Review

Past, present and future perspectives on groundnut breeding in Burkina Faso

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Abstract: Groundnut (*Arachis hypogaea* L.) is a major food and cash crop in Burkina Faso. Due to growing demand for raw oilseeds, there is an increasing interest in groundnut production from traditional rain-fed areas to irrigated environments. However, despite implementation of many initiatives in the past to increase groundnut productivity and production, the groundnut industry still struggles to prosper, due to several constraints including minimal development research and fluctuating markets. Yield penalty due to drought and biotic stresses continue to be a major drawback for groundnut production. This review traces progress in the groundnut breeding that started in Burkina Faso before the country's political independence in 1960 through to present times. Up to the 1980s, groundnut improvement was led by international research institutions such as IRHO (Institute of Oils and Oleaginous Research) and ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). However, international breeding initiatives were not sufficient to establish a robust domestic groundnut breeding programme. This review also provides essential information about opportunities and challenges of groundnut research in Burkina Faso, emphasising the need for institutional attention to genetic improvement of the crop.

Keywords: Peanut, plant breeding, research, funding, genomics, INERA, cultivar, selection, Arachis hypogaea.

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1. Introduction: the importance of groundnut in Burkina Faso

Groundnut (*Arachis hypogaea* L.) is a self-pollinated crop and allotetraploid ($2n = 4x = 40$) with a genome size of 2891 Mbp [1], which belongs to the Fabaceae family [2,3]. Also known as peanut, groundnut is an important food and cash crop in Burkina Faso (formerly known as Upper Volta), contributing significantly to both food security and poverty alleviation [4]. As in many low-income countries in Africa and Asia, the crop is primarily grown for subsistence by smallholder farmers [5], predominantly women [6-8], under rain-fed and low input conditions [9]. Groundnut can account up to 50% of cash income, while providing many benefits, including a food rich in digestible proteins, high quality oils and many functional compounds such as iron and zinc which are important to nutrition and health, especially in children [10-12]. As a legume crop, groundnut cultivation improves soil fertility and productivity by fixing atmospheric nitrogen [13]. Additionally, the plant's haulm and by-products have value as a feed for livestock [14,15]. The groundnut value chain in Burkina Faso employs a significant number of people and contributes substantially to the economy [4,16] and to family wellbeing [6,17]. Clearly, groundnut improvement has a direct positive impact on the nutritional and economic status of smallholder farmers.

Despite the importance and benefits of groundnut for farmers and consumers in Burkina Faso, production of this legumes has stagnated around 400,000 tonnes per annum for the last 20 years or so [18]. Groundnut yields remained low (~ 800 kg/ha), contrasting sharply with the crop's potential that can reach over 3000 kg/ha in intensive agriculture systems (USA, China) [19]. This low level of productivity is attributable to several constraining factors, including diseases and pests, erratic rainfall, drought, poor soils, market instability and lack of locally adapted high-yielding varieties [19,20]. The highest production in Burkina Faso was 519,345 tonnes in 2016 [18], more due to extension of cultivated land than to increase in crop productivity (Figure 1). The stagnation of domestic production has been exacerbated by an unreliable seed supply system for groundnut [19] and weak organisation of the groundnut industry which has left a current gap in processing capacity.

Groundnut breeding in Burkina Faso has been tightly correlated with activities in the crop's value chain, which drive the whole groundnut industry, including the research and development [4]. For more than a decade now, no major action plan has been established to develop the groundnut industry, especially after the 2008 food crisis [21]. To this extent, the focus of breeding efforts at INERA (Institute of Environment and Agriculture Research) was directed to the main staple food crops (sorghum, maize, pearl millet, rice), overlooking groundnut which is often considered as a cash crop, and thereby hampering groundnut cultivar development.

At present, information about progress and the current state of groundnut breeding in Burkina Faso is patchy. Most research results are confined to annual reports of individual projects, with little published in international journals [22]. To our knowledge, publications in recent years have focused mainly on yield evaluation [23] and disease of local and exotic varieties for early leaf spot [24,25]. Earlier research activities involved evaluation of resistance to foliar diseases in lines introduced from ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) or the USA through the Peanut CRSP (Peanut Collaborative Research Support Program) [26-28] and similar development programmes.

In this paper, research on groundnut improvement in Burkina Faso is reviewed, with an outlook for future breeding strategies. It appears that groundnut research started under colonial projects before the country's independence in 1960. However, it took nearly three decades before the national agriculture research programme emerged. Between 1980 and 2010, groundnut research was conducted by nationals with minimal access to technical and financial capacities. The most consistent support was from the USAID-funded Peanut CRSP. This was followed by years of resource scarcity, before groundnut research was rekindled with ICRISAT-led Gates-funded projects (Tropical Legumes) and local initiatives. Today, modern technologies offer the opportunity to advance and deliver improved groundnut varieties that meet farmer, consumer, processor, and export demands.

