure 1. Map of Sudan vegetation zones (Eltoum *et al*, 2023)

1. Geographical areas known for their richness in PGRFA diversity across different ecological zones in the country. This was the case for Kordofan and Darfur regions in western Sudan, Blue Nile State in central to eastern Sudan, River Nile and Northern States in northern Sudan.
2. Major geographical gaps that were identified after 2014 in the Darfur region in far western Sudan.

B. Taxonomical prioritization

Different crops and plant taxa for collection were identified and prioritized according to the following criteria:

1. Specific taxonomical gaps within the existing germplasm collections for specific crops already held by APGRC, as identified in consultation with different crop specialists, such as for crops like sorghum and pearl millet.
2. Overall taxonomical gaps in terms of crops and plant groups almost or fully absent within the APGRC collection, as was the case for taxa and plant groups such as banana, date palm, crop wild relatives and natural range plants.

Detailed collection work plans were developed annually by the APGRC researchers in consultation with the APGRC technical staff and/or directors of the ARC stations in the targeted regions, as well as with technicians and local communities there.

The whole processes of planning at different stages were coordinated, guided, supervised and approved by the APGRC director, who afterwards closely followed the implementation processes.

Targeted PGRFA

Regular germplasm collecting missions were organized annually across the different cultivation seasons starting from season 2002–2003 to season 2013–2014. They targeted different PGRFA, including cereals such as sorghum and pearl millet; oil crops such as sesame and groundnut; legumes such as cowpea and faba bean; vegetables and cucurbits such as okra, tomato, melons and watermelon; medicinal and aromatic plants such as roselle and fenugreek, and fruit producing plants such as banana and date palm. Starting from 2014, the focus was on filling geographical and taxonomical gaps, of which the latter included date palm, natural range plants and crop wild relatives.

Targeted locations

Germplasm collecting activities targeted various farming systems in the different ecological zones during the appropriate seasons, including rain-fed, irrigated and river-flooded systems. The administrative states of the country were the broad targeted geographical locations for the different collecting missions. The ecological zones covered across the different states included (Supplemental Table 1):

- The desert and semi-desert zones in Northern, River Nile, Khartoum, Kassala and Red Sea States;
- The low-rainfall savannah on clay and sand in the States of Gezira, Sennar, Blue Nile, Gedarif, and in the states within Kordofan and Darfur regions;
- High-rainfall savannah in southern parts of the Blue Nile State, and Kordofan and Darfur regions.

The major geographical gaps targeted since 2014 were the different states within the Darfur region of far western Sudan, which was difficult to cover earlier because of the civil war since 2003.

Means of transportation to these locations was usually a 4 WD vehicle facilitating reaching to different collection points that were usually away from asphalt roads. However, they were accessible under the guidance of the representatives of the local authorities and communities within the collecting teams.

Collecting approaches

The collecting missions were implemented following either multi-species or single-species collecting approaches. The cultivation season in Sudan usually starts in summer from May to October, and extends to winter from November to April. Therefore, the germplasm collecting activities from *in situ* habitats were usually carried out during the harvesting times, which were from October to December or beyond for summer-adapted crops such as sorghum, sesame, cowpea and okra; and from February to April for winter-adapted crops such as wheat, faba bean and tomato.

Multi-species collecting missions

A total of 39 multi-species collecting missions were organized across 17 years during the period extending

Table 1. Approaches and total numbers of collecting missions conducted from 2002 to 2022. More details are available in Supplemental Tables 1 and 2.

Approach	Targeted plants	Total
Multi-species	Different crop groups	27
	Vegetables	1
	Crop wild relatives	8
	Range plants	3
	Sub-total	**39**
Single-species	Banana	11
	Date palm	4
	Sorghum	1
	Watermelon	1
	Sub-total	**17**
Grand Total		**56**

between the cultivation seasons of 2002–2003 and 2021–2022, with the exception of three seasons (2009–2010, 2011–2012 and 2012–2013), with at least one mission per year (Table 1 and Supplemental Table 1). Those missions covered different areas of the country and targeted different crop and plant species, including in some years vegetables, crop wild relatives or natural range plants (Supplemental Tables 1 and 2).

Single-species collecting missions

Seventeen single species collecting missions were organized during the specified period. They targeted sorghum, watermelon, banana and date palm from different states (Supplemental Table 1, Table 1).

Collecting teams

Each team carrying out a collecting mission was usually headed by an APGRC researcher and might include a collaborating or assisting scientist and/or a technician from APGRC or ARC (Supplemental Table 1). Missions conducted since 2014 in the states of the Darfur region were led by directors of the agricultural research stations in such states. Each team also included a representative from the State Ministry of Agriculture, and a representative from the local community in the targeted area.

Germplasm sampling

Germplasm samples were collected from farmers' fields, wild habitats or rangelands. Each population at each specific site was sampled separately with a basic approach targeting around 50 plants per population. However, for populations with fewer than 50 plants, only the available plants were sampled.

Materials collected included seeds, panicles, fully ripe or dry fruits in the form of soft berries, pods or capsules, corms for banana, and off-shoots for date palm (Figure 2). Seeds were then extracted and processed for long-term conservation in the seedbank, while banana corms and date palm off-shoots were prepared and planted in the field genebanks.

