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Checklist and prioritization of crop wild relatives in Sudan and South Sudan

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Abstract: Crop wild relatives (CWR) encompass wild plant species or subspecies closely related to domesticated crops. This study presents the first comprehensive checklist and prioritized inventory of CWR for Sudan and South Sudan. Building on the regional CWR list for Northeast Africa, we identified 499 CWR taxa belonging to 44 families, with 90% of these being native species. The most prominently represented families were Poaceae (148), Fabaceace (72) and Convolvulaceae (43), while *Panicum* (32), *Eragrostis* (27), *Ficus* (24) and *Pennisetum* (20) were the most frequent genera. A prioritized inventory of 85 CWR taxa was developed based on three criteria: economic value, utilization potential and threat status. The prioritized CWR are predominately native (78%) and encompass 12 families dominated by Poaceae (38), followed by Solanaceae (9), Fabaceae (6) and Cucurbitaceae (6). Priority genera included 27, with *Digitaria* (17), *Solanum* (9) and *Cucumis* (5) emerging as key genera for conservation attention. This comprehensive national CWR inventory provides a crucial foundation for developing targeted conservation strategies in Sudan and South Sudan.

Keywords: Crop wild relatives, conservation, checklist of crop wild relatives, priority inventory

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Introduction

Crop wild relatives (CWR) are wild ancestors of plant taxa that are closely related to domesticated crops. These wild plants possess a high reservoir of genetic diversity for improving the resilience and productivity of our cultivated crops (Ford-Lloyd *et al*, 2011). CWR possess a broader genetic diversity compared to domesticated crops because of their adaptation to various climatic conditions (Dempewolf *et al*, 2017). This genetic richness allows CWR to share valuable genes with their domesticated counterparts, enhancing crop resistance to pests, diseases and environmental stresses (Barazani *et al*, 2008). Globally, an estimated 50,000–60,000 CWR occur, with 10,740 identified as potential contributors to future food security (Maxted and Kell, 2009). Recognizing their importance, a study by Vincent *et al* (2013) established an initial global priority list of 1,392 species for conservation and utilization to ensure food security. However, CWR face numerous threats, including nitrogen deposition, land-use alterations, invasive alien species, overgrazing, urbanization and climate change (Ford-Lloyd *et al*, 2011).

Climate change is projected to have a detrimental impact on global crop production (Lobell *et al*, 2011). Over the past three decades, global warming has accelerated and is expected to intensify further in the years to come (IPCC, 2020). In Africa, the effects of climate change on food production are already apparent, manifesting as changes in rainfall patterns, rising temperatures and an increased frequency of extreme weather events (IPCC, 2020). These changes have resulted in reduced crop yields, particularly in sub-Saharan Africa (IPCC, 2020), which is home to

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approximately 45,000 plant species (Linder, 2014), and where a significant portion of the population relies on plant resources as the foundation of their diet (Gollin and Rogerson, 2014).

For the comprehensive utilization of CWR in crop improvement programmes, it is vital to conserve, classify and make them accessible to researchers and plant breeders at national, regional and global levels (Maxted *et al*, 2015). Hence, urgent measures involving complementary protection, both *in situ* (on farms) and through storage in *ex situ* facilities (genebanks), are essential steps to preserve these genetic resources and ensure their availability to researchers and breeders (Maxted and Kell, 2009). The initial phase of CWR conservation planning entails the development of a checklist, defining the taxon names of existing CWR within a specific region or country (Maxted *et al*, 1997). Subsequently, the creation of a priority CWR checklist involves reducing the number on the checklist to more manageable levels. This is achieved by applying criteria such as threat status, endemicity and potential utilization (Ford-Lloyd *et al*, 2008).