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2. History of groundnut cultivation in Burkina Faso

Intensive groundnut production started in West Africa during the colonial period in the 1900s, providing raw material for the French oil factories as well a source of revenue [29], stimulating groundnut commercialization throughout the whole of Western Africa [30]. Subsequently, migrant groundnut farming arose as a labour system in West Africa associated with cash-cropping, which drew thousands of young men from Burkina Faso and elsewhere (Mali, Guinea, Senegal, Mauritania) towards the Gambia River basin (Gambia), a hot-spot of groundnut cultivation at the time [29,30]. Although farmers had been growing the crop in many places in Burkina Faso, migrants returning home from the Gambia River basin were most likely the first to advance groundnut cultivation in the country. The swift widespread adoption of groundnut was probably due to its similarity to the West African native Bambara groundnut (*Vigna subterranea*) [30], to which farmers were already accustomed [30,31].

After successful promotion of groundnut cultivation in the region of Bobo-Dioulasso by the colonial administration in the early 1920s, crushing machines became operative in Ouagadougou and Banfora in 1922 and 1928, respectively [32]. Cultivation of groundnut extended rapidly around the country after 1936 [33,34], prompting the installation of the main factory for oil processing in 1941 in Bobo-Dioulasso [33]. Post-independence political unrest, drought waves, epidemics of groundnut rosette disease, and continuous decline in groundnut price on global markets drastically reduced production by more than 50% in the 1970s [29,30,35-37]. Production increased again after 1985 due to expanded acreage for cultivation of the crop [38] and significant governmental support to the groundnut sector by the SOFIVAR (Groundnut Funding and Extension Society) [35]. The crop yield was very low (<400 kg/ha) up to the mid-1980s, when for the first time yields reached 600 kg/ha (Figure 1). The best average yields (800-900 kg/ha) were achieved during the mid-1990s, driven by market opportunities and national support provided to groundnut sector [35,39]. However, yield has stagnated since then (Figure 1), highlighting the need for improved locally adapted varieties.

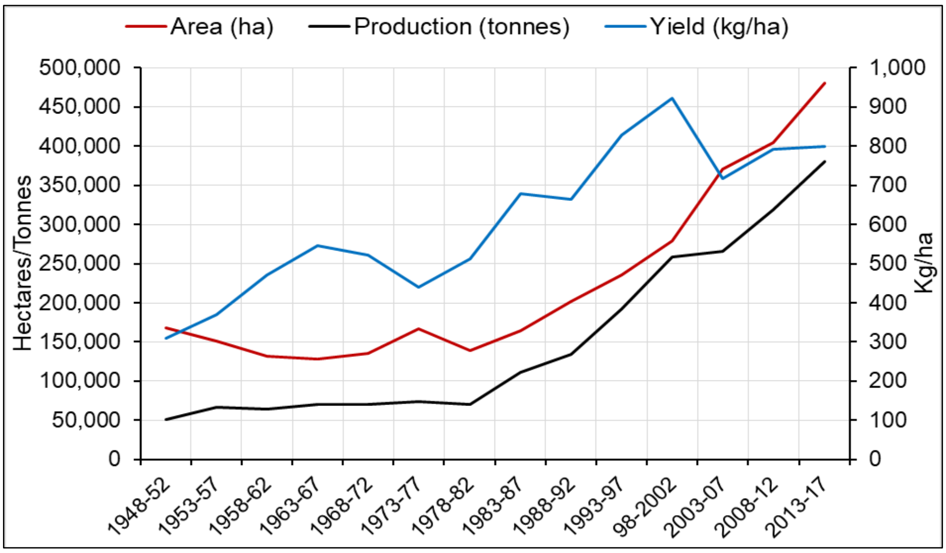

Figure 1. Evolution of groundnut production, area and yield (mt/ha and kg/ha) in Burkina Faso between 1948 and 2017 [18,31,36]. Plotted data points are the average data of every 5 years.

3. Groundnut research in Burkina Faso

Groundnut research in Burkina Faso started before the country's autonomy, with French projects targeting the crop production for export. The French national institute for colonial agriculture (called CNRS post-1939) was created to conduct development research to increase revenues from agricultural production in the French colonies of Africa [40,41]. The hardship of World War II further prompted the creation of specialised research institutions such as IRHO

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(Institute of Oils and Oleaginous Research), to increase food and oilseed production in Africa [41,42]. Subsequently, IRHO, having merged with GERDAT (Study and Research Group for the Development of Tropical Agriculture), has conducted research on groundnut, with focus in the main production area in southwestern regions of Burkina Faso [34]. The research objectives were to increase yields while developing resistance to rosette disease, which could totally decimate production during years of disease outbreaks [34]. This prompted IRHO, based at Niangoloko, to undertake groundnut improvement research to develop cultivars resistant to rosette disease and adapted to southwestern regions of the country [34]. Resistant cultivars were identified in 1952 around the Burkina/Côte-d'Ivoire border and used in breeding crosses at Bambey Agricultural Research Centre in Senegal [43]. By 1959, about 20 resistant cultivars with limited infection rate (≤6%) and better productivity (20-35% yield increase compared with local varieties) were introduced in Burkina Faso [34]. Additionally, experiments conducted between 1955 and 1963 resulted in some varieties with potential yields about three metric tonnes per hectare, and showed that, 1) groundnut densities between 111,100 and 133,300 plants/ha are optimal for top yields, and 2) phosphorus is the most limiting nutrient for groundnut in soils of western Burkina Faso [34]. The creation of ICRISAT in 1972 and nomination of groundnut as a mandate crop in 1976 [44] added momentum to research on groundnut [3,45]. Major constraints to production were identified [46], including pests [38,47], diseases [9,48], drought and aflatoxins [49-52].

