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Research status of seed improvement in underutilized crops: prospects for enhancing food security

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Abstract

Planning future directions and adapting approaches for seed improvement in underutilized crops requires the assessment of research activities. We have examined the trends and research activities conducted on seed improvement of underutilized crops. We identified research hotspots based on keywords and prolific research titles mapped across three decades (1990 to 2021). Data were compiled using Google Scholar, Web of Science and Scopus databases, loaded into the bibliometric R-package and viewed via VOSviewers software. In research on seed improvement among underutilized crops (SUC), we have observed 7.2% annual growth in publication and increase in the studies and citations. There were strong research publications with strong research links from studies conducted in USA, Canada, India, Nigeria and China, while South Africa and Egypt were among the African countries with high research studies in SUC. Among underutilized crops with improvement among their seed traits are sorghum, quinoa, Bambara groundnut, amaranth, barley, tef, cowpea and millet. Some of the trending research areas are genetic diversity, seed performance, seed domestication, yield, crop management, water use efficiency, nutritional properties, molecular strategies and genetic analysis tools for seed improvement. There is gradual increase for international collaborations and funding in SUC studies. The current research emphases are on qualitative studies, appropriate methodological procedures and advanced breeding resources to help understand and promote seed improvement among underutilized crops.

Introduction

Underutilized crops are beneficial plant species that are either marginalized or totally ignored by food consumers, researchers, breeders and policymakers (Padulosi *et al*., 2014). They are mostly non-commercial crops and belong to a large, species-rich plant group of domesticated, semi-domesticated or wild species (Padulosi *et al*., 2013). Approximately 70% of the world's calories are produced from four staple crops (maize, wheat, rice and soybean), whose increased yield over the last century can be attributed to adequate knowledge in advanced tools and management techniques used genetically to control its agronomic traits (Bailey-Serres *et al*., 2019). A similar effort can reproduce excellent yields with underutilized crops (>6000 species) that have greater potential to dramatically improve food production, are resilient to climate change, rich in nutrient composition, have a high capacity to reduce pest and disease infestations and improve agricultural sustainability (Mabhaudhi *et al*., 2019). However, these crops have experienced minimal seed improvement while their valuable genetic resources are disappearing rapidly (Mustafa *et al*., 2019). Adequate information on genetical resources of most underutilized crops is not readily available as compared to staple crops. Few studies have reported on the ongoing significant efforts to increase genomic resources of the crops through innovative breeding techniques for nutritional quality and yield of underutilized legumes while limited studies have been conducted on neglected vegetables, cereals and oil crops (Ebert, 2014; Feldman *et al*., 2019; Popoola *et al*., 2019). The poor documentation of indigenous knowledge on seed enhancement and genetic diversity, seed characterization using microsatellite markers, seeds quality and conservation indicated that seed quality is one of the main factors limiting underutilized crop production (Mayes *et al*., 2012; Aliyu *et al*., 2016).

To prevent total genetic loss among untapped plant genetic resources and enhance the crop future usage, a holistic approach is needed for improvement in the qualities of seed and planting materials. Seed improvements through genetic, physiological, seed enhancement and physical quality are important requirement for most of the underutilized crops to reach their potentials (Anumalla *et al*., 2015; Muthamilarasan *et al*., 2019). Thus, all areas of seed improvement of underutilized crops require extensive studies ranging from genetic diversity, breeding, seed production, seed germinability and vigour, seed marketing and delivery to application of sound approaches by the farmers. The conservation of underutilized germplasm could only be guaranteed if high quality seeds are available for its production.

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Seed vigour is a complex physiological trait that involves regulatory networks, integrated genetic programmes, metabolic signals and hormonal signalling pathways (Wu *et al*., 2017). Clearer understanding of the molecular pathways in underutilized crop's seed may influence its seed vigour and performance (Afzal *et al*., 2020). High seed vigour guarantees rapid and uniform emergence of plants, tolerance to environmental stresses and the ability to withstand prolonged storage. Practices such as seed invigoration via priming techniques are being devised to increase the vigour of seed lots (Mukherjee, 2019; Adelabu and Franke, 2022). Over the past three decades, several studies on breeding approaches through genomics, transcriptomics and proteomics, have been identified with high efficiency for enhancing seed vigour (Rajjou *et al*., 2012; Kumar *et al*., 2020). However, seed improvement in underutilized crops (SUC) is still sparse. Compilation and evaluation of information about research activities on the history of underutilized crop's seed improvement will be useful for breeders, farmers and the seed industries to ensure detailed improvement measures in the seed systems, which is crucial for future protection and adaption strategies in food production. Since the crops are mostly locally adapted, re-strategizing crop improvement and agronomic practices of the underutilized crop would help identify climate-resilient cultivars that have improved grain traits (Popoola *et al*., 2019). Therefore, research activities on underutilized seed crops focusing on seed preparation methods, breeding, ecophysiology, quality, nutrition, food security, biotechnology, perceptions, climate change, postharvest, genetic resources, medicinal properties and seed commercialization studies were explored. This study is a response that has a strong link to Sustainable Development Goals 1 (no poverty), 2 (zero hunger), 3 (good health and wellbeing), 8 (creation of employment opportunities) and 15 (sustainable environment). Also, it is based on calls for papers from specialized and reputable peer reviewed journals in the field of crop improvement, hence the current study was conducted to analyse the research activity of underutilized seed improvement. The current study will establish the first baseline data on this topic for future comparisons and for policymakers to design plans raw plans on ways to improve underutilized crop production. Therefore, this investigative research aims to improve underutilized crop's seed and will aid a clearer understanding of the crop agronomic traits and management practices. The objective of this study is to provide baseline data on the trends, research activities and research hotspots on seed improvement of underutilized crops across three decades (1990 to 2021).

Methodology

A bibliometric analysis was used to identify key research themes, patterns, activities and active research institutions in SUC field for future planning. The use of bibliometric analysis is an appropriate methodology that identifies the extent and growth pattern of literature focused on seed improvement in underutilized crops. A literature search using known databases and search engines such as Scopus, Web of Science and Google Scholar revealed very limited details of the seed improvement trajectory of underutilized crops.

Databases

A literature database-based descriptive bibliometric analysis was used, collecting peer-reviewed articles that specifically studied the categories of indigenous (such as pseudocereals, legumes, root and tuber, medicinal and vegetable crops), underutilized or orphan crops were collected from-recognized international peer-reviewed journals retrieved from Scopus, Google Scholar and Web of Science databases. These databases were used because they are equipped with efficient search and filter tools and are highly informative when it comes to the number of articles published. Also, they are widely recognized for their completeness and their reliability in conducting high effective scientific research (Orimoloye *et al*., 2021). Data were retrieved from peer-reviewed articles that were published during the last three decades (1990–2021).