Data recorded

A germplasm collection form was used to record passport data on each sample collected (Supplemental Material 1). The form was derived from the FAO-IPGRI Multi-Crop Passport Descriptors (FAO and IPGRI, 2001). It consisted of major information such as taxonomic data, georeferenced data on the site of collection, date of germplasm collection, and local names. However, a specific germplasm collection form including more descriptors was used for collecting crop wild relatives during 2016 and 2017 (Eastwood *et al*, 2022). GPS was used to determine the coordinates and altitudes of the collection sites.

Results

Results obtained through the collecting activities across the cultivation seasons from 2002–2003 to 2021–2022 are summarized in terms of geographical locations covered, germplasm materials collected and phenotypic variations observed on the collected samples.

Missions conducted and sites covered

A total of 56 germplasm collecting missions were conducted, including 39 for multiple species and 17 for single species (Table 1). Among the single-species missions, 11 and 4 targeted banana and date palm genetic resources respectively, while sorghum and watermelon were targeted each by only one mission in Delta Elgash in Kassala State, and North and West Kordofan States, respectively.

Germplasm samples were collected from 1,155 sites within the 18 states of Sudan (Supplemental Table 2). They were located within latitudes ranging between 09.52° N in South Kordofan State and 20.93° N in Northern State; and longitudes ranged between 21.85° E in West Darfur State and 38.43° E in Red Sea State (Figure 3). In terms of collection sites, the most covered states were West Darfur and South Kordofan, where germplasm entries were sampled from 142 and 135 sites, respectively. The least covered states were Sennar and Khartoum, where germplasm entries were sampled from five and nine sites, respectively.

The number of states contributing to the total accessions of each crop varied considerably between the different crops, reflecting the diverse growth habitats and requirements. While okra (*Abelmoschus* spp.) accessions were sampled from 17 states, and sorghum (*Sorghum* spp.) and roselle (*Hibiscus sabdariffa*) were sampled from 16 states each, genetic resources of 20 crops were sampled from only five states or less, including the date palm accessions, which were sampled from only two states (Supplemental Figure 1).

Germplasm materials collected

A total of 7,720 accessions were collected from more than 40 cultivated crops and other PGRFA species (Supplemental Table 3). They were composed of different crop groups including cereals such as sorghum

Banana corms

Date palm off-shoots

Figure 2. Banana and date palm materials collected

(*Sorghum* spp.), pearl millet (*Pennisetum* spp.) and maize (*Zea mays*); grain legumes such as cowpea (*Vigna* spp.), faba bean (*Vicia faba*) and chickpea (*Cicer arietinum*); oil crops such as sesame (*Sesamum* spp.) and groundnut (*Arachis hypogea*); vegetables such as okra (*Abelmoschus* spp.), tomato (*Solanum lycopersicum*), and pumpkins and squashes (*Cucurbita* spp.); medicinal and aromatic plants such as roselle (*Hibiscus* spp.) and fenugreek (*Trigonella foenum-graecum*); fruit-producing plants such as banana (*Musa* spp.) and date palm (*Phoenix dactylifera*), in addition to natural range plants. Cereal genetic resources were the most represented in the collected materials, accounting for 49%, followed by vegetables at 17%, while medicinal and aromatic plants, range plants and fibre crops were the least represented, comprising 5%, 2% and less than 1%, respectively (Figure 4).

The total number of collected accessions varied greatly between cultivated crops ranging from only one to a few thousands. Out of 47 cultivated crops covered, 12 crops were represented by more than 100 accessions of each, collected from different numbers of states that varied between different crops (Table 2), adding up to 6,656 accessions and representing 86% of the total collection. The rest (1,064 accessions) were from other cultivated crops, wild plants or natural range plants, including 38 genera of other cultivated crops and wild plants, in addition to 39 genera of range plants.

The most collected crops were sorghum and pearl millet, of which 2,481 accessions and 1,022 accessions were collected, respectively (Table 2). Hundreds of accessions ranging from 179 to 449, were collected from date palm, melons, maize, watermelon, roselle, groundnut, banana, okra, sesame and cowpea.

All 18 states of Sudan were represented in this top collection, with the total number of accessions varying from 14 in Khartoum and Sennar States to 1,550 from South Kordofan State (Table 2).

Almost 90% of the accessions collected were from cultivated varieties, while only 8% were wild, including crop wild relatives and other wild plants apart from range plants. The rest of the accessions were from natural range plants, representing 2% of the total materials collected.

Taxa of crop wild relatives fully identified ranged between five for sorghum (*Sorghum virgatum, S. purpureosericeum, S. halepense, S. bicolor - verticilliflorum* and *S. aethiopicum*), three for eggplant (*Solanum incanum, S. dubium* and *S. cerasiforme*), and two for pearl millet (*Pennisetum stenostachyum* and *P. glaucum monodii*) and melons (*Cucumis melo agrestis* and *C. metulikerus*). Others including watermelon, sesame, cowpea, and rice had only one fully identified wild species, which were *Citrullus colocynthis, Sesamum alatum, Vigna vaxillata* and *Oryza barthii*, respectively (Supplemental Figure 2).

The total accessions collected of natural range plants were 181. They included 151 accessions, fully or partially identified taxonomically, belonging to 50 species across 37 genera. However, 30 accessions were taxonomically unidentified and documented only using their local names (Supplemental Figure 3).