To assess the potential utilization of CWR in plant breeding, researchers rely on two main concepts: the gene pool concept (Harlan and De Wet, 1971) and the taxon group concept (Maxted *et al*, 2006). These concepts are crucial as they help us to understand the genetic relationships between cultivated crops and their wild relatives. Close relatives hold a higher likelihood of intercrossing than distant ones. The gene pool concept furnishes valuable information to plant breeders, aiding them in selecting germplasm for crossbreeding and plant improvement. It is divided into three categories: the primary gene pool (GP1), where GP1a represents the cultivated forms and GP1b the wild or weedy forms; the secondary gene pool (GP2), consisting of species that are less closely related but still capable of gene transfer, albeit with difficulty; and the tertiary gene pool (GP3), consisting of distantly related species where gene transfer is either impossible or requires advanced methods such as genetic engineering (Harlan and De Wet, 1971). In cases where gene pool concept information is unavailable, the taxon group concept serves as an alternative. The taxon group concept categorizes relationships as follows: taxon group 1a (TG1a) is the crop itself, taxon group 1b (TG1b) includes the same species as the crop, taxon group 2 (TG2) consists of species within the same series or section as the crop, taxon group 3 (TG3) refers to species in the same subgenus as the crop, taxon group 4 (TG4) includes species in the same genus as the crop, and taxon group 5 (TG5) includes species in the same tribe as the crop but belonging to a different genus (Maxted *et al*, 2006).

CWR checklists and prioritized inventories have been established in various countries worldwide, including Mexico (Contreras-Toledo *et al*, 2019), the United States (Khoury *et al*, 2013), Spain (Rubio-Teso *et al*, 2018), Portugal (Magos-Brehm *et al*, 2008), Benin (Idohou *et al*, 2013), Tunisia (Mokni *et al*, 2022), Italy (Ciancaleoni *et al*, 2021) and South Africa (Holness *et al*, 2019). A recent study by Aldow *et al* (2023) developed the first regional CWR inventory for Northeast Africa. However, there has been no prior investigation into CWR diversity in Sudan and South Sudan. Thus, the objectives of this study are 1) to prepare Sudan and South Sudan CWR checklist, and 2) annotate this checklist to prioritize it for active conservation using the Interactive Toolkit for CWR Conservation Planning (Magos *et al*, 2017).

Geographical context

Sudan and South Sudan, located in Northeast Africa between latitudes 4° and 22° N and longitudes 22° and 38° E (Zaroug, 2006), are bordered by Ethiopia and Eritrea to the east and Egypt to the north. The combined total area of both countries is approximately 2.5 million km^2, with Sudan covering about 1,878,000km^2 and South Sudan about 646,883 km^2 (Zaroug, 2006; World Bank, 2021). Pasture and forests cover 40% of the land, while cultivated area accounts for about 33% of the total area, of which only 21% is actively cultivated, resulting in very low crop yields (UNEP, 2007). The two countries are divided into five ecological zones: desert, semi-desert, woodland savannah, flood region and montane vegetation. Agriculture is the main source of income for 60–80% of the population (Elgali *et al*, 2010). The five agricultural systems include mechanized rain-fed agricultural schemes, traditional rain-fed agriculture, mechanized irrigation schemes, traditional irrigation and livestock husbandry/pastoralism (Zaroug, 2006). Approximately 90% of the farming areas in the country depend on precipitation (Siddig *et al*, 2020), while in South Sudan, despite more favourable climatic conditions, agricultural output remains low (Diao *et al*, 2012).

Materials and methods

CWR checklists and inventories are the main starting points for effective conservation strategies (Maxted *et al*, 2015). This study is based on the CWR diversity identified for Northeast Africa (Djibouti, Eritrea, Ethiopia, Sudan, and South Sudan) by Aldow *et al* (2023) to create a checklist and a priority inventory for Sudan and South Sudan. We excluded invasive species documented for Sudan and South Sudan from the Global Invasive Species Database (GISD) of IUCN (http://www.iucngisd.org/gisd/) and the Invasive Species Compendium (CABI) (http://www.cabi.org/isc/).

Our approach involved a three-step process:

1. Starting point: We began with the comprehensive CWR checklist for Northeast Africa compiled by Aldow *et al* (2023), which included 1,020 taxa.