Until the inception of PNRA in mid-1980s, agricultural research was administered by the Ministry of Rural Development, with little contribution of national scientists. Major research projects on groundnuts were implemented by international institutions [28,31,42,53], with the research station of IRHO at Niangoloko contributing somewhat but at a far lower level [31]. Varietal creation was limited at Niangoloko, as it was used primarily as a testing site, while breeding populations were developed at the research centre in Bambey, Senegal [43]. Apart from a few French agronomists, no Burkinabe conducted research in Niangoloko, probably because groundnut was not a priority for the government [53]. Government investment in agricultural extension prevailed over research even before technologies were developed to support food production as suggested by donors [31]. Then, progressive departure of international researchers and lack of resources, equipment and trained scientists halted research activity and led to a loss of valuable germplasm and breeding records [22,54]. Restructuring in the 1980 to 1985 timeframe gave rise to INERA, which initiated breeding programmes in 1988 [55].

In this context, programmes supported by donors such as USAID (United States Agency for International Development), the European Union (EU) and the Bill and Melinda Gates Foundation (BMGF) were instrumental in re-establishing groundnut research and development in Burkina Faso [22]. USAID-funded Collaborative Research Support Program (CRSP) stimulated and sustained research activities from 1975 to 2012 [26-28]. This Peanut CRSP network involved the Institute for the Sahel (INSAH), IRHO and ICRISAT. However, these activities focused primarily on pest and disease management and resistance to leaf spot diseases, as well as testing of advanced lines for production efficiency [27]. These programmes resulted in improved groundnut varieties which still hold a large share of production in Burkina Faso today [22,36]. They enabled many works that would not be possible otherwise. In this research collaboration, cultivar development was conducted mainly by IRHO and ICRISAT [34,46,48,54] while work at INERA involved testing only. Such involvement of international research in national programmes has been at the core of crop breeding activities in West Africa [22]. The growing number of trained and qualified scientists in Burkina Faso and in the region opens opportunities for more research leadership within countries. However, breeding programmes continue to be handicapped by the lack of the resources needed to conduct research activities [22], and lack of research leadership to some extent. Consequently, most of groundnut varieties cultivated in Burkina Faso today were developed before or shortly after 1960, some from Senegal as sharing cultivars has been common practice between countries in the sub-region [56-58]. Varieties such as 28-206, 59-426, 69-101 and Fleur 11 were introduced from Senegal to Burkina Faso [22]. To date, more than 20 varieties have been registered in the national

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catalogue of crop varieties. Some of these (e.g. TS 32-1, CN94 C, RMP 91, RMP 12, KH 241D) have been under cultivation for more than 50 years (

). Cultivar development was stagnant in the country until 1990 when two varieties (SH 67A, SH 470P) were released (

); and the average age of commercial groundnut varieties is about 30 years [54].

Table 1. Groundnut varieties released from the 1950s to date and registered in the National catalogue of plant varieties

Variety/line	Pedigree	Botanical type	Cycle (days)	Year	Institution/ Origin	Ref.
CN 94C	90 Saria /Tougan 1) F_6	Spanish	90	1966	IRHO Saria, Burkina Faso	[9,60]
Te. 3	Local pop. Burkina	Spanish	90	1958	IRHO Niangoloko, Burkina Faso	[9,22,57,60,62]
TS 32-1	Spanlex /Te. 3,	Spanish	90	1966		
KH 149A	GH119-7.1II-III /91 Saria	Spanish	90	1964		
KH 241D	GH 1185.2 II /91 Saria	Spanish	90	1964		
QH 243 C	KH 184 A /424 A, F_7	Spanish	90	1971		
RMP 91	48-37 /Mani Pintar, F_9	Virginia	135	1963		
RMP 12	1036 /Mani Pintar, F_9	Virginia	135	1960		
SH 67A	QH 243C X PI 1166	Spanish	90	1990	INERA Niangoloko, Burkina Faso	[60]
SH 470P	Flower 113 X QH 200A, F_7	Spanish	90	1990		
69-101	55-455 14*28-206, F_5-B_3	Virginia	120	1969	IRHO/ CNRA Bambey, Senegal	[9,22,56,60,62]
59-426	NA	Virginia	120	1959		
ICGSE 104	NA (Segregating material ICRISAT)	Valencia	75-80	1990	INERA - ICRISAT	[60]
Fleur 11	NA (Variety from China)	Spanish	90	1990	CNRA Bambey Senegal	[60,62]
Nafa 1 (ICGV 01276)	ICGV 92069 /ICGV 93184	Virginia	110	2018	INERA - ICRISAT	[61]
Lokre (ICGV 91328)	J11 /U4-7-5	Spanish	90	2018		
Miou Pale (ICGV 93305)	Var 27 /U4-7-5	Valencia	90	2018		
Touinware (ICGV-IS 13806)	ICGV 86124 /ICG 7878	Spanish	90	2018		
Beeda (ICGV-IS 13830)	ICGV 86124 /ICG 7878	Spanish	90	2018		
Soukeba (ICGV-IS 13912)	ICGV 86124 /ICG 7878	Spanish	90	2018		
Kiema 1	Local pop. Burkina	Spanish	90	2018		

NA = not available; pop. = population.