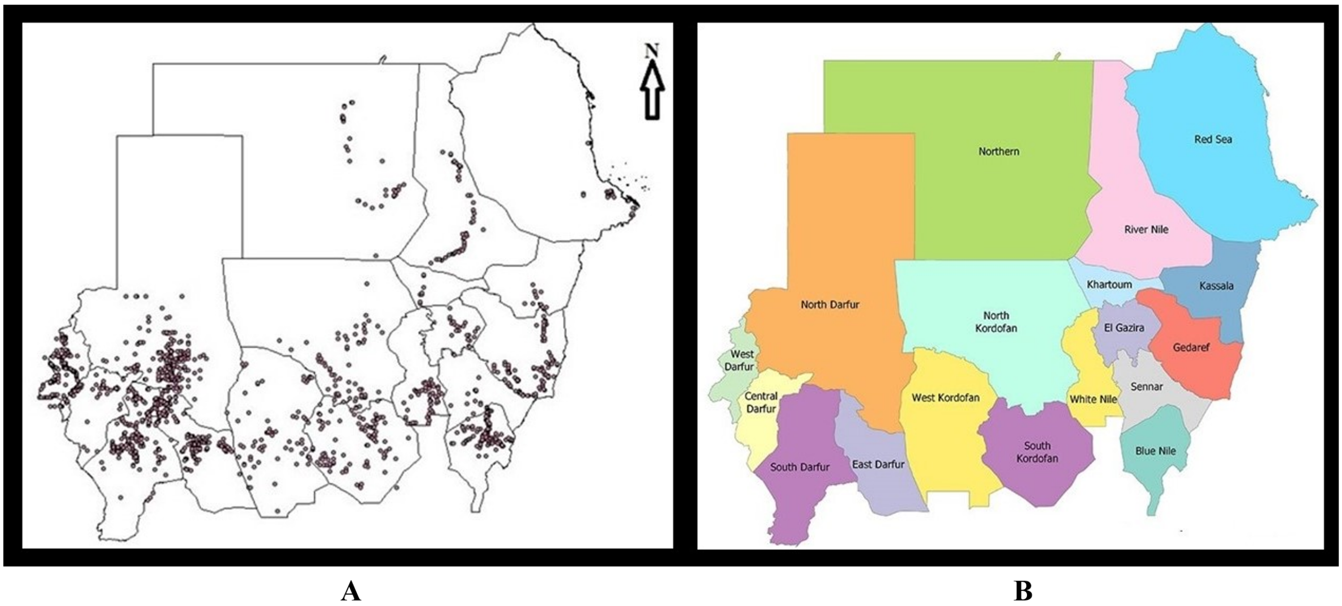

Figure 3. Sites where most germplasm accessions were collected from 2002–2022 (map A) across different states of Sudan, with state names shown on map B.

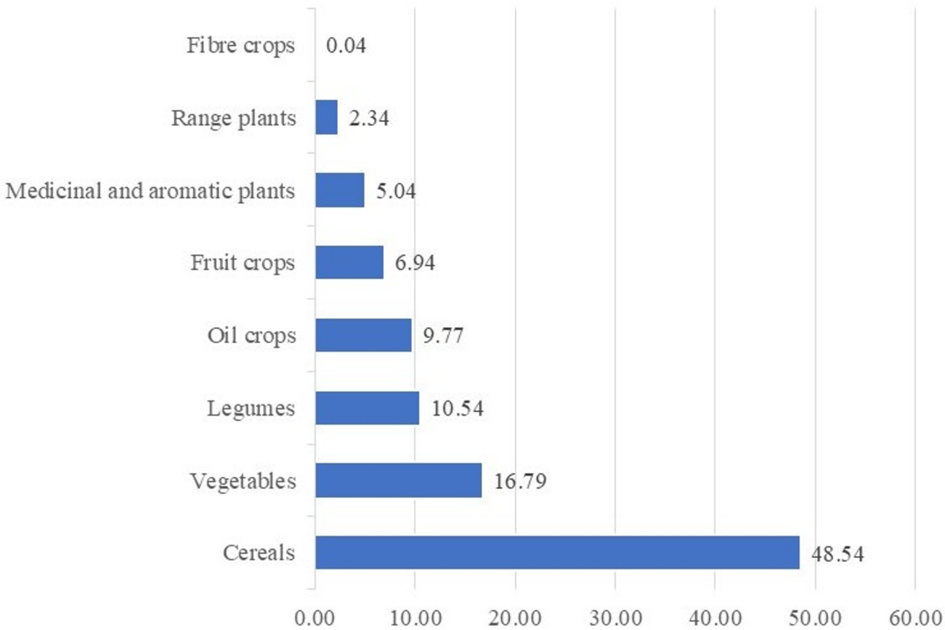

Figure 4. Distribution of percentages of total accessions collected from different plant groups

Table 2. Distribution of number of accessions of the top 12 crops collected among different states in Sudan between 2002 and 2022.