2. Regional refinement: We then used a digitalized floristic checklist of Sudan and South Sudan, compiled by the first author based on *Plants of Sudan and South Sudan: An Annotated Checklist* (Darbyshire *et al*,

2015) during the establishment of the CWR checklist for Northeast Africa, to retain a checklist with taxa occurring only in these two countries. Note that in the flora of Sudan and South Sudan, the Compositae family is referred to as the Asteraceae family.

3. A priority inventory of CWR was selected based on three criteria:

(A) Economic value: FAOSTAT crop valuation (FAO, 2021) was used to select taxa with economic importance based on the related crop.

(B) The utilization potential: priority taxa within gene pool categories 1b, 2, 3 and taxon group categories 1b, 2, 3 and 4 (with documented use in crop development only) were selected based on the information available in the Germplasm Resources Information Network Taxonomy (USDA, 2023) and the Harlan de Wet CWR inventory (Vincent *et al*, 2013).

(C) Threat status: although (Kell *et al*, 2017) recommended incorporating threat status as a prioritization criterion, its application was limited due to the scarcity of Red List data for these countries (only 7% of plant species according to Darbyshire *et al* (2015). However, based on expert consultation, the endangered South Sudanese coffee species *Coffea neoleroyi* A. P. Davis (IUCN, 2022), was added to the priority checklist.

Additional information was incorporated into the compiled CWR checklist and inventory. This supplementary data encompassed taxonomic details such as accepted taxa names, synonyms and authorities. Additionally, it included the common names of related crops, native status, the utilization of the crop, the type of relatedness (gene pool or taxon group), confirmed or potential use in crop breeding, distribution status along with relevant references, and *in situ* and *ex situ* conservation statuses.

Results

CWR Checklist

The CWR checklist of Sudan and South Sudan contains 449 taxa (including subspecies and varieties), belonging to 88 genera across 44 families. Both native and introduced taxa are included. Invasive taxa, like *Sorghum halepense* (L.) Pers, were removed from the checklist. Sudan has 133 taxa, 59 genera, and South Sudan 161 taxa and 47 genera. Over 90% of the listed CWR are native to these two countries. The most common plant families include Poaceae (grasses) with 148 taxa, Fabaceae (legumes) with 72 taxa, and Convolvulaceae (morning glories) with 43 taxa. The genera with the highest number of CWR taxa are *Panicum* (32), *Eragrostis* (27), *Ficus* (24) and *Pennisetum* (20). Details on the distribution of taxa can be found in Supplemental Table 1 and Figure 1.

Priority checklist

The priority checklist of Sudan and South Sudan contains 85 taxa related to 12 families and 27 genera. Figure 2 illustrates the distribution of these priority taxa across both countries. The most mentioned families were Poaceae (38), Solanaceae (9), Fabaceae and Cucurbitaceae (6 each), while *Digitaria*, *Solanum*, *Cucumis* and *Echinochlo* were the most mentioned genera (Supplemental Table 2 and Figure 3).

The closest wild relatives to the crop GP1b, TG1b, TG2 and GP2 represent about 49% and GP3 counts for about half of the priority taxa (Figure 4a and Supplemental Table 3). The confirmed use of taxa is about 8%, potential use 17%, confirmed and potential use 14%, and unconfirmed use 61% (Figure 4b and Supplemental Table 3).

CWR in the checklist have provided a number of beneficial traits to crops such as chickpea, teff, coffee, finger millet, cassava, rice, cotton and sorghum found in Sudan and South Sudan (Table 1).

Discussion

The inventory conducted in Sudan and South Sudan reveals a rich diversity of native and introduced taxa associated with a broad range of crops. This provides a crucial foundation for the development of national policies and strategies in both countries. These strategies should prioritize the conservation of the identified CWR genetic diversity, both *in situ* and *ex situ*, with the ultimate goal of ensuring the long-term conservation of these valuable resources for the benefit of future generations (Kell *et al*, 2017). In light of the critical importance of CWR for global food security and sustainable agriculture, researchers and scientific institutions have advocated for a coordinated global CWR conservation strategy (Dempewolf *et al*, 2014), which should encompass both *in situ* and *ex situ* approaches for effective conservation.