The current increase in groundnut production has been almost entirely due to land expansion [18]. With the exhaustion of the country's arable lands, future increase in production must come from yield improvement based on genetic improvement and appropriate management practices. It has been estimated that less than 25% of about 460,000 hectares of land cultivated yearly in groundnut, were occupied with improved varieties [54,59]. Replacement of popular groundnut varieties (TS 32-1, SH470-P, CN94 C, Fleur 11) with more productive ones is sought. Only recently,

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in 2018, have seven new varieties developed by ICRISAT been tested, registered in the national seed catalogue [61], and subsequently released for cultivation in Burkina Faso (

). However, extension efforts are required to facilitate farmers' awareness and adoption of these varieties.

4. Research resources

In the early 2000s, Burkina Faso began investing more in agricultural research capacity. As of January 2019, more than 65% of scientists hold a doctorate degree (HRM, personal communication), compared to less than 50% before 2000. Currently, the number of scientists at INERA alone reaches over 300, not counting scientists at university-based agricultural research centres. However, the increase in number of researchers did not go along with increase in research capacity [63]. Lack of resources coupled with poor competitiveness of local salaries with that of international positions, motivated departure of many scientists to CGIARs, NGOs or Western countries. National research programs struggle to keep up with evolving breeding methods and required infrastructures and equipment [63], limiting their effectiveness.

Furthermore, expenditures dedicated to research and development have been irregular [37] or reduced, sometimes due to political turmoils [31]. Since transitioning from PNRA, INERA has been chiefly financed through World Bank loans supporting three main projects [37,64,65]. What is more, of the proportion of funding dedicated to agriculture research, little goes to groundnut, making this crop less attractive to researchers. The consequence of resource limitation was attenuated by regional research initiatives through WECARD (West and Central African Council for Agricultural Research and Development) and ICRISAT. Regional efforts essentially guard against unnecessary replication of research in countries with similar agro-ecologies in the region and have the benefit of mobilising more donors [63]. International initiatives as the Peanut CRSP enabled many research activities on groundnut in the country for over three decades in collaboration with the University of Ouagadougou [28,31]. With the end of the world bank-funded project PNDSA (National Project for Development of Agricultural Sector) in 2003, there was no funding at all for groundnut research at INERA until 2012 when groundnut development research started almost afresh with the second phase of Tropical Legumes project sponsored by the Gates Foundation. This project provided substantial support to the breeding programme in Burkina Faso, allowing INERA to reflect on product targets, breeding objectives to achieve these targets, and breeding process modernisation [66]. This funding had the merit of rekindling groundnut breeding in Burkina Faso, although there is still need to develop clear and specific improvement goals, build technical capacity and secure long term funding.

In a nutshell, public sector groundnut breeding has not made satisfactory progress in Burkina Faso. As in most sub-Saharan countries; no increase in genetic gain has been recorded in the last 30 years [67,68]. Furthermore, the national breeding programme struggles to keep up with the evolving breeding methods, suffering from a lack of research leadership and insufficient technical expertise [67,69]. While technology can be accessed, especially through outsourcing, the primary challenge for groundnut improvement in Burkina Faso is the capacity to assemble relevant technological options to create an optimized varietal development pipeline [67]. A workforce of researchers able to apply advances in breeding methods, approaches, and tools for cultivar development is needed.

5. Production environment

Groundnut was the top cash crop in Burkina Faso before cotton until 1977 [70]. Since then, groundnut production has primarily served domestic needs as a food crop [36,70]. Of the yearly production of more than 350,000 tonnes [18], only about 2% on average is exported [70], and this to other countries in West Africa [4]. A sharp increase in groundnut prices in early 1990s boosted production and exports towards Europe, at least for a few years [35,71]. However, the increased production and export levels were not sustained due to the decline in groundnut demand in Europe [70,72] and lack of adequate support to farmers [71]. Nevertheless, domestic demand for

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groundnut has been increasing in recent years, to complement cotton seed for an increase of oil production, which covers only around 30% of needs at the moment [73]. Currently, although groundnut production meets the demand for household consumption as food, little surplus is available for the processing market [31,36,70]. The development of productive cultivars for the farming system upstream is necessary to meet growing demands and sustain a stable value chain.