Data search strategies

Extensive searches were performed using bibliometric analysis to retrieve all potential documents focusing on seed improvement of underutilized crops were carried out. The search query was mainly based on title search using keywords to ensure that the retrieved documents were obviously and directly related to seed improvement among underutilized crops with minimal irrelevant results. A crop-specific search that includes various underutilized crops with keywords like 'seed priming' or 'seed breeding' or 'seed quality', 'landraces seed' or 'seed genetic diversity' or 'seed enhancement in underutilized crops was retrieved. Other non-specific keywords used are; 'tissue culture in landraces', 'wild cultivar genome sequence' and 'seed physiology', provided that the document title/abstract includes a phrase relating to 'seed improvement' and 'underutilized crop'. Documents retrieved from the search query on seed improvement of underutilized crops were called 'SUC'. The topic-specific search was used for easy for retrieval. To avoid non-traceable papers, the search results were limited to conference proceedings, original articles, reviews and books and all other categories of documents were excluded.

Validation and duplication

The validation of the search queries was based on two approaches. In the first approach, the 50 most cited documents in the field of SUC were reviewed to ensure they fit within the framework of seed improvement in underutilized crops. The retrieved data from the databases were imported into RStudio to remove duplicate articles and convert it into a bibliographic data frame.

Data processing and analysis

The data analysis process was conducted using Biblioshiny software in R to analyse and visualize co-authorship, citation analysis, co-occurrence, co-citation and bibliographic coupling. This identification resulted in 24 561 publications. The publications from each database were screened by document type, research area, English-language publications, discipline (agricultural and biological sciences) and excluded document types designated as 'undefined'. Thus, we retained 18 535 published articles from the databases. These data were merged using R software then imported into Biblioshiny for analysis using a bibliometrix package in RStudio v.3.4.1. The retrieved data for bibliometric factors were further analysed to create network visualization maps using VOSviewers software.

Results

Description of the publications

A total of 13 235 publications on seed improvement in underutilized crops were retrieved from the databases after removing duplicates (Table 1). The distribution of publications was grouped according to the categories of underutilized crops (Table 2). The publication distributions were 94.7% for research articles (n = 12 530), 4.3% for review, book and book chapter (n = 575), while conference proceedings (n = 155) accounted for 1.0%, the annual publication growth rate for SUC related research was 7.2% (Table 1). This indicates progressive growth in the field, although, there was a limited study on seed improvement of the underutilized crop in the 1990s (Fig. 1). However, research interest peaked in 2021 with the highest number of publications (1174).

Research analysis

According to SUC keyword used, the top 20 research articles most cited and relevant in the field were listed in Table 3. These include a research article titled 'The use of wild relatives in crop improvement: A survey of developments over the last 20 years'. The study reviewed available information on the presence of genes in wild crop relatives, among 16 mandated crops of the Consortium of International Agricultural Research Centers (CGIAR), the article received 1100 citations (Hajjar and Hodgkin, 2007). The research publication titled 'Quinoa biodiversity and sustainability for food security under climate change' received 327 citations. The study reviewed the beneficial properties of quinoa (*Chenopodium quinoa* Wild,) seed, and reported that research on genetic resources to improve quinoa began several decades ago, these properties enhance quinoa to thrive in marginalized soils and extreme weather conditions (Ruiz *et al.*, 2014). Their study characterized quinoa seeds, showing their evolutionary trends and rich genetic diversity, stress tolerance traits and the role of farmers in their preservation.

The research article by Rastogi and Shukla (2013) titled 'Amaranth: a new millennium crop of nutraceutical values' received 264 citations. The publication considered seed improvement in Amaranth cultivars, their high genetic diversity, quantitative yield- enhancing traits, phenotypic plasticity and extreme adaptation to unfavourable growing conditions. The article reported that amaranths crop is a future crop with the potential to create high food demand from its vast seed and leaf yield potential and nutritional qualities. The research article by Ford-Lloyd *et al.* (2011) titled 'Crop Wild Relatives – Undervalued, Underutilized and under Threat?' has 251 citations. The study reported the importance of seed improvement using new technological tools to enhance and conserve the plant genetic resources, revealed the risk of biodiversity loss, which pose a major threat to underutilized crop species. The publication of Ebert (2014) entitled 'Potential of Underutilized Traditional Vegetables and Legume Crops to Contribute to Food and Nutritional Security, Income and More Sustainable Production Systems' received 367 citations. His study demonstrated the importance of seed breeding in three underutilized legume namely; Amaranth, drumstick tree and mung beans which possessed valuable constituents and competitive traits with broad adaptation and potential for achieving food and household income security. Among the most prolific publications in SUC-related fields was the article by Munns and James (2003) entitled 'Screening methods for salinity tolerance: a case study with tetraploid wheat' with 1036 citations (Table 3). The work reported on a range of previously unexplored tetraploid wheat genotypes, examined the genetic seed breeding potentials of the crop and ways to overcome its production and consumption limitations. Watson *et al.* (2018) publication entitled 'Speed breeding is a powerful tool to accelerate crop research and breeding' with 596 citations, reported breeding methods that could accelerate crop improvement rates for spring and durum wheat, barley, chickpeas, peas and canola. Yu *et al.* (2016) research titled 'Genomic prediction contributing to a promising global strategy to turbocharge gene banks'. It received 154 citations, stating that large plant accessions in gene banks are mostly underutilized due to various resource constraints, but current genomic and analytical technologies are being optimized to mine this natural heritage. Other important research titles on seed improvement in underutilized crops are; 'Diversity, conservation and wild relatives species of fonio millet (*Digitaria* spp.) in north-west of Benin ' (Dansi *et al.*, 2010), ' Genome-wide association study of agronomic traits in common bean' (Kamfwa *et al.*, 2015), 'breeding in Bambara groundnut (*Vigna subterranea* (L.) Verdc.): strategic considerations' (Massawe *et al.*, 2005) and other important researches in diversified scientific field, enrich knowledge on seed improvement in underutilized crops (Table 3).

Table 1. Main information of the dataset on SUC related studies

Timespan	1990–2021
Sources (Journals, Books, etc)	298
Documents	13 235
Article	12 530
Conference proceedings	155
Review and book chapters	575
Collaborative index	2.89
Annual growth rate	7.2%

Organization collaboration analysis and spatial distribution of SUC publications

Based on the observed network of co-authors, a total of 1118 organizations from 104 countries participated in SUC-related research, while only 589 organizations have research affiliations with SUC studies (Figs 2 and 3). The five most influential institutions indicated by publications and citations are: Agri & Agri Food Canada (85 publications and 1638 citations), Univ Copenhagen (38 publications and 977 citations), Univ Saskatchewan (41 publications and 601 citations), Univ Alberta (38 publications and 685 citations) and Int Crops Res Inst Semi-Arid Trop.