The checklist of CWR identified a significantly higher diversity of CWR in South Sudan (37,9%) compared to Sudan. Interestingly, about one-third of the CWR identified are found in both countries. Additionally, nearly half (45%) of the priority CWR are shared between the two nations. Unfortunately, most documented plant taxa in these countries are outdated due to a lack of recent research, likely a result of long-standing civil conflicts. This highlights the urgent need for taxonomic experts to update the classification of these CWR.

National CWR conservation strategies should be harmonized with regional and international initiatives. As proposed by Maxted *et al* (2015), integrating national and regional CWR conservation strategies is highly beneficial. This recognizes that prioritization criteria for CWR conservation at the national level can often be aligned with the regional level. This overlap facilitates collaboration between various agencies (governmental, private, or voluntary) at both levels, leading to the development of more effective CWR conservation strategies.

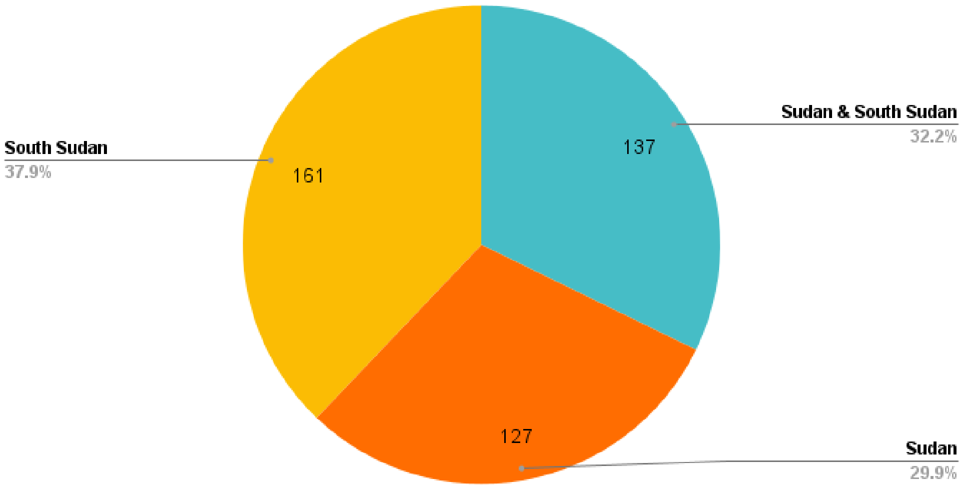

Figure 1. Distribution of CWR taxa in the checklist in Sudan and South Sudan

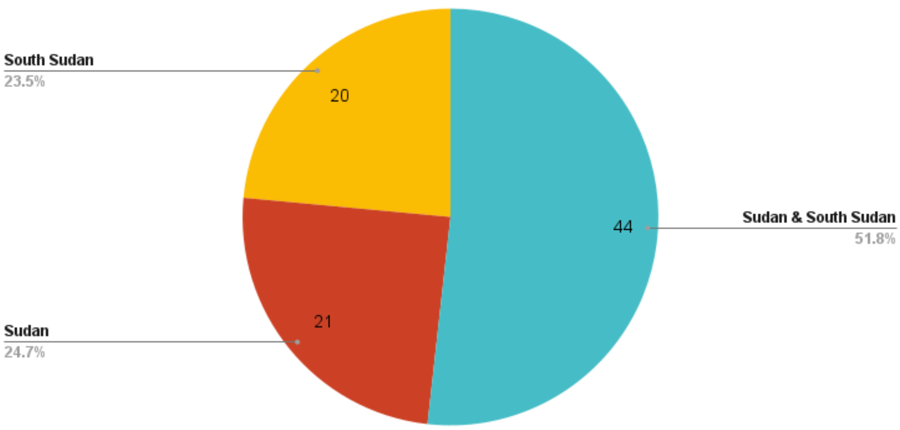

Figure 2. Distribution of priority CWR in Sudan and South Sudan

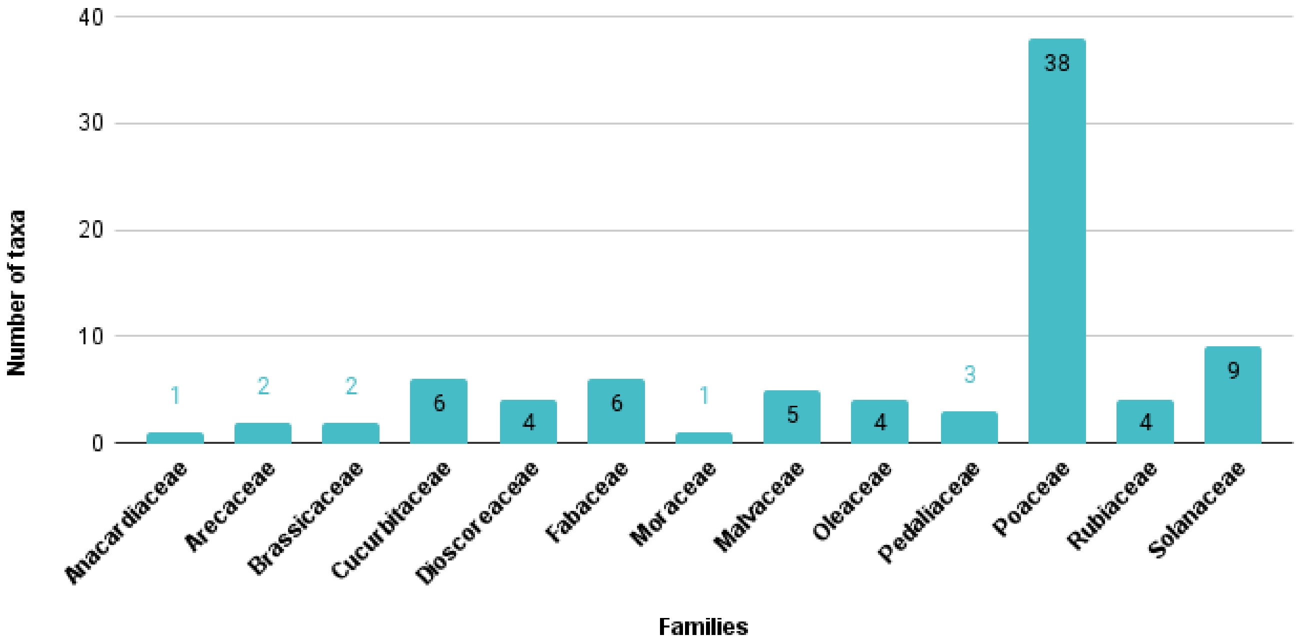

Figure 3. Diversity of taxa among CWR families within the priority CWR inventory in Sudan and South Sudan.