The distribution of groundnut cultivation in Burkina Faso (Figure 2) indicates *Centre-Ouest* as the top groundnut producing region, followed by the *Boucle du Mouhoun* region. Production is mid-level in *Hauts-Bassins*, *Centre-Sud*, *Centre-Est* and *Est* regions. This distribution has remained consistent since the 1960s [34], reflecting minimal efforts to expand groundnut to new areas. Nevertheless, Burkina Faso is among the top ten groundnut producing countries in Africa, based on area harvested (

Figure 2. **Map of groundnut production per administrative region in Burkina Faso, adapted based on average of the last five years (2013-2017) [18]. 1: Boucle-du-Mouhoun ; 2: Cascades ; 3: Centre ; 4: Centre-Est ; 5: Centre-Nord ; 6: Centre-Ouest ; 7: Centre-Sud ; 8: Est ; 9: Hauts-Bassins ; 10: Nord ; 11: Plateau-Central ; 12: Sahel; 13: Sud-Ouest. The chloropleth map was drawn using R package GADMTools with breaks option "sd" (standard deviation).**

Table **2**). Moreover, an estimation of country production proportionally to the population size, shows that the importance of groundnut production in Burkina Faso is similar to that of Nigeria, the top producer in Africa [18]. Groundnut has great economic potential for the country [71], if only more political support were provided to increase investment in the sector.

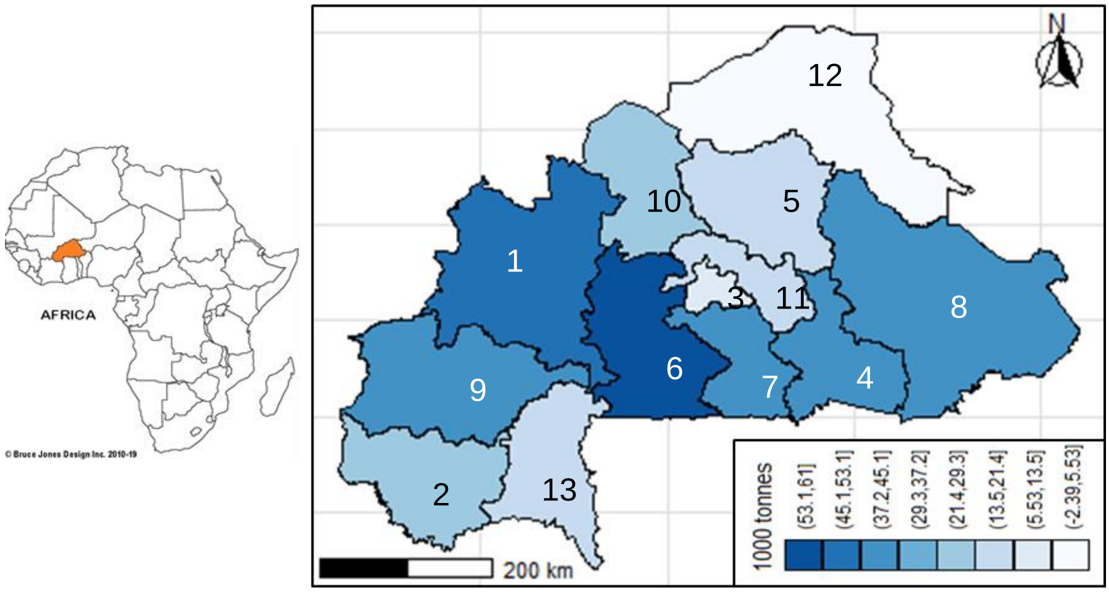

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Table 2. **Top 10 groundnut producing countries based on average area harvested in the last five years (2013-2017) [18].**

Rank	Country	Area (ha)	Production (tones)	Yield (kg/ha)
1	Nigeria	2766845.8	3068586.8	1110.4

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2	Sudan	2027954.4	1629402.2	797.8
3	UR* Tanzania	1208903.0	1285027.0	1052.8
4	Senegal	950149.6	806165.4	843.2
5	Niger	779283.6	417776.0	537.4
6	Chad	760472.6	843546.2	1117.1
7	Guinea	553012.0	469918.2	887.5
8	DRC*	492000.0	370447.4	753.6
9	Burkina Faso	480635.4	380894.2	799.8
10	Cameroon	439308.4	610196.2	1386.4

*** UR Tanzania = United Republic of Tanzania; DRC = Democratic Republic of the Congo**

6. Constraints to groundnut productivity

The difference between groundnut potential yield and actual yields in farmer fields, referred to as yield gap [74,75], reaches over 50% Burkina Faso [18,60], due to several biotic and abiotic constraints [9,13,25,38,56]. With rain-fed systems, up to 50% of the yield potential can be compromised by moisture stress due to inconsistent rainfall [75]. Identifying ways to manage constraints that undermine the crop productivity and widen yield gap is key to developing an effective groundnut improvement programme. Desmae et al. [46] summarized the main traits of breeding interest identified in recent years: drought tolerance; resistance to rosette, foliar diseases (leaf spots and rust) and aflatoxin; and quality traits such as high oil content, especially with high proportion of high oleic acid. They also pointed to potential sources to improve groundnut varieties for these traits [46]. Not discounting the effects of G x E which can lead to inconsistent trait expression, these resources could be important assets to the groundnut improvement programme in Burkina Faso.