State	Sorghum	Pearl millet	Cowpea	Okra	Sesame	Banana	Groundnut	Roselle	Watermelon	Maize	Melon	Date palm	Total
South Kordofan	706	93	158	124	122	0	69	62	9	132	75	0	**1,550**
South Darfur	237	168	58	40	38	22	46	23	14	11	21	0	**678**
West Darfur	147	147	42	52	45	0	69	94	44	1	25	0	**666**
Blue Nile	172	94	57	33	68	84	27	18	0	36	10	0	**599**
North Kordofan	134	167	31	26	27	0	4	40	19	10	13	0	**471**
Kassala	273	3	2	9	2	151	2	2	10	2	12	0	**468**
East Darfur	135	49	7	16	13	0	79	54	11	0	6	0	**370**
North Darfur	144	141	11	7	21	0	13	17	7	0	0	0	**361**
Gedarif	142	35	52	13	51	0	21	6	4	9	16	0	**349**
Northern	9	0	6	16	0	21	0	2	5	11	4	139	**213**
Central Darfur	69	53	7	12	6	0	15	14	2	4	2	0	**184**
White Nile	169	3	4	1	1	0	1	2	0	0	0	0	**181**
Red Sea	89	48	0	26	0	0	0	4	0	1	13	0	**181**
West Kordofan	18	19	5	5	2	0	2	1	120	0	7	0	**179**
River Nile	28	0	7	5	0	12	0	4	3	3	0	40	**102**
Gezira	9	2	2	3	2	49	1	0	4	1	3	0	**76**
Sennar	0	0	0	0	0	14	0	0	0	0	0	0	**14**
Khartoum	0	0	0	6	0	4	0	1	0	0	3	0	**14**
Total accessions	2,481	1,022	449	394	398	357	349	344	252	221	210	179	**6,656**
Total states	16	14	15	17	13	8	13	16	13	12	14	2	

As a result of these collecting efforts and other germplasm acquisition activities, the total PGRFA accessions conserved by APGRC reached more than 16,000 accessions by 2022 compared to around 6,000 accessions in 2002, as shown in the APGRC Genebank Documentation System, with a total increase of around 10,000 accessions (Figure 5). The collecting missions reported here contributed significantly to this increase with 7,720 accessions, while the rest came from other germplasm acquisition activities during the same period, including repatriation of Sudanese germplasm from outside the country, and donations of germplasm samples by others such as crop breeders.

Phenotypic variations observed

Remarkable phenotypic variations on some morphological traits were visually observed on the plant organs collected such as the panicles, fruits and seeds. Such observations will be further studied and documented through detailed characterization using standard descriptor lists. In cereals, variations in shapes, sizes and colours were observable on panicles and seeds of sorghum, pearl millet, maize and rice (Figure 6). Seed colours of sesame and groundnut, both oil crops, were varied among the accessions collected from different sites (Figure 7). Remarkable variations were also observed in colours and sizes of seeds of some leguminous crops such as cowpea, faba bean, hyacinth bean and Bambara groundnut (Figure 8).

Variations were also observed on a number of horticultural crops, including Malvaceous and Solanaceous vegetables and medicinal plants (Figure 9). Capsule shapes were variable among the okra accessions, as well as the colours of dry enlarged calyces of roselle accessions. Fruit sizes and shapes also varied among tomato, hot pepper and eggplant accessions. Prominent variations were also observed in shapes, sizes and colours of fruits and seeds of different cucurbits such as watermelons, melons, pumpkins and squashes, and bottle gourds (Figure 10).

Discussion

The total number of PGRFA accessions conserved by APGRC before 2002 was approximately 6,000. A significant increase in the APGRC holdings occurred during the following 20 years resulting in more than 16,000 accessions by 2022. This increase of around 10,000 accessions, was primarily due to the intensive germplasm collecting activities undertaken during the cultivation seasons from 2002 to 2022, which accounted for 77% of the germplasm acquired, in addition to repatriation of Sudanese germplasm from outside the country, and donations of samples by others. On the other hand, direct collection by APGRC from *in situ* habitats contributed by only 21% before 2002, during the 20 years since the start of formal germplasm collecting activities in 1982. In fact, the horticultural germplasm materials collected in 1982, 1983 and 1985, as reported by Hassan *et al* (1983), Hassan *et al* (1984) and Geneif *et al* (1985), were the first accessions deposited in the genebank unit that later evolved to become APGRC.

The increased role of APGRC as a germplasm collecting institute after 2002 was mainly due to the availability of necessary resources from different streams, including funding for germplasm collecting. For example, the period between 2002 and 2010 witnessed a substantial increase in the resources available for APGRC from the capacity-building project for PGR under the EAPGREN network, of which Sudan was a founding member (Marandu and Kamau, 2008). This project, financed by the Swedish International Development Cooperation Agency, aimed to implement national and regional activities, including germplasm collecting activities. Also, APGRC obtained funds from a project financed through the Crop Trust from 2015 to 2017 for collecting crop wild relatives, which contributed significantly to increasing the APGRC holdings of crop wild relatives (Eastwood *et al*, 2022). Additional financial support was obtained from the Crop Trust through the CGIAR Genebank Management Platform and the International Center for Agricultural Research in the Dry Areas (ICARDA) in 2021 for collecting PGRFA to fill gaps in the collections held by APGRC and other international research centres.

The number of sites sampled was considerably large, which was made possible by reliable transportation means that enabled access to various locations, even those far from asphalt roads. Membership in the collecting teams of representatives from local authorities and communities was invaluable in guiding those teams through local internal roads connecting villages and leading to wild habitats.