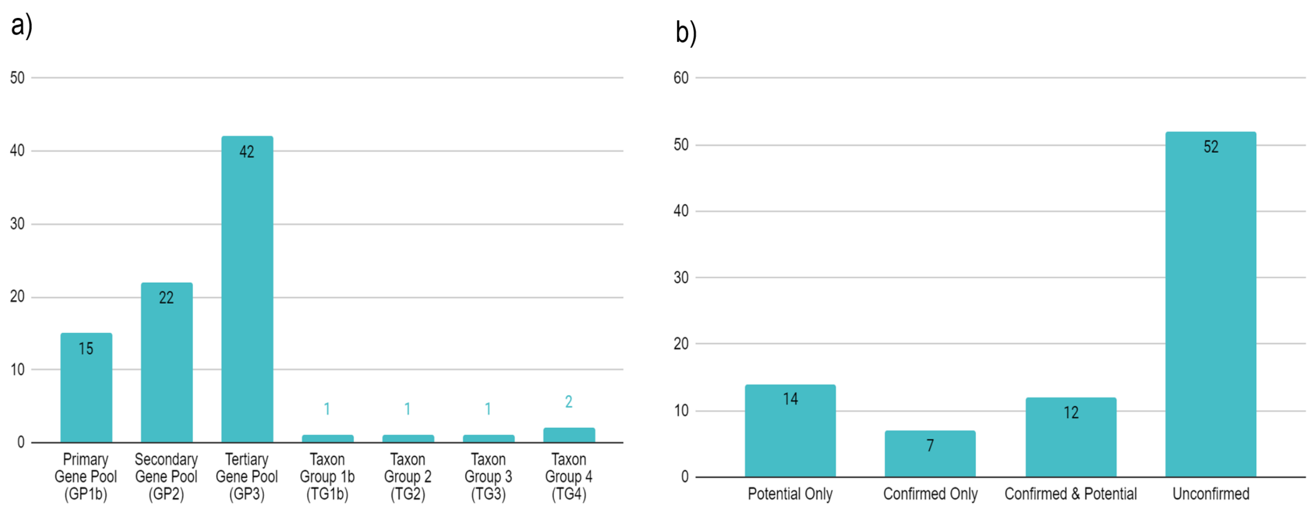

Figure 4. Genetic relatedness and use potential for priority CWR inventory in Sudan and South Sudan. a) shows the genetic relatedness of the priority CWR inventory in Sudan and South Sudan, based on the gene pool and taxon group concepts. b) illustrates the status of the priority CWR inventory in Sudan and South Sudan for crop improvement, categorized as potential, confirmed, confirmed and potential, and unconfirmed.

Table 1. Relatedness of CWR taxa and their confirmed use in crop improvement in the priority inventory of Sudan and South Sudan. GP1, primary gene pool; GP2, secondary gene pool; GP3, tertiary gene pool. 'b' indicates the wild or weedy form.

Taxon	Relatedness to CWR	Confirmed use of CWR to broaden crop improvement	References
Coffea canephora var. *gossweileri* A. Chev.	GP2b	Coffee berry disease resistance; coffee rust resistance; root-knot nematode resistance	Anthony *et al* (2011); Levi *et al* (2005); Noir *et al* (2003); Prescott-Allen and Prescott-Allen (1988)
Coffea liberica Hiern	GP2b	Coffee rust resistance	Anthony *et al* (2011); Prakash *et al* (2009); Prescott-Allen and Prescott-Allen (1988)
Fragaria chiloensis (L.) Duchesne.	GP1b	Fruit size; Fruit quality	Ahmadi and Bringhurst (1992)
Fragaria vesca L.	GP3	Anthracnose resistance; Powdery mildew resistance; improved aroma	Ahmadi and Bringhurst (1992); Scott (1951)
Fragaria virginiana Duchesne.	GP1b	Fruit number; fruit size; powdery mildew resistance; scorch resistance; day neutral	Ahmadi and Bringhurst (1992); Hancock *et al* (2002)
Diplotaxis erucoides (L.) DC.	GP3	Alternaria blight resistance; blackleg resistance; cytoplasmic male sterility	Klewer *et al* (2003); Prakash *et al* (2009); Siemens (2002)
Diplotaxis harra (Forssk.) Boiss.	GP3	Gene transfer	Begum *et al* (1995)
Eleusine africana K. OByrne	GP1b	Fertility trait	Dida and Devos (2006)
Eleusine kigeziensis S.M.	GP1b	Fertility trait	Dida and Devos (2006)
Thinopyrum junceum (L.) Á. Löve	GP3	Soil salinity tolerance	Nevo and Chen (2010)
Gossypium longicaly x Hutch. & B.J.S. Lee.	GP2	Reniform nematode resistance	Robinson *et al* (2007)
Ipomoea purpurea (L.) Roth.	GP3	Gene transfer	Cao *et al* (2009)
Lens ervoides (Brign.) Grande	GP2	Seed size; Yield improvement; anthracnose resistance; *Ascochyta* blight resistance; *Stemphylium* blight resistance	Ahmad *et al* (1997); Kumar *et al* (2014); Tullu *et al* (2011)
Lupinus mexicanus Cerv. er Lag.	GP3	Gene transfer	Busmann-Loock *et al* (1992); Clements *et al* (2005)
Malus sylvestris Miller	GP1b	Agronomic trait	Volk *et al* (2015)
Manihot carthagenensis subsp. *glaziovii* (Müll. Arg.) Allem	GP2	Cassava bacterial blight; resistance; cassava mealy bug resistance; Cassava mosaic Virus Resistance	Hahn *et al* (1980); Hajjar and Hodgkin (2007); Nair and Unnikrishnan (2007); Prescott-Allen and Prescott-Allen (1988)
Medicago arborea L.	GP3	Anthracnose resistance	Armour *et al* (2008); Quiros and Bauchan (1988)
Olea europaea subsp. *cuspidata* (Wall. ex G. Don) Cif.	GP2	Crop ontology trait	Hannachi *et al* (2009)