6.1. Abiotic constraints

In Burkina Faso where rain-fed agriculture is predominant, rainfall patterns represent the most significant climatic factor affecting groundnut production. Low, erratic rainfall and increasing periods between rains render groundnut cultivation subject to substantial yield losses [76,77]. A strategy to cope with drought stress is to develop short-duration varieties to escape end-of-season drought as well drought tolerant varieties that hold up under conditions of low soil moisture[78].

Another constraint to realize yield potential is low levels of inputs in managing the crop. In Burkina Faso, groundnut is grown mostly under subsistence agriculture by smallholder farmers [71]. Fertiliser use for all crops since 2000 has averaged 11.1 kg/ha, which is shockingly inadequate [63]. Appropriate use of fertilisers can lead to a 45% increase in groundnut yields [35]. However, farmers are incentivised to apply fertilisers and improve soil conditions only when there are market prospects [39]. Yet, critical elements such as phosphorus and calcium prove to be the top limiting nutrients for groundnut production, especially in the western regions of the country [34]. Although this issue can be overcome by applying appropriate chemical fertilisers, these are often out of reach for most smallholder farmers. Only 4% and 16% of farmers use chemical fertilisers or compost, respectively, in groundnut production, resulting in very low yields [35,71]. Therefore, it is advisable to develop cultivars that withstand deficiency of both calcium and P to keep a good level of crop productivity. Soils in Burkina Faso present optimum pH between 6.0 and 6.5 for groundnut growth [79], which typically results in adequate availability of calcium and manganese [80]. Nevertheless, acidic pH should be taken into consideration in the breeding programme to anticipate the growing soil acidification in some areas in the country [81].

6.2. Biotic constraints

As in most tropical regions of the world, diseases are major constraints to groundnut production in Burkina Faso [22]. Problems with foliar diseases including rust have been

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longstanding [82] with persistent occurrence in Burkina Faso [25]. Rosette disease, which affects the leaves and stem, is common in Western Burkina Faso [56,83,84] and is transmitted by the vector *Aphis craccivora* Koch [85] in a persistent manner [86]. Also, peanut clump disease, common in West Africa [87] has been reported in the country [56,83] and needs to be monitored. These diseases can cause important losses in groundnut production if not controlled [87]. Often foliar diseases occur simultaneously and collectively can cause from 24% up to 70% yield loss, following severe defoliation [9,22].

Groundnut productivity can also be reduced by soil pests [88]. Taxa associated with groundnut damage with high economic impact include termites (Isoptera), millipedes (Diplopoda) and scarabaeid larvae (Coleoptera) usually referred to as white grubs [38]. Species *Trochalus sp*., *Microtermes lepidus Sjöstedt* and *M. parvulus Sjöstedt* have been reported in Burkina Faso [89]; however, little is known about the economic importance of these pests at present. Additionally, the current erratic weather pattern can cause pests profiles to change thereby necessitating frequent nationwide surveys to document key pests associated with groundnut productivity. Studies at ICRISAT identified sources of resistance to these pests, which hold promise for improving crop productivity [38,47]. Genetic resistance could be a key element of a broader strategy for effective pest control and control of pest-induced diseases, integrating use of pest-resistant varieties, cultural practices to minimize insect populations, and bio-insecticides.

7. Suggested foci for groundnut improvement in Burkina Faso

In principle, the target traits for groundnut improvement depend on farmers' needs, consumer and market demands, and processing requirements [69]. The most pressing need in Burkina Faso is for groundnut varieties with high yield potential that also possess tolerance to major biotic and abiotic yield-reducing factors. Closing the yield gap is the main focus besides improving yield *per se*, as in most of the developing countries [90]. Improved varieties must be able to thrive under minimal management conditions as farmers often simply cannot afford inputs such as pesticides and chemical fertilizers [82]. Furthermore, improved varieties must be developed to meet demands of the value chain including both women and men consumers [91], to stimulate market growth and viability.

7.1. Elements to consider in cultivar development

In Burkina Faso as elsewhere in West Africa, market desirable traits in groundnut include high seed yield, high oil/high oleic oil content in the seeds, and resistance to aflatoxins for food safety [72,92]. There is now a call for groundnuts specifically developed for end-use application: cooking oil, confectionary and peanut butter [46,93,94]. The product target should be designed based on regular consultations with key stakeholders including men and women farmers, marketers, processors and consumers [67]. High oil content groundnut varieties are currently in high demand to supply oil-crushing factories. Recent studies have demonstrated the possibility to raise oil content to as much as 55% of seed composition, presenting up to 80% oleic [95,96]. Oil quality in terms of high proportion of oleic acid is desirable to increase product shelf life [97] and provide many health benefits to consumers [98-100]. The challenge is to build on these advances in groundnut improvement for oil content and quality [101] to put these traits together with other desirable agronomic traits (i.e. yield and disease resistance) in an ideal cultivar for stakeholders of the value chain. More generally, groundnut breeding should be steered by market demand [102], as needs of stakeholders of the groundnut value chain evolve.