Almost half (48%) of the accessions collected from 2002 to 2022 were cereal crops, of which sorghum was represented by 66%, and pearl millet by 27%. This highlights the importance of cereals, especially sorghum and pearl millet, in the country in terms of the extent and distribution of cultivated areas, as well as the diversity they encompass, including farmers' cultivars and wild relatives. Both crops are major staples in Sudan, and are annually cultivated in areas of more than 10 million hectares for sorghum, and 4 million hectares for pearl millet (Ministry of Agriculture and Forestry, 2015). Moreover, Sudan is part of the primary diversity regions for these crops in East and West Africa, as indicated by Khoury *et al* (2016). It is located within sub-Saharan and Northeast Africa, which is the primary centre of origin and diversity of sorghum as mentioned by Barmel *et al* (2022b). Pearl millet was domesticated in West Africa and then diffused into eastern Africa, southern Africa and South Asia (Barmel *et al*, 2022a). Therefore, eastern Africa, including Sudan, contains remarkable variability in pearl millet as was observed in the number of pearl millet accessions collected by APGRC and the variations observed. This was proved by Bashir *et al* (2014), who identified clear genetic

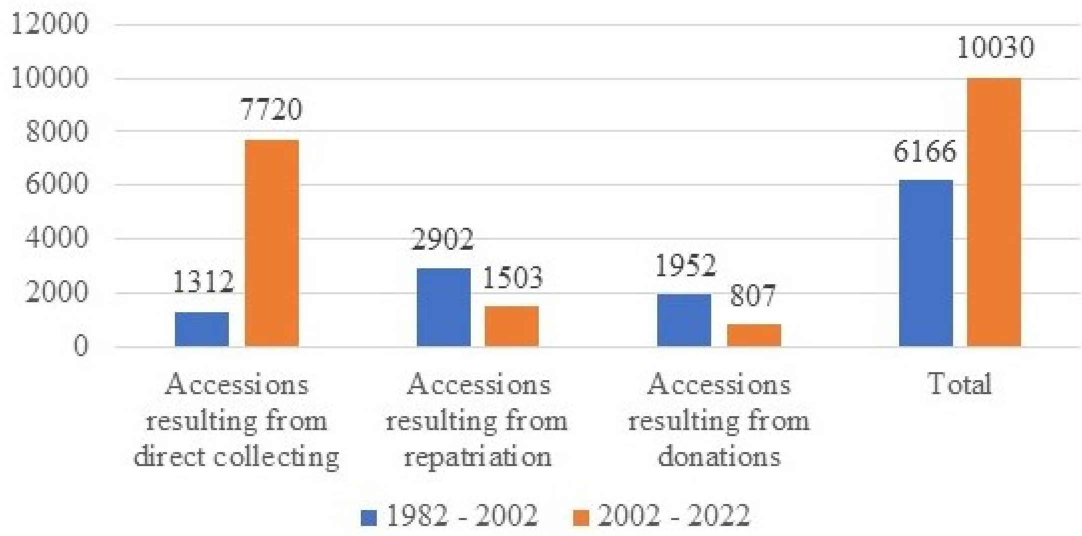

Figure 5. Comparisons between total accessions acquired by the Agricultural Plant Genetic Resources Conservation and Research Centre (APGRC) from different sources during the periods before and after 2002

Figure 6. Variations among panicles and seeds of different cereal crops accessions (sorghum, pearl millet, maize and rice) collected from different Sudan states during different seasons

diversity within a sample of 214 accessions from Sudan, using marker-based analysis.

Vegetables, including Malvaceous, Solanaceous and Cucurbit crops were the second largest group among the materials collected, representing 17%. Various vegetables are consumed in Sudan; among them are wild species, indigenous vegetables and introduced types, as mentioned by Ahmed and Mohamed (1995). Among the collected vegetables, true indigenous forms of okra, melons and watermelons were present showing remarkable morphological variation. One piece of evidence of the geographical origin of okra is partially based on the presence of a putative ancestor (*A. ficulneus*) in East Africa (Kumar *et al*, 2011). Schippers (2002) reported that *A. ficulneus* was found in Sudan and other regions of the Sahel and East Africa, but more so in South and South East Asia. Okra is one of the most important traditional vegetables in Sudan that is used almost all over the country in a number of ways of cooking either after being dehydrated or as fresh pods (Mohamed, 1991). This explains the widest geographical range from which okra genetic resources were collected making it the leading crop in terms of the number of states (17) from which samples were obtained. Variations observed among okra fruits collected were further shown on vegetative, inflorescence and fruit traits through morphological characterization results as recently reported by El-Tahir (2023).

The collections made over 20 years contained a considerable number of melon accessions totalling 210, including cultivated and wild melons with observed

Figure 7. Variations among seeds of different oil crops accessions, including sesame and groundnut, collected during different seasons from various Sudan states

variations among them. Mohamed and Yousif (2004) described Sudan as unique, in terms of the presence of different melon subspecies, containing both wild and cultivated genotypes. Cultivated melons in Sudan are composed of sweet melon, known locally as Shammam; snake melon, known locally as Ajjour; a local vegetable melon named 'Tibish'; and a local type of melon of which seeds are eaten, known locally as Seinat. Wild melon plants (*C. melo agrestis*) are also found in Sudan and are known as Humaid. Among them are types of melon that are truly indigenous to the country, either of typical wild type such as *C.melo agrestis*, or grown only in Sudan such as Tibish (Mohamed and Pitrat, 1999). In contrast, cultivars of sweet melons and snake melons are introductions from outside the country. According to Pitrat (2013) the Tibish melon is considered a primitive cultivated melon that evolved and domesticated independently in a domestication event separate from other cultivated melons in Africa and belonging to the subspecies agrestis. The latter subspecies agrestis was considerably represented in its wild form in the collections made from 2002 to 2022 by 153 accessions, providing supportive proof of the probability that Tibish melon might have been domesticated in Sudan through evolution from such wild forms. This collection is uniquely important since the wild and cultivated agrestis melons Tibish and Humaid have been proved to be sources of resistance to a number of viral and fungal diseases, as well as insect pests, as reviewed by Mohamed and Yousif (2004).