Continued on next page

Table 1 continued

Taxon	Relatedness to CWR	Confirmed use of CWR to broaden crop improvement	References
Oryza brachyantha A. Chev. & Roehr.	GP2	Bacterial blight resistance	Brar and Singh (2011)
Oryza longistaminata A. Chev. & Roehr.	GP1b	Drought tolerance; yield improvement; bacterial blight resistance; Grassy stunt resistance	Brar and Singh (2011); Hajjar and Hodgkin (2007); Jena (2010)
Pistacia khinjuk Stocks.	GP2	Rootstock	Hormaza and Wünsch (2007)
Pennisetum purpureum Schumach.	GP2	Cytoplasmic male sterility; fertility restoration genes; panicle length; days to maturity; yield improvement	Dujardin and Hanna (1989) Hajjar and Hodgkin (2007); Hanna (1997); Palit *et al* (2014)
Pennisetum squamulatum Fresen.	GP2	Fertility restoration genes	Dujardin and Hanna (1989)
Phaseolus coccineus L.	GP2	Aluminium tolerance; yield improvement; angular leaf spot resistance; anthracnose resistance; bean stem maggot resistance; bean yellow mosaic virus resistance; common bacterial blight resistance; fusarium root rot resistance; white mould resistance	De Ron *et al* (2015); Freytag *et al* (1982); Loskutov and Rines (2011); Mahuku *et al* (2003); Miklas *et al* (1999); Porch *et al* (2013); Schwartz and Singh (2013); Singh *et al* (2008); Singh (2001); Wilkinson and Re (1983); Zapata *et al* (2004)
Saccharum spontaneum L.	GP2	Cold tolerance; red rot resistance; smut resistance; sugarcane mosaic virus; early maturing	Cordeiro *et al* (2003); Prescott-Allen and Prescott-Allen (1986)
Setaria viridis (L.) P. Beauv.	GP1b	Triazine resistance	Darmency and Pernes (1985)
Sinapis arvensis L.	GP2	Blackleg resistance; sclerotinia resistance; cytoplasmic male sterility	Hu *et al* (2002); Snowdon *et al* (2000); Wei *et al* (2010)
Solanum aethiopicum solan L.	GP3	Rootstock; yield improvement; bacterial wilt resistance; fusarium wilt resistance	Collonnier *et al* (2001); Daunay (2008); Frary *et al* (2007); Rotino *et al* (2014); USDA (2011)
Solanum incanum L.	GP2	Drought tolerance; rootstock; verticillium wilt resistance	Frary *et al* (2007); Knapp *et al* (2013); USDA (2011)
Solanum linnaeanum Hopper & Jaeger	GP2	Fungal wilt resistance	Frary *et al* (2007); Rotino *et al* (2014); Yin *et al* (2015)
Solanum macrocarpon L.	GP3	Rootstock	USDA (2011)
Solanum marginatum L. f.	GP3	Gene transfer	Borgato *et al* (2007)
Sorghum purpureosericeum (Hochst. ex A. Rich.) Schweinf. & Asch.	GP3	Sorghum shoot fly resistance	Nwanze *et al* (1990)
Vigna radiata var. *sublobata* (Roxb.) Verdc.	GP1b	Bruchid resistance	Konarev *et al* (2002)
Vigna vexillata (L.) A. Rich	GP3	Gene transfer	Gomathinayagam *et al* (1998)

The development of the national checklist and inventory of CWR focused exclusively on those associated with food crops, such as rice, sorghum and finger millet. This focus is justified by the crucial role these crops play in providing nutrition and ensuring food security in these two nations.