The visualization of the geographic distribution of the productive countries is based on the corresponding author's country. The total link strength between countries researching SUC is shown in Fig. 4. Published studies on SUC-related fields from the USA was ranked first (150 publications and 2916 citations) followed by research studies from Canada (137 publications and 2615 citations) and India (101 publications and 820 citations), Nigeria (79 publications and 776 citations), followed by China (66 publications and 679 citations), South Africa (52 publications and 512 citations) and Italy (51 publications and 616 citations) (Fig. 3; Table 4). The research link strength and networking started to increase from the year 2012, while countries with the strongest link strength are the USA, Denmark, Germany, China, Australia and France (Table 5 and Fig. 4).

Analysis of the keyword

The bibliometric analysis of the keywords provides a structured assessment of the keyword domain that is relevant for SUC

Table 2. Number of publications retrieved on seed improvement among different categories of underutilized crops

Categories	Underutilized crops (UUC)	Number of publications on UUC seed improvement
Pulses and legumes	Lablab *(Lablab purpureus* L.)	166
	Jack beans (*Canavalia ensiformis*)	21
	Cowpea (*Vigna Unguiculata* L.)	755
	Bambara groundnut (*Vigna subterranea* L.)	451
	Pea *(Pisum sativum)*	326
	Marama bean *(Tylosema esculentum)*	30
	Chickpea *(Cicer arietinum)*	364
	Mung bean *(Vigna radiata)*	198
	Faba beans (*Vicia faba* L.)	508
	Kersting's groundnut (*Kerstingiella geocarpa*)	3
	African yam bean (*Sphenostylis stenocarpa*)	17
	Lima bean (*Phaseolus lunatus*)	13
	Hyacinth bean (*Lablab purpureus*),	15
	Spanish bunch groundnut *(Arachis hypogaea)*	5
	Dwarf French bean (*Phaseolus vulgaris* L.)	846
	lentil *(Lens culinaris)*	221
	Clitoria ternatea	19
	Pigeon pea *(Cajanus cajan*)	653
	Yam bean (*Pachyrhizus erosus* L.)	23
	Gemsbok *(Tylosema esculentum)*	16
Forage legumes	Alfalfa (*Medicago sativa*)	254
	Birdsfoot trefoil (*Lotus corniculatus),*	51
	warf koa (*Desmanthus virgatus),*	4
	winged beans (*Psophocarpus tetragonolobus)*	20
	Velvet bean (*Mucuna spp.*)	11
	Sesame (*Sesamum indicum)*	196
	canary seed (*Phalaris canariensis* L.),	2
	Cicer (Lathyrus cicera L.)	451
	Sprawling bauhinia *(Tylosema fassoglense)*	1
	Sesban *(Sesbania* spp.*)*	33
Cereals and Pseudocereals	Pearl millet (*Pennisetum Glaucum* L.)	365
	Panicum miliare	24
	Buckwheat (*Fagopyrum esculentum* L.),	298
	Sorghum (*Sorghum bicolor*)	699
	wild rocket (*Diplotaxis tenuifolia*)	32
	Finger millet *(Eleusine coracana)*	30
	Foxtail millet (Setaria italica)	36
	Broomcorn millet (Panicum miliaceum)	103
	Quinoa *(Chenopodium quinoa)*	510
	Chia (*Salvia hispanica* L.)	74
	Teff *(Eragrostis tef)*	214
	Tassel flower *(Amaranthus caudatus)*	269
	Maize landraces	129

(*Continued*)

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Table 2. (*Continued.*)

Categories	Underutilized crops (UUC)	Number of publications on UUC seed improvement
Vegetables	Bottle gourd *(Lageneria siceraria)*	27
	Eggplant (*Solanum melongena*)	158
	Water Spinach (*Ipomoea aquatica*)	26
	Jew mallow *(Corchorus olitorius)*	30
	Spider plant *(Cleome gynandra)*	229
	Amaranth *(Amaranthus spp.)*	224
	Night shade *(Solanum nigrum)*	52
	Wild watermelon *(Citruilus Lanatus L.*)	21
	Okra *(Abelmoschus esculentus)*	107
	Sweet cucumber *(Solanum muricatum)*	13
	Rapeseed-mustard *(Brassica juncea L.)*	128
	Water leaf *(Talinum triangulare)*	14
	Blackjack *(Bidens pilosa)*	36
	Cockscombs *(Celosia spp.)*	78
	(Brassica carinata)	729
	wild mustard (*Sinapis arvensis*),	33
	canola *(Brassica napus)*	521
	Squash (Cucumis spp)	301
Medicinal plants	Cumin (*Cuminum cyminum*)	108
	Physic nut *(Jatropha curcas)*	179
	Moringa *(Moringa oleifera)*	135
	Bitter leaf *(Vernonia spp)*	12
	Wild ginger (*Siphonochilus aethiopicus*)	6
	bitter gourd (*Momordica charantia* L.)	51
	Rooibos *(Aspalathus linearis*)	9
Roots and tubers	Taro *(Colocasia esculenta)*	711
	Sweet potato *(Ipomea batatas)*	332
	Cocoyam *(Xanthosoma sagittifolium)*	55
	Cassava (*Manihot esculenta*)	386
	Yam *(Dioscorea spp)*	68
Total		13 235

research (Fig. 5). These keywords were divided into clusters based on the number of frequency or occurrence of the keywords, there were five different clusters of keywords represented by different colours.

Cluster one (green) represents the largest cluster; it had 91 keywords, 30–35 word occurrences and total link strength ranging from 200–280. The main topics in this cluster are the relationship of seed improvement among underutilized crops to cropping system, seed treatment, tillage, seed performance, seedling emergence, gene, seed dormancy, cultivar, pollination, yield and yield components in different agroecosystem. The most common crops in the cluster are canola (*Brassica-napus*) and summer oil rapeseed, while it also features fertilizer management, fungicides, irrigation and heat stress. High occurrences words in this cluster include 'yield' (69 occurrences and 516 total link strength (TLS) 'germination' (62 occurrences and 448 TLS), 'quinoa' (85 occurrences and 630 TLS), 'resistance' (23 occurrences and 174 TLS), oil seed rape (17 occurrences and 131 TLS). Yield 'management' 'tillage' 'fertilizer' and 'disease' keywords are prominent in the cluster, implying that the words have a strong association with other keywords. This means that most research studies on SUC focus on improving seed yield, seed quality and management of underutilized crops.