The collecting efforts resulted in 252 accessions of watermelon, of which more than 50% were from Kordofan region. One of the reasons for the importance of this collection is the recently reported information by Renner *et al* (2021), indicating that the closest relative to the domesticated watermelons was the Kordofan melon (*Citrullus lanatus* subsp. *cordophanus*) from Sudan. An earlier study by Goda (2007) on morpho-

Figure 8. Variations among seeds of different accessions of leguminous crops, including cowpea, faba bean, hyacinth bean and Bambara groundnut, collected during different seasons from different Sudan states.

Figure 9. Variations among accessions of Malvaceous crops, including capsules of okra and dry calyces of roselle, as well as among fruits of the Solanaceous crops tomato, hot pepper and wild relatives of eggplant, collected from some Sudan states during different seasons

Figure 10. Variations among fruits and seeds of some accessions of cucurbit crops, including watermelon, melon, pumpkin and bottle gourd, collected during different seasons from different Sudan states

logical characterization of 28 *Citrullus* accessions from Sudan, revealed remarkable variations shown by clustering analysis distinguishing between four main distinct groups. The first group was characterized by 88% similarity within the group members and consisted of cultivated accessions collected mainly from Kordofan and Darfur regions in the west. This group was further divided into three subgroups indicating the variation of the genetic resources of this group within a region, from where watermelon is believed to have originated (Goda, 2007).

Among the Solanaceous vegetables collected were tomatoes, hot peppers and eggplants. All of them originated in regions far away from Sudan but have been introduced into the country some time ago. An earlier study on tomato accessions collected from the western and northern regions of Sudan showed distinctive features of each compared to the other (El-Tahir, 1993). Tomatoes from western Sudan were mostly small or very small in size and were mostly used for making dried tomato paste from fruit slices. On the other hand, tomatoes from the Northern region of Sudan were medium or relatively big and mainly used as salad tomatoes. Such wide variations in tomato fruits were proved to be still there as shown within the collections obtained from 11 states, including from western and northern Sudan. Capsicum species originated in South America from where they dispersed into different regions of the world forming secondary centres of diversity, among which eastern and southern Africa, where Sudan lies. West and Central Africa represent a significant secondary region of diversity for *C. chinense*, while East Africa is likely to be an important secondary region of diversity for *C. frutescens* (Barchenger and Khoury, 2022); both hot pepper species were present in Sudan as suggested by El-Tahir (2001), and, therefore, are likely to have been collected during the last 20 years. The popularity of this crop and its production in smallholdings, in diverse environmental conditions of different regions substantially contributed to the observable vast variability of this crop in Sudan (Geneif, 1984). This variability was further confirmed by El-Tahir (1994), who indicated the availability of high variation between and within 116 accessions from Sudan in plant and fruit characters. Accordingly, it was recommended to have further collections of hot peppers to cover new areas. The collections made after 2002 resulted in dozens of accessions from nine states in response to this earlier recommendation.

Among the food grain legumes, the total collected accessions of cowpea ranked third after sorghum and pearl millet with 426 accessions, originating from different states in the west and south-east with clear phenotypic variations of the collected seeds (Figure 8). In a study on cowpea accessions from Sudan, collected in the last 20 years, Sudanese germplasm showed high similarity to West African cowpeas (Ali *et al*, 2015). This was interpreted by an earlier suggestion that the cowpea crop was introduced to Sudan from West African countries to the western part of Sudan (Kordofan and Darfur), from where it spread to the rest of the country (Ali *et al*, 2015). This is further supported by the relatively large collection obtained from Kordofan and Darfur regions in Sudan.

A considerable number of accessions of oil crops sesame and groundnut were collected especially from the States of South Kordofan, South Darfur, East Darfur and West Darfur in the west of the country, and Blue Nile and Gedarif States in the southeast and east of the country, the traditional production areas for such crops. The sesame collection was relatively abundant, ranking fourth among the top collected crops from 13 states, encompassing mostly farmers' cultivars with about 10% of wild sesame species. Such a relatively big collection of sesame from a wide geographical distribution with observable variation in seed colours is indicative of the broad diversity of sesame genetic resources in Sudan, similar to that of cowpea and okra. This could be attributed to the fact reported by Mahmoud *et al* (1995) that the selection by subsistence farmers resulted in many landraces of sesame adapted to different ecological areas, varying mainly in rainfall and soil, and to the needs of the farmers. Sesame was suggested to have been domesticated in Africa (Bedigian, 2004), as several wild relatives are still growing there. Sudan is one of the countries in sub-Saharan Africa where a variety of cultivated and wild sesame is found, as proved by the germplasm collecting activities reported here. This indicates the importance of the country as a place of diversity for this crop, and suggests the possibility that it may be one of the regions where sesame was domesticated.

As discussed by Williams (2022), the groundnut is believed to have originated in South America in the area of southern Bolivia and northwestern Argentina. It was introduced to West Africa by Portuguese traders in the 16^{th} century, and in the following centuries it became fully integrated into subsistence farming systems and various ethnic cuisines, causing the crop to diversify into dozens of distinct African landraces. West African immigrants are believed to have brought the crop to Sudan about 200 years ago, and they grew it in parts of western Sudan and along the Blue Nile (Mahmoud *et al*, 1995). This is supported by the germplasm collecting activities resulting in a relatively large collection of locally cultivated varieties of groundnut, the absolute majority of which was from Darfur and Kordofan regions in the west, and the Blue Nile State in the southeast of the country.