This region has historically been affected by food insecurity as a direct consequence of social conflict and warfare, making the prioritization of food security crops in the CWR inventory a strategic approach.

Climate change poses a significant threat to the future of food crops, including their wild relatives. Jarvis *et al* (2008) emphasized the critical need to identify and conserve CWR that are threatened by climate change, such as cowpea (*Vigna*), a crucial food security crop in sub-Saharan Africa. Studies by Jarvis *et al* (2008) estimate that 2-6% of *Vigna* species in sub-Saharan Africa could face extinction by 2055, highlighting the urgency of identifying and conserving these threatened CWR. Fortunately, Sudan and South Sudan contain three vital CWR of *V. unguiculata* subsp. *dekindtiana* (Harms) Verdc, *V. unguiculata* subsp. *pubescens* (R Wilczek) pasquet and *V. vexillata* (L.) A. Rich. These CWR represent a valuable genetic reservoir that could be important for developing climate-resilient cowpea varieties in the future, potentially preserving food security in the region and beyond.

CWR conservation priorities are an important step in conservation planning at the national, regional and international levels. This newly developed inventory in Sudan and South Sudan identifies CWR associated with essential food crops such as sorghum, rice, cowpea and pearl millet. While this inventory represents a valuable resource, the number of taxa in Sudan and South Sudan (449 taxa) is lower compared to the checklists of other countries such as Indonesia (Rahman *et al*, 2019), China (Kell *et al*, 2015), Portugal (Magos-Brehm *et al*, 2008), USA (Khoury *et al*, 2013) and Zambia (Ng'uni *et al*, 2019). This difference highlights the importance of continued CWR conservation and exploration efforts in Sudan and South Sudan.

Conclusion

This study highlights the important role of CWR in Sudan and South Sudan in enriching crop diversity and promoting sustainable food production at all levels – national, regional and international. By identifying and prioritizing 85 CWR taxa from a comprehensive checklist of 449, this research provides a crucial foundation for targeted conservation efforts. The establishment of the first CWR checklist and inventory for these two countries offers the basis for further research to ensure the long-term sustainability and utilization of the prioritized CWR. Key areas for future research include:

- Protecting genebanks during civil conflicts: The ongoing civil conflict in Sudan tragically exemplifies this threat. Researchers were forced to call upon the international community to intervene and protect the country's main seedbank from the potential loss of irreplaceable crop varieties and damage to its facilities (Nordling, 2024). Similar situations have been observed with ICARDA in Syria (Darvish *et al*, 2023) and Yemen (Aljarmouzi *et al*, 2024) This incident highlights the urgent need for a comprehensive regional and global initiative to safeguard genebank during conflicts.
- Enhanced floras and CWR inventory validation: Develop separate, comprehensive floras for Sudan and South Sudan, collaborating with agronomists to validate the CWR inventory accuracy.
- Taxonomic expeditions for new CWR discovery: Conduct taxonomic research projects in remote, untapped areas, potentially leading to the discovery of new CWR, and work with national genebanks on collaborative efforts and germplasm preservation.
- Gap analyses: Initiate *in situ* and *ex situ* conservation gap analysis for the priority CWR taxa in each country. These analyses will inform the development of comprehensive conservation plans for each CWR's specific needs.
- Climate change impact assessment: Assessing climate change models to evaluate potential threats to CWR populations.

Supplemental data

Supplemental Table 1. Checklist of CWR in Sudan and South Sudan

Supplemental Table 2. Priority inventory of CWR in Sudan and South Sudan

Supplemental Table 3. Related crop and concept level of the priority inventory of CWR taxa in Sudan and South Sudan

Author contributions

Ahmed Aldow: Conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing (original draft, review and editing). Joana Magos Brehm: Supervision. Maha Kordofani: Resources, validation. Fatouma Abdoul-latif: Resources, validation. Nigel Maxted: Supervision.

Conflict of interest statement

The authors confirmed that no conflict of interest exists.

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