Cluster two (red) had 87 keywords with 5–15 word occurrences and total link strength of 50–180.The most commonly studies crops in this cluster are okra, bambara groundnut, cereals, amaranth seed, finger millets and potato. This cluster emphasizes the nutritional, functional properties and nutrient composition of underutilized crops. These include starch, amino acid, fatty acid, sensory properties, thermal properties and dietary fibre,

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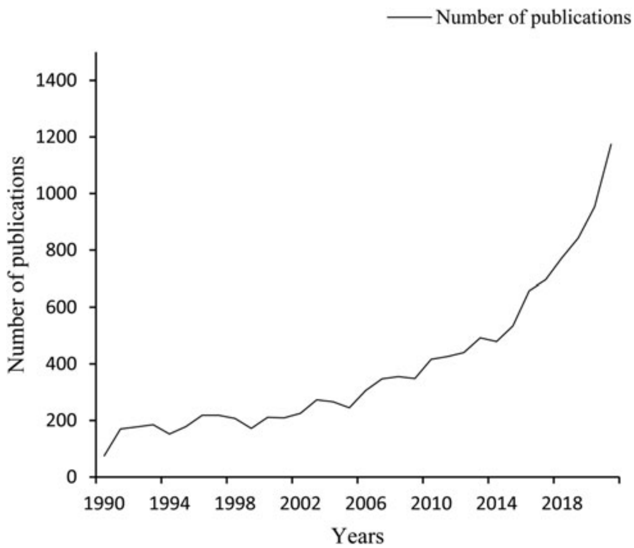

Figure 1. Number of publications on SUC related studies from 1971 to 2021.

digestibility, physicochemical properties, nutritional values, farmer perceptions, crop adaptation, crop production and sustainability. It had a strong connection to food security, plant breeding, food supply, seed nutritional values such as fatty-acid, protein and antioxidants. This cluster mainly consists of keywords related to studies on digestibility properties for seed improvement of underutilized crops. The prominent keywords are; 'antinutrients, chemical composition, tannins, processing methods, infrared heating, phytic acid and antioxidant activity.

Cluster three (blue), consists of 80 keywords with 3–12 word occurrences and total link strength of 29–73. The most common crops in the cluster are tef, barley, sorghum and foxtail millet. It focuses on agrobiodiversity, climate change, arid environment, breeding, food security, drought tolerance, genetic diversity, genetic resources, germplasms among underutilized crops. This cluster has keywords such as 'genetic analysis', 'genetic diversity, 'selection', 'crosses', germination, domestication,' gene expression, 'genetic analysis', 'variability', 'SSR markers', 'landraces,''adaptation'. This clusters includes keywords such as molecularly assisted techniques to improve seed performance and seed physiological properties in response to stress such as seed longevity, drought and salinity. This cluster also revealed studies on the effect of climate change on seed production of the crops and various human responses in past and present, to genetic variability of the crop were indicated by the keywords.

Cluster four (yellow) had 38 keywords with 50–60 word occurrences and total link strength of 250–285 that focused on the evolution and domestication of underutilized crops (Fig. 5). Analysis of the keywords present in the cluster revealed studies on climate change, salinity, dry matter, growth, tolerance, soil moisture, responses, seed performance, grain yield.

Additionally, cluster 5 (purple) had 11 keywords with 6 to 13 word occurrences and total link strength of 40–85 (Fig. 5). This cluster has fewer keywords such as sorghum, plant population, metabolism, saponin, water, efficient water use, seed viability, salinity tolerance and dormancy. The sparse visibility of the purple node indicates that research in this area is still very little.

Keyword timeline view

The timeline shows the years with the highest occurrences of keywords and research linkage. The superimposed visualization of all keywords from 1990 to 2021 clearly shows that in 2005, most studies on SUC dealt with rapeseed, canola, cowpea, foxtail millet, pearl millet, dormant seeding, seedling growth, vigour, seed population structure, seed availability, allozyme variation, tissue culture, plant regeneration and trait loci (Fig. 6). The studies identifying underutilized seed population, seed performance, its opportunities and challenges to promote its genetics conservation began to attract attention (Mayes *et al*., 2012; Galluzzi and López Noriega, 2014). By 2010, following the development of the subject area, the focus shifted to management practices such as nitrogen fertilization, planting date, plant density, seed hybridization, protein digestibility and nutritional benefits. Further studies were conducted in 2015 on underutilized crop pollination system, disease resistance, drought, salinity, crop tolerance, yield, germination, genetic diversity, landraces and the most prominent crops: Bambara groundnut, sorghum, quinoa and amaranth. Studies conducted from 2020 to present addressed SUC improvement of phenolic compounds, gene expression, macro and micronutrient compositions, bio-active compounds and phytochemicals. The emerging issues in seed improvement of underutilized crop studies are indicated by the node size (Fig. 6).

Seed germination, yield, landraces, cultivar selection, crop management, physicochemical properties, antioxidant activities of the seeds are some of evolving themes in SUC studies. Some other notable emerging themes are seed genetic diversity, nutrition, seed vigour and quality. There has been gradual research progress in the SUC field, most of the earlier studies focused on seed dormancy, processing method, adaptation, grain yield and population selection. Currently, research is focused on solving most of the limitation associated with wide acceptance of underutilized crops by improving seed protein digestibility, phytochemical properties and identifying bioactive compounds in the seed of underutilized crops.

The word cloud further broaden the keywords that cover most of the crop species commonly researched over the past three decades as millet, wheat, quinoa, canola, sorghum, landrace, cowpea, quinoa, Amaranthus spp, winged beans, Dioscorea spp, indigenous vegetables. The word cloud shows the most trending words or the most important keywords in the SUC-related studies:'seed system', 'yield', 'quality'," genetic diversity', 'landraces'," cultivar", 'water', 'resistance' 'seed characterization', 'stress', 'growth', 'molecular studies', breeding, 'germplasm', 'domestication', 'germination', 'resistance','yield'. The upcoming keywords are ' management efficiency', ' molecular markers' 'nutritional composition', 'ex-situ conservation',"drought", 'seed accession', 'bio-priming', 'antioxidant', 'heritability', biotechnology', 'genotyping' and others (Fig. 7). However, frequencies of words such as genetic improvement, seed priming, tissue culture, temperature and mapping in SUC research are still low.

Discussion

This study provides an overview of research on seed improvement of underutilized crops. The gradual increase in the number of publications in the field over the last three decades may be related to the awareness raised by the United Nations 2030 Agenda, which aims to eradicate hunger, achieve food security, improve nutrition and promote sustainable agriculture by 2050 (Lartey, 2015). The prospects that underutilized crops can mitigate environmental risks in crop production systems, improve nutrition, generate income, maintain ecosystems health and contribute to the development of biological and cultural diversity were outlined

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Table 3. The most cited and relevant articles and journal sources on SUC related fields