The cornerstone and highest priority trait in crop breeding is the yield. Pod number per plant, shelling percentage, proportion of mature kernels per pod, and seed weight are important parameters contributing to groundnut yield [69]. Other traits to consider include early maturity, ease in harvesting (peg strength) and shelling, kernel size, shape and colour, fresh seed dormancy, and blanching ability [3,46,69]. Additionally, reticulation (venation and ridging visible on the pod), beak (appendage of the tip of the indehiscent pod) and constriction of pods are traits that provide not only varietal specifications, but also reflect market preferences [103]. For instance slight pod

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constriction is preferred in the market as it prevents flattened kernels; whereas pods with prominent reticulation or deep constriction tend to carry soil on them, thus reducing the market value [103].

To sustain productivity, groundnut resistance to biotic and abiotic stresses must be improved. To this end, ICRISAT has identified and developed sources of key traits, including resistance to early leaf spot (caused by *Cercospora arachidicola*), late leaf spot (caused by *Phaeoisariopsis personata*), rust (caused by *Puccinia arachidis*), and aflatoxins [9,24,25,27,46,52]. Additionally, significant progress has been achieved at ICRISAT in developing drought tolerant [104,105] and early maturing cultivars [46]. These sources can be utilized by Burkina-based breeding programmes to develop improved locally-adapted germplasm.

7.2. Exploring novel industrial uses of groundnuts

Groundnut is considered as a "smart food", that is, a food that is highly nutritious, resilient to climate change, with relatively low carbon and water footprints; as such, it has the potential to alleviate poverty [106]. Having high protein content, a healthy oil profile and serving as a source of a key micronutrients including magnesium, groundnut has been used to make ready-to-use therapeutic food [107] used by UNICEF to treat acute malnutrition among children, women and men in developing countries [108,109]. Acute malnutrition affects near 500,000 children in Burkina Faso [109], visible by 24.4% underweight and 10.2% mortality among children under five [110]. More generally, 25% of the population (~5 million people) are affected by hidden hunger [111,112]. To add more to the health benefit of groundnut, improvement for nutritional traits, i.e. bio-fortification, such as iron and zinc must be on the breeding agenda [106,113]. This is important to reduce the prevalence of anaemia among preschool-age children (≥40%) [110].

Besides, groundnut haulms can be an used for livestock feed [114], thus giving additional value to the crop. Groundnut haulms are protein-rich and easy for animals to digest [15]. The need for feed has been increasing in recent years, due to drastic reduction of pasture land and the development of suburban farming in towns [115]. Therefore, animal feed production and market are promising sector of domestic economy [116], especially during the dry season when fresh grazing is not available [16]. However, livestock feed is rarely a production objective *per se* in subsistence farming. The development of dual-purpose varieties offering both high kernel yield and above-ground biomass could offer new opportunities to expand the groundnut value chain.

7.3. Broadening genetic base of breeding population

Cultivated groundnut is said to have a relatively narrow genetic base globally [117-119], perhaps due to polyploidisation [120]. Therefore, useful genetic variability must be created through judicious choice of parents in creating new breeding populations for crop improvement [121]. The nature and magnitude of genetic variability present in the breeding population and the extent to which the trait is heritable are key to success of the crop improvement programme [121]. Pre-breeding activities deploying strategic crossing among cultivated varieties and also between cultivars and wild groundnuts [120,122-124] has enlarged the crop base genetic diversity. Interestingly, accessions and advanced breeding lines which are stored in gene banks across the globe [90] are abundant and accessible through appropriate legal procedures [125]. These resources constitute invaluable material for national and international breeding programmes.

8. Modernization needed to maximise genetic gain in developing varieties that meet stakeholder demands

In principle, plant breeding is implemented through three basic steps, viz. (1) crossing choice individuals with traits of interest to create breeding populations with useful genetic variation, (2) identification and selection of progeny from the breeding crosses having outstanding performance aligned with the product target, and (3) development of stable new cultivars from selected progeny [126]. The success of this process can be measured by estimating the rate of genetic gain over time,

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using the so-called breeder's equation [127,128]: $\Delta G = \left(h^2\ \sigma_p\ i\right)/L$. The estimate of the rate of genetic gain (ΔG) is a product of the narrow sense heritability for the trait under selection (h^2), the standard deviation of the phenotypic variance of the trait (σ_P), and the selection intensity (i), divided by the length of time to complete a full breeding cycle(L). As such, it is also a function of selection accuracy (h; the square root of narrow sense heritability) and the additive genetic variation within the population (σ_a^2; a component of h^2). Each of these parameters can and should be manipulated in the breeding programme to maximise genetic gain in achieving the product target [67]. Such a strategy implies increasing heritability, selection accuracy, selection intensity and the speed of the breeding cycle, and effectively exploiting genetic variation [126]. Modern breeding approaches, technologies, and tools offer the means to increase the rate of genetic gain to effectively and efficiently reach product targets, and thus get improved varieties out to farmers faster.