According to what was mentioned by McClintock and El-Tahir (2004), roselle (*Hibiscus sabdariffa*) probably originated from Africa, where it may have been domesticated in Sudan about 6,000 years ago. It is locally known as Karkade and is grown in various parts of Sudan, particularly Kordofan and Darfur, where it is one of the cash crops cultivated by traditional farmers under rain-fed conditions, for local consumption and export (Mohamed *et al*, 2012). It is therefore understandable that it ranked among the top crops, with a relatively large number of accessions collected, totalling 344. The absolute majority of these were from Darfur and Kordofan States, where the crop is traditionally grown. The variation observed during collection, especially on enlarged calyces, which are the main parts of the plant used to make cold or hot beverages, is indicative of high diversity to be detected through morpho-agronomic and genetic characterization studies.

The vegetatively propagated fruit-producing crops represented in this collection were banana and date palm. Banana is a plant that is grown in Sudan for its sweet-flavoured fruits that are used as dessert by Sudanese people. It is produced commercially in small and medium scattered orchards along the River Nile and its tributaries banks, and in large plantations at Kassala (Elsadig, 2014). The Dwarf Cavendish has been the only old cultivar grown in Sudan for about 100 years (Mahmoud *et al*, 1995). However, new banana cultivars were introduced, tested and released in the early 2000s, and might replace the traditional cultivar for their superior yield potential and quality. The collection of local banana germplasm was planned to safeguard it against any possible losses due to the use of the new improved varieties or any other factors, including the recently frequent seasonal flooding of the rivers over the banks where banana plantations are established. Therefore, the collecting activities since 2003 have reasonably covered the different areas where bananas used to be grown. The highest number of accessions (151) came from Kassala State, where banana production is believed to have started during the late 18th century and is considered historically one of the most important banana-producing centres in Sudan (Elsadig, 2014).

Date palm has been grown in Sudan for a long time in the northern region using local cultivars producing different types of dates, including dry, semi-soft and soft dates. A study to describe the phenotypic vegetative and fruit characters of a number of date palm cultivars at on-farm level in northern Sudan has revealed high variability between these cultivars, where 14 out of 16 qualitative and quantitative traits used showed a strong discriminating factor (Elsafy *et al*, 2015). Genetic variation has also been detected within and between 18 cultivar groups obtained from northern Sudan as reported by Elsafy *et al* (2016). Findings of a study reported by Ezebilo *et al* (2013) revealed that the date palm cultivars in northern Sudan are diverse, implying that date palm farms in Sudan can also serve as sites for conserving genetic resources. However, having an *ex situ* collection of such diverse date palms in Sudan has been an APGRC strategy to back up collections as a means to safeguard such materials against hazards at on farm level. Following that, the collection of date palm accessions from Northern and River Nile States began in 2015 resulting in materials from both states for conservation in a field genebank.

Rangelands in Sudan are estimated at 68.6 million hectares or 36% of the total country area (Ministry of Agriculture and Forestry, 2015). Surveys conducted from 2000 to 2014 revealed that certain important range plant species were becoming scarce or extinct and some areas were invaded by unpalatable plant species. Thirteen valuable herbaceous species were reported as decreasing in semi-desert and low-rainfall savannah zones. Among these, were species belonging to genera such as *Andropogon, Aristida* and *Blepharis* (HCENR, 2013). The APGRC's collection of genetic resources of range plants started relatively late, in 2015. The areas surveyed for collection were limited to only three states in the semi-desert and low-rainfall savannah zones, indicating the pressing need for intensive collecting efforts in the future for range plants as an important component of the PGRFA in the country.

It is interesting to note that South Kordofan State was significantly represented in the collection of the top twelve crops, with a total of 1,550 accessions, a number much higher than that of the second-ranking state, South Darfur, which contributed 683 accessions. This can be attributed to the fact that South Kordofan was one of the states most intensively covered during germplasm collection, with 135 sites visited. Additionally, South Kordofan is known for its high diversity of cultivated crops grown in different farming systems including what is known as the 'Jubraka', the local name of kitchen home gardens, as well as in small lands held by smallholder farmers locally known as Bildat. Moreover, materials were collected from sites located at a wide range of altitudes from 117 to 976 masl. On the other end, Sennar State, which is part of the central clay plains in Sudan, was the least covered in terms of crops collected, as only banana clones were collected from the farms along the river banks of the Blue Nile. This makes Sennar State among the top geographical gaps for germplasm collection in the future. Planning for multi-species collecting from Sennar should consider areas around and within the Dinder National Park, which is one of the largest protected areas in the country covering about 890,000 hectares (UNEP and HCENR, 2020). It stretches in areas within Sennar, Gedarif and Blue Nile States, with the biggest area within Sennar State. This will require close collaboration with the park authorities for effective targeted germplasm collection within and around the park.