No	Authors and year of publication	Title	Journal source	Citations
1	Hajjar and Hodgkin (2007)	The use of wild relatives in crop improvement: A survey of developments over the last 20 years	Euphytica	1100
2	Ruiz *et al.* (2014)	Quinoa biodiversity and sustainability for food security under climate change. A review	Agronomy Sustainable Development	327
3	Ebert (2014)	Potential of Underutilized Traditional Vegetables and Legume Crops to Contribute to Food and Nutritional Security, Income and More Sustainable Production Systems	Sustainability	367
4	Rastogi and Shukla (2013)	Amaranth: a new millennium crop of nutraceutical values	Critical Reviews in Food Science, and Nutrition	264
5	Munns and James (2003)	Screening methods for salinity tolerance: a case study with tetraploid wheat	Plant & Soil	1036
6	Ford-Lloyd *et al.* (2011)	Crop Wild Relatives-Undervalued, Underutilized and under Threat".	Bioscience	258
7	Watson *et al.* (2018)	Speed breeding is a powerful tool to accelerate crop research and breeding	Nature Plants	596
8	Yu *et al.* (2016)	Genomic prediction contributing to a promising global strategy to turbocharge gene banks.	Nature Plants	154
9	Mohammed *et al.* (2016)	Phenotypic characterization of diverse Bambara groundnut (*Vigna subterranea* [L.] Verdc.) germplasm collections through seed morphology'	Genetic Resources and Crop Evolution	23
10	Geisen *et al.* (2021)	Physical and Structural Characterization of Underutilized Climate-Resilient Seed Grains: Millets, Sorghum and Amaranth	Frontiers in Sustainable Food System	46
11	Massawe *et al.*, 2005	Breeding in bambara groundnut (*Vigna subterranea* (L.) Verdc.): strategic considerations	African Journal Biotechnology	146
12	Mayes *et al.* (2012)	The potential for underutilized crops to improve security of food production	Journal of Experimental Botany	261
13	Jain (2005)	Major mutation-assisted plant breeding programs supported by FAO/IAEA	Plant Cell Tissue Organ Culture	181
14	Eshed and Lippman (2019)	Revolutions in agriculture chart a course for targeted breeding of old and new crops.	Science	135
15	Vollmann and Eynck (2015)	Camelina as a sustainable oilseed crop: contributions of plant breeding and genetic engineering	Biotechnology Journal	116
16	Kamfwa *et al.* (2015)	Genome-Wide Association Study of Agronomic Traits in Common Bean	Plant Genome	87
17	Dansi *et al.* (2010)	Diversity of the Neglected and Underutilized Crop Species of Importance in Benin	Science World	219
18	Hammer *et al.* (2003)	Agrobiodiversity with emphasis on plant genetic resources	Genetic Resource Crop Evolution	187
19	Dansi *et al.* (2010)	Diversity, conservation and related wild species of Fonio millet (*Digitaria* spp.) in the northwest of Benin	Genetic Resource Crop Evolution	110
20	Masondo *et al.* (2018)	Influence of biostimulants-seed-priming on *Ceratotheca triloba* germination and seedling growth under low temperatures, low osmotic potential and salinity stress	Ecotoxicology and Environment Safety	68

in 2011 in the Global Action Plan on Plant Genetic Resources for Food and Agriculture (FAO, 2012). This was later expounded at the International Seminar on Crops for the XXI Century which focused on eradicating hunger and rural poverty using underutilized crops. Although, seed improvement in underutilized crops is still a challenge, the number of institutions actively engaged in its research and development is gradually increasing. Institutions such as the International Institute of Tropical Agriculture and Biodiversity International have initiated various programmes aimed at establishing certain underutilized crops in Africa, Asia and Latin America (Padulosi et al., 2013). FAO (2018) reports on the Future Smart Crops documentary explain the role of initiatives by China, Germany, India and Malaysia to improve production and germplasm conservation of underutilized crops, by preserving local agrobiodiversity on the farm. These awareness and government initiatives have led to an increase in research publications and exploration of the prospects for underutilized crops and their reintroduction into the food nutrition stream. The clusters analysis provides current challenging or dominant keywords and future scopes for interdisciplinary themes on SUC studies. The challenging issues of seed improvement for underutilized crops were closely related to genetic diversity, conservation, seed system and climate change.

Figure 2. Institutional collaborations on SUC related research from 1990 to 2021.

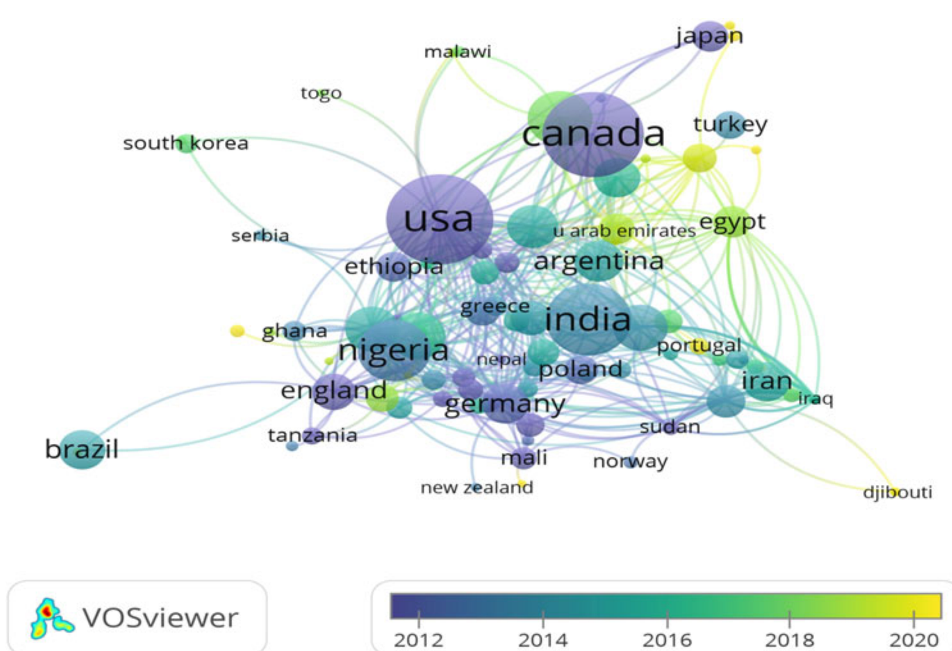

Figure 3. Co-authorship network among countries where SUC-related research was conducted from 1990 to 2021.