8.1. Modern approaches, technologies, and tools to benefit choice of parents and creation of breeding populations

Choice of parents is one of the most critical decisions to achieving success in cultivar development. Firstly, parental lines must represent viable sources of the suite of traits defined in the product target. Crossing of parents offers the opportunity for genetic recombination to result in new combinations of favourable alleles in the offspring. Ultimately, a potential new cultivar must contain favourable alleles for all the traits of interest. Genomics can aid in identifying lines with favourable alleles to employ as parents. For example, GWAS (genome wide association studies) can be conducted to characterize germplasm, identify new sources of favourable alleles, and tag genes to be tracked through the breeding process. Genomic approaches using GEBV (genomic estimated breeding values) can be used to leverage genetic information as well as phenotypic information collected from prospective parent lines and their relatives to guide the breeder in choosing parents. Once crosses are made, mating designs and tailored breeding approaches can be deployed to maximize seed returns and accelerate progress to homozygosity. Technologies such as doubled haploidy has been used to create "instant inbreds" in some crops, including groundnut [129,130], which offers advantages in testing by cutting "noise" due to segregation that is present in early generations.

To create useful genetic variation, technologies such as mutation, transformation, and gene editing can be deployed. Mutation breeding involves irradiating seed with gamma rays or using chemical mutagens like ethyl methane sulphonate, diethylsulfate or sodium azide [131-133] to evoke changes in the DNA. Successful cases of mutation breeding have been reported extensively for the improvement of important traits including groundnut yield [134,135], allergen reduction [132], and oleic acid content in the oil profile [136]. Therefore, mutation breeding can be a useful breeding approach, especially with genetic improvement of crops having narrow genetic base such as groundnut [132,137].

Groundnut improvement for tolerance to some of the biotic and abiotic stresses can be difficult, either due to complex genetic control of the trait or absence of resistant sources. For instance, it has been difficult to develop resistance to *Aspergillus flavus* infection and aflatoxin production in groundnut in a sustainable manner [138,139]. Similar issues observed with groundnut response to other stress contexts such as drought and virus attacks have warranted alternative approaches to conventional breeding. In such conditions, genetic transformation presents great potential in groundnut improvement to utilize genes from other species [44,69,140,141]. Likewise, the difficulties of plant regeneration by tissue culture techniques and selection of transgenic events [141-143] are being overcome by recent advances in groundnut transformation process [144]. To date, at least a dozen of successful groundnut transformations have been reported in the literature [68]. Recently, agrobacterium-mediated transformation and groundnut tissue culture techniques were refined for optimum use, which enabled development of genetically-modified groundnut that was near-immune to aflatoxin contamination [144].

Furthermore, gene editing has shown great promise in creating new allelic variants, using various technologies such zinc finger nucleases (ZFNs), transcription activator-like effector

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nucleases (TALENs), and clustered regularly interspaced short palindromic repeats (CRISPR) [145-148]. Gene editing can result in gene modification (e.g. single base change), gene silencing (i.e. knockout), or gene insertion (i.e. knock-in) [147]. Recent studies have shown that multiple genetic changes can be performed in concert [149], suggesting the potential to utilize CRISPR to generate new genetic diversity for quantitative traits. For example, work by Campa et al. [150] demonstrated simultaneous editing of up to 25 target sites using CRISPR in conjunction with nuclease Cas12A. Thus, genetic engineering is a powerful tool to achieve groundnut improvement for difficult traits, but also any other traits of interest [140-142]. However, public reluctance to consume food made from genetically modified plants [151-153] and complex regulation processes [147,154-156] could preclude the application of genetic engineering approaches in groundnut breeding. Public education and government support for appropriate review and regulation of genetically engineered products is key to overcoming potential obstacles.

8.2 *Modern approaches, technologies, and tools to benefit evaluation and selection*

The rate of genetic gain toward product targets can be increased by increasing selection intensity. However, this can cripple progress if the selection intensity is so high as to effectively eliminate genetic variation. This potentially negative effect can be managed by increasing population size, that is, creating more progeny from each breeding cross. To deal with a larger number of individuals to test for each trait specified in the product target, technologies that can screen more individuals in less time with fewer resources are needed. Mechanization can help to manage activities such as planting, harvesting, threshing. In addition, technologies to facilitate high-throughput phenotyping can be used to increase efficiency in screening. Thus, the near infrared spectroscopy (NIRS) provides a robust, quick, cost-effective, and non-destructive phenotyping for groundnut seed oil content and fatty acid profile [157,158]. Additionally, modern phenotyping facilities such as that at ICRISAT offer the possibility to dissect physiological factors with tight correlation with traits of interest (transpiration efficiency and drought tolerance, for instance, www.gems.icirisat.org). Likewise, advanced experimental designs are useful in effectively partitioning genetic variation from environmental variation, GxE, and error, which can increase the accuracy of selection. Here again, technologies can come into play. For example, laser levelling of fields has been used to create more uniform fields for testing [159], which has been shown to result in more precise data upon which to make selection decisions [160,161]. However, cost may be a limitation for the use of this technology in resource poor breeding programmes [161].

To reduce the length of the breeding cycle, various approaches and technologies are available. Off-season nurseries offer the opportunity for more generations per year, cutting the overall time to complete the breeding cycle [67,158]. The term "speed breeding" has been coined to describe approaches and technologies to shorten the life cycle of the plant in generations where selection is not exercised [162,163]. For example, O'Connor et al. [164] was able to cycle 145-day groundnut lines at the rate of three generations per year to advance inbreeding from F