Around 65% of the accessions collected (4,982 accessions) were from crops and species covered by the Multilateral System (MLS) for Access and Benefit Sharing established by the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) (FAO, 2009). The total crops belonging to this system that were sampled were 22 accounting for 43% of the total crop genera covered. Such a relatively big number of accessions collected from the MLS crops and species indicates the importance of this collection from a global perspective, as Sudan is a party to the ITPGRFA and obliged to provide facilitated access to such accessions based on the MLS terms. Moreover, the crops and plant species belonging to the MLS covered by these collections were almost more than 30% of the total plant genera covered by the MLS. They included crops under genera such as *Sorghum*, *Pennisetum*, *Zea*, *Vigna*, *Musa*, *Vicia*, *Phaseolus*, *Solanum*, and a range plant under the genus *Andropogon*. This shows how Sudan could be an important contributing party to the effective functioning and success of this system at the global level. In fact, Sudan has officially notified the ITPGRFA Secretary on 23 September 2010 that 6,351 samples of sorghum, pearl millet, banana and other PGRFA listed in Annex I and maintained in the Plant Genetic Resources Unit of the Agricultural Research Corporation in Wad Medani, Sudan, have been included in the Multilateral System (https://www.fao.org/plant-treaty/areas-of-work/the-multilateral-system/collections). Since then, APGRC has been engaged in exchanging PGRFA with others using the Standard Material Transfer Agreement, which has been set out by the ITPGRFA to regulate the germplasm exchanges within the MLS.

Conservation of collected PGRFA is challenging in Sudan. Arrangements have been taken through an evolutionary process that started in the early 1980s with the establishment of genebanks at central and subnational levels. The seed samples of different accessions have been kept under long-term seed storage conditions in the central seedbank at Wad Medani (14.3931° N, 33.5392° E), with copies of some of them in a subnational seedbank unit in Elobeid Agricultural Research Station at Elobeid (13.1782° N, 30.2167° E) in North Kordofan State. However, the war that erupted in the country in mid-April 2023 and extended to Wad Medani in mid-December 2023 has posed serious threats to seed collections at the APGRC headquarters there. Hence, there is a pressing need to accelerate the duplication of all the materials in the Svalbard Global Seed Vault (SGSV), where only around 3,000 accessions have already been deposited by 2022. If the situation continues to deteriorate due to the ongoing conflict, temporary relocation of the collection from Wad Medani to other safer place(s) should be an option, as experienced by other genebanks in conflict areas. A recent example is the ICARDA genebank, which was originally located in Aleppo, Syria. As a consequence of the Syrian civil war and severe combat operations in Aleppo starting in 2012, the genebank had to be relocated in 2016 to Lebanon and Morocco. Part of the germplasm collection could be restored, with safety duplicates preserved at international genebanks and SGSV, as mentioned by Herbold and Engels (2023) in their study on genebanks risks. Overall, some African and Asian countries were identified as having high political instability, as is currently the situation in Sudan, necessitating the implementation of effective mitigation measures including safety duplication outside the country, which has occurred at low rates so far, and relocation to safer places if the war continues.

Conclusion

The activities for collecting PGRFA from *in situ* habitats in Sudan during the reported period have reasonably succeeded in covering almost all agroecosystems, as well as different farming systems within almost all the Sudan states resulting in a substantial number of accessions from different cultivated crop and plant groups. Among the areas covered were regions that had been affected by armed conflicts in previous years, such as South and West Kordofan States before 2004, and the Darfur region in the far western parts of the country before 2014.

The germplasm collecting activities have successfully gathered a considerable number of accessions from crops for which Sudan is part of the region of diversity and/or origin. Among those were crops such as sorghum, pearl millet, sesame, watermelon, melon, okra and roselle, with each crop having between 200 and more than 2,000 accessions collected.

The collection of local genetic resources of vegetatively propagated crops such as banana and date palm, was initiated for the first time during this period. However, further collecting activities are needed for these crops as well as other vegetatively propagated fruit-producing plants such as mango, guava and citrus.

The genetic resources of indigenous range plants remain a major taxonomic gap, which needs to be filled through extensive germplasm collecting activities. This should include a wide coverage of rangelands across the different ecological zones, including the desert, semi-desert, low-rainfall savannahs on both sandy and clayey soils, as well as high-rainfall savannahs towards the borders with the South Sudan Republic, and the unique mountain vegetation such as in Jebel Marra in the far west. Moreover, crop wild relatives, although relatively covered, still remain poorly represented, and continue to be another major taxonomic gap, including relatives to MLS crops such as sorghum, pearl millet and eggplant, which were somehow sampled during the last years, as well as relatives to non-MLS crops of local importance in Sudan such as melons, watermelon, okra and sesame.

It was interesting to note that accessions were collected in relatively large numbers from about 30% of the genera covered by the MLS of the ITPGRFA, positioninig Sudan, as a party to this treaty, to play a significant role in conserving and providing facilitated access to such PGRFA for use under the MLS terms.

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Supplemental data

- Supplemental Table 1. Germplasm collecting missions across the cultivation seasons from 2002–2003 to 2021–2022.
- Supplemental Material 1. Germplasm Collection Form.
- Supplemental Table 2. Total of collection sites visited by the germplasm collection missions in the different states during the cultivation seasons between 2002 and 2022 and the ranges of coordinates within which they were geographically located.
- Supplemental Table 3. Total accessions collected from each crop or plant and the total number of states from where they were collected.
- Supplemental Figure 1. Total number of states from where total accessions of the genetic resources of different crops collected.
- Supplemental Figure 2. Total number of accessions collected from different crop wild relatives.
- Supplemental Figure 3. Total number of accessions collected from each range plant species.

Author contributions

I.M. El Tahir: Leading germplasm collection planning and coordination, proposing the paper, writing the first draft, revising and finalizing the manuscript.

A.Z. Babiker, E.A. Abdalla, A.A.E. Ahmed: Participation in planning, leading some collection missions and revising manuscript drafts.

M.O.Y. Goda: Participation in planning, leading documentation process for all collection data and revising manuscript drafts.

M.A.M. Elgabri: Participation in planning, assisting in leading some collection missions, and revising manuscript drafts

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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