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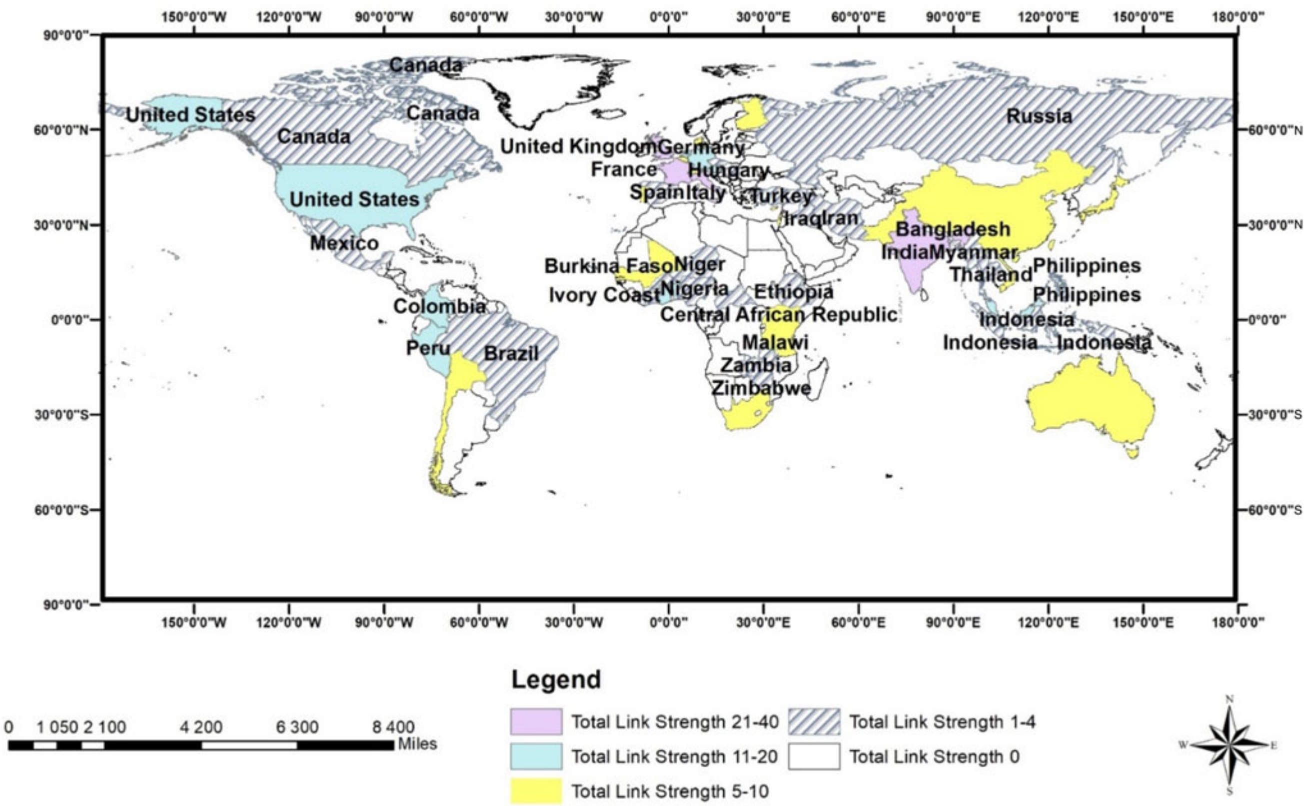

Figure 4. World map distribution of total link strength in the SUC research field.

Table 4. Top twenty active organizations ranked by number of publications and citations in SUC research

No	Organization names	Countries	No of publications	Citations
1	Agriculture & Agri-Food Canada	Canada	85	1638
2	University of Saskatchewan	Canada	41	601
3	University of Copenhagen	Denmark	38	977
4	University of Alberta	Canada	38	685
5	International Crops Research Institute for the Semi-Arid Tropics	Asia and sub-Saharan Africa	32	491
6	University of Manitoba	Canada	28	570
7	Kansas State University	USA	25	461
8	University of Agriculture Faisalabad	Pakistan	24	345
9	University of Hohenheim	Germany	24	406
10	Washington State University	USA	24	428
11	Alberta Agricultural & Rural Development	Canada	23	436
12	University of Nottingham	UK	23	315
13	USDA ARS	USA	23	343
14	University of Arkansas	USA	22	345
15	University of Pretoria	South Africa	21	279
16	International Institute of Tropical Agriculture	Nigeria	20	264
17	University KwaZulu-Natal	South Africa	20	165
18	Federal University of Agriculture	Nigeria	19	123
19	Swedish University of Agricultural Sciences	Swedish	19	191
20	Purdue University	USA	18	356

Table 5. Top twenty active countries ranked by citations and number of articles in publishing seed improvement of underutilized crops

No	Country	No of publications	TC	TLS
1	USA	150	2906	98
2	Canada	137	2615	25
3	India	101	910	20
4	Nigeria	79	776	40
5	China	66	616	54
6	South Africa	52	512	30
7	Italy	51	837	45
8	Denmark	49	1126	69
9	Australia	46	743	47
10	Argentina	43	880	28
11	Germany	41	679	59
12	Pakistan	41	465	35
13	Iran	40	365	18
14	England	36	547	31
15	Chile	34	876	28
16	France	32	599	47
17	Egypt	30	324	39
18	Spain	29	189	21
19	Ethiopia	28	316	26
20	Netherlands	28	221	26

TC, Total citations; TLS, Total Link Strength.

Genetic diversity

In contrast to staple crops, where great strides have been made in genetic diversity research, mapping genetic diversity in underutilized crops is recognized as an important issue in seed improvement programmes (Muhammad *et al.*, 2020). The conservation and preservation of the genetic diversity of underutilized crops in gene bank, DNA libraries and biorepositories, are essential for rapid crop improvement and addressing future global food challenges (Engels and Ebert, 2021). This provides plant breeders with the opportunity to develop new models for varietal innovation, conserve genetic resources and improve varieties with desirable traits. Khoury *et al.* (2022) emphasized that current loss of genetic diversity varies by crop species, taxonomic and geographic scales and regions.

Similar to the evolution and domestication of staple crops, extensive studies are currently underway on the genetic diversity of crops such as *Citrullus lanatus*, assessing it seed quality, viability, seed system, conservation, morphological and agronomic traits (Achigan-Dako *et al.*, 2009). Approximately 88% of quinoa accessions are conserved in gene banks in the Andean region, but are not shared globally due to highly political issues of national sovereignty (Rojas *et al.*, 2015). Gerrano *et al.* (2015) evaluated amaranthus germplasm for morphological characteristics using various statistical methods and classified amaranthus genotypes into six different groups based on their genetic similarity which could be useful for their breeding programme. Minnaar-Ontong *et al.* (2021) studied the genetic diversity and structure of Bambara groundnut (*Vigna subterranean* L) landraces South Africa using SSR markers. They discovered that most South African accessions were restricted to one subpopulation, which could result in unique haplotypes in different environments. Some of the underutilized crops have gained popularity in developed countries in terms of dietary trends and consumption (Akinola *et al.*, 2020). Germplasm conservation is another challenging topic in SUC-related research.

Genetic conservation of underutilized crop seed

Most underutilized crops lack adequate genetic characterization compared to staple crops because most germplasm collections are not maximally optimized. The rich genetic diversity in underutilized crops is threatened with extinction unless the germplasm is conserved and fully characterized (Kamenya *et al.*, 2021). Underutilized crop seeds are mostly conserved on-farm, rarely available in ex-situ collections and there is limited documentation freely available for research and development plans in various targeted agro-ecologies (Engels and Ebert, 2021). Galluzzi and López Noriega (2014) have compiled a list of underutilized crops that have undergone breeding evaluation in selected Andean countries. Padulosi *et al.* (2014) reported on the need to establish a global underutilized crop conservation programme that would strengthen *in situ* and ex situ conservation of wild species in gene banks. The collation of details on SUCs from different environmental regions and climatic conditions will help in conservation of the crop genetic resources. Since, the food production system is highly dependent on selected cultivars in better-endowed environments (Adelabu *et al.*, 2020; Kamenya *et al.*, 2021).

Currently, climate change affects total precipitation, temporal dynamics and biodiversity, resulting in low variability of genetic loci that control crop physical and phenotypic traits (Garcia *et al.*, 2014). Climate change adaptation strategies include maintaining genetic diversity of underutilized crops over the evolutionary period (Chiurugwi *et al.*, 2019). This is because the plants contain important alleles that allow them to thrive in marginal soil and extreme weather conditions, and they have tolerance traits to pests and diseases (Mabhaudhi *et al.*, 2019). For example, in intercropping with cereals, *Desmodium spp* suppressed *Striga hermonthica* by producing allelochemicals that inhibit the weed root growth (Midega *et al.*, 2017). Kamenya *et al.* (2021) reported that a combination of spider plant and snap beans reduce thrips infestations during cultivation. Foxtail millet (*Setaria italica*) and quinoa (*Chenopodium quinoa* Willd.) exhibit high levels of drought stress, due through their osmotic adjustment, leaf area reduction, stomatal closure and genetic mechanism but increase in their productivity are still under-researched (Hinojosa *et al.*, 2018; Mabhaudhi *et al.*, 2019). Despite the potentials of underutilized crops against climate change, the seed breeding strategies are still conventional and limited in innovations when compared with staple crops. However, there is a gradual improvement in funding initiatives for research on genomic characterization and gene identification of underutilized crops (Padulosi, 2017; Chiurugwi *et al.*, 2019; Paliwal *et al.*, 2021). Exploring the potentials in the genetic resources of underutilized crops and the classification of valuable traits for climate change adaptation programmes are necessary to attain increase seed improvement of the crops (Chivenge *et al.*, 2015). Kamenya *et al.* (2021) reported progress in genome determination for more than 28 underutilized crops by gene sequencing but explained the importance of modern crop tools for crop improvement such as speed

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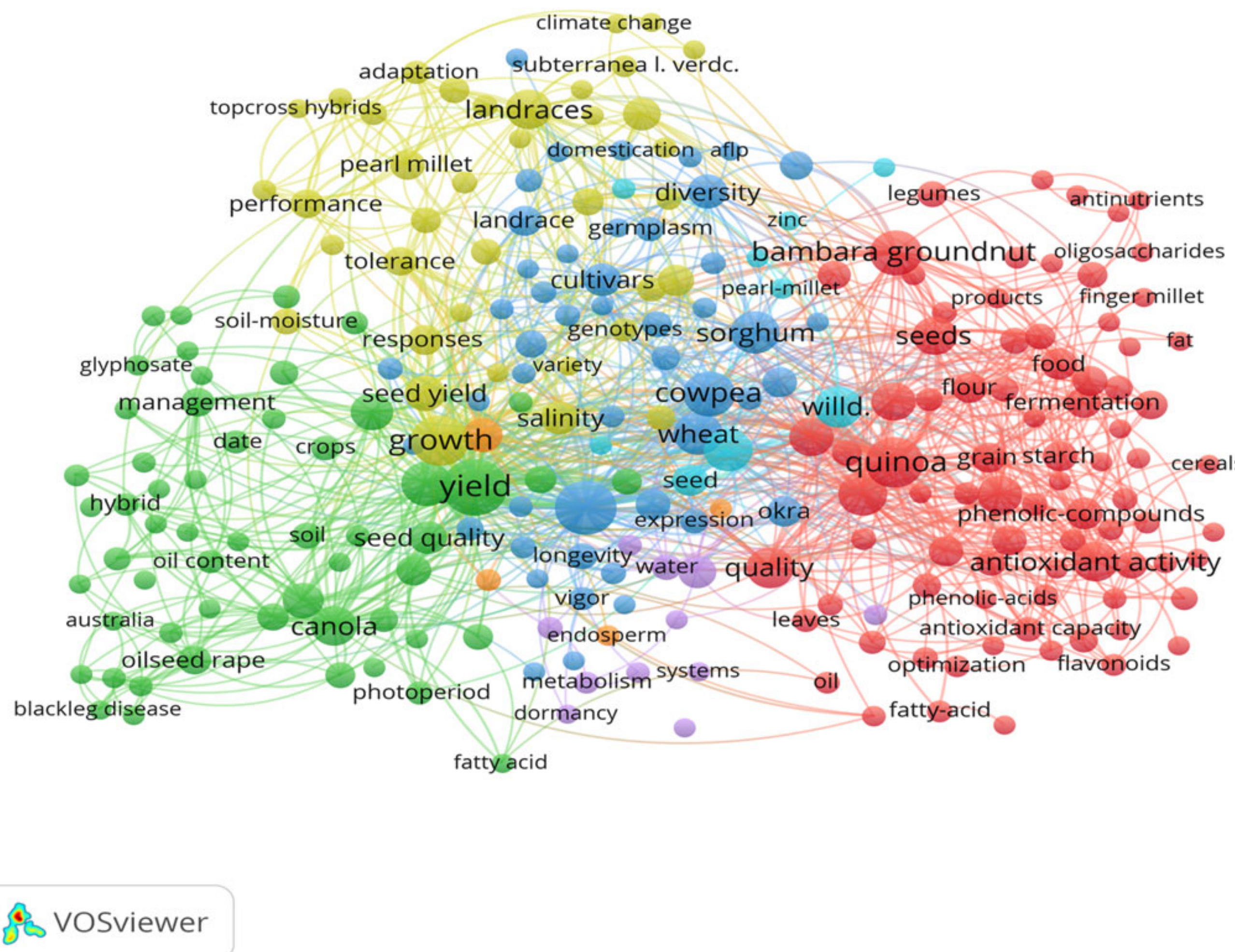

Figure 5. Major keywords in SUC studies from 1990 to 2021.

breeding, genome editing, breeding digitization and phenotyping which require heavy and coordinated research investments. The richness of genetic diversity among underutilized crops confers incredible resilience to biotic and abiotic stresses but identification of genomic resources is still very limited.

Seed system

The seed systems details and documentations for mostly cultivated underutilized crops are quite low especially in most developing countries, where seed system is characterized by recycling of poor quality seeds resulting in extremely poor yields (Mabhaudhi *et al.*, 2019). The extension agents who serve as a feedback channel between farmers and the global research community to disseminate the best seed practices have not made much progress with underutilized crops (Mabhaudhi *et al.*, 2017). Although, some of the extension services have been digitized, helping to reach farmers via mobile-based services with verified information about the target crop in the remote villages (McCampbell *et al.*, 2021). McMullin *et al.* (2021) reported that interdisciplinary teams are important for developing mainstreaming strategies for underutilized crops, but there was no clear consensus on specific measures such as production practices and pest and disease interventions, seed delivery system, pervious production data. To provide improved cultivars and relevant management information, extension services need to be structured based on regions and targeted crops that dominate regional livelihoods (Kom *et al.*, 2020).

Research gaps and future directions

The current study reveals the current state and future research directions in seed improvement of underutilized crops that allow the utilization of their genetic resources. The introduction of advanced breeding resources used in staple crops closely related to underutilized crops is required. Furthermore, optimal growth conditions via controlled environment similar to those optimized for cereals such as wheat (*Triticum aestivum* L.) could be of great benefit in pseudocereals crops breeding (Kamenya *et al.*, 2021; Seguí-Simarro *et al.*, 2021). Moreover, government, private sector and international agricultural research funding should prioritize underutilized crops just as being done to most staple crops breeding schemes in many countries (Jayne *et al.*, 2021). Likewise, dissemination of prospects embedded in the underutilized crop will help in its conservation and utilization as supplementary food crops with the staple crops.

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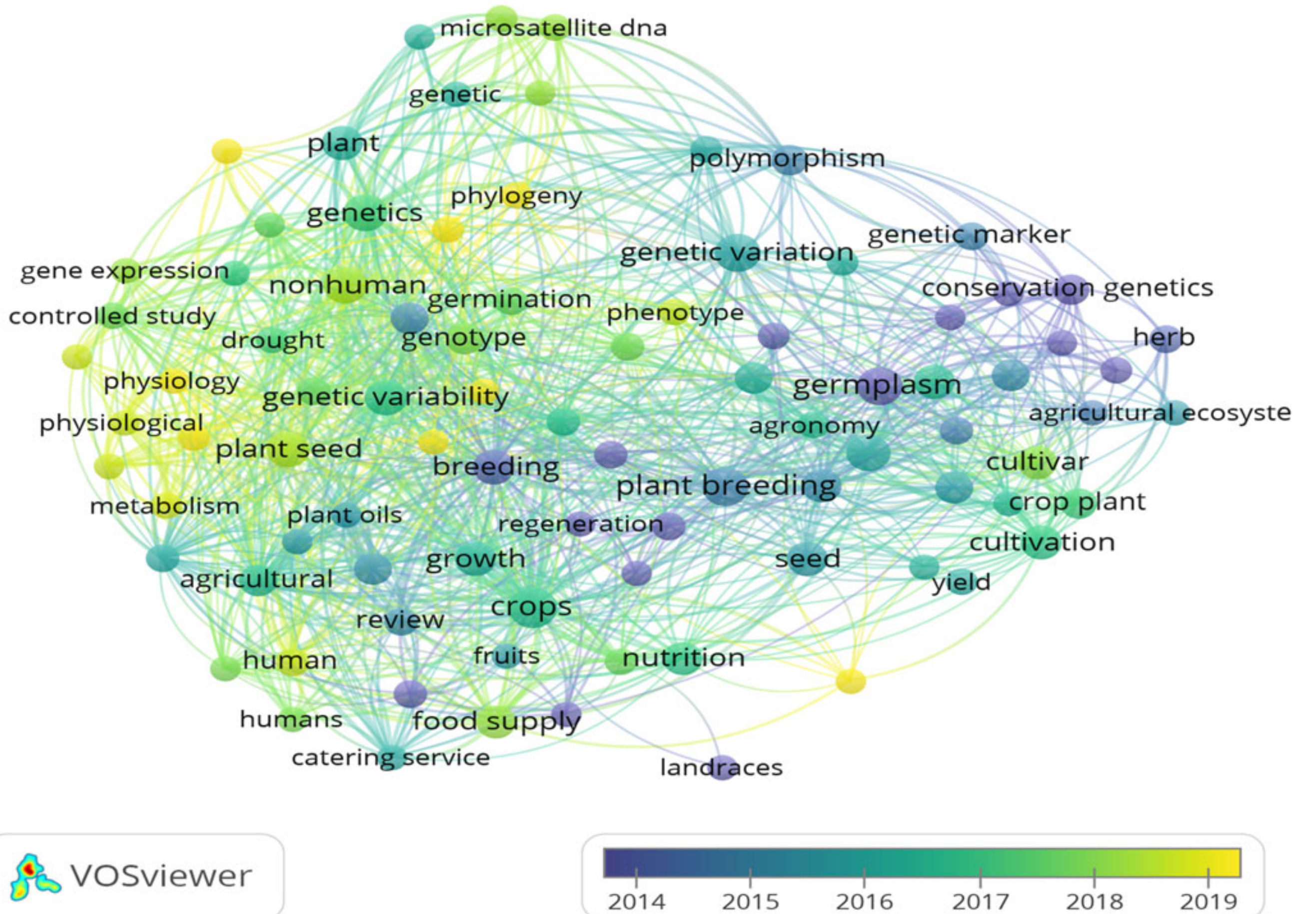

Figure 6. All keywords on SUC related studies based on timelines.

Figure 7. Word cloud for SUC research and studies from 1990 to 2021.

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This study did not analyse grey publications in non-indexed journals that were not in the databases of Google Scholar, Scopus and Web of Science. Consequently, journals from non-English speaking countries may be underestimated and influence the position of the most active authors, countries, institutions and journal sources. Additionally, the methodology used to determine the frequency of each publication across countries and institutions may have increased the research output of countries with larger international collaborations. Furthermore, the citation analysis did not take into account self-citations, which may have skewed the number of citations for countries and journals. This study is the first bibliometric study on seed improvement of underutilized crops. Key players, research topics and gaps have been identified. It gives better appreciation of the complex distinctions that characterize seed improvement of underutilized crops and proposes a solution to quantify these differences through increasing interventions in genetic resource conservation.

Conclusion

This study provides researchers and policymakers with baseline data on seed improvement in underutilized crop studies. This study emphasizes the need for further research studies on seed genetic diversity, conservation and seed system of underutilized crops that can help preserve the crop genetic resources, similar to current seed advancement in staple crops. Moreover, there is a need for more international collaborative research with national and international initiatives on genetic variability of landraces, conservation and adaptation to climate change especially among African countries. Finally, national and international food security organizations should encourage and fund more researchers to conduct studies and collate information to improve the seeds of underutilized crops. Thus, the availability of resources for crop breeding programmes and the ability to increase yields in production areas will increase farmer income and food security.

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Author contributions. Both authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by D. B. Adelabu and A. C. Franke. The first draft of the manuscript was written by Dolapo Bola Adelabu and both authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest. The authors declare that there is no conflict of interest concerning this manuscript.

Ethical standards. Not applicable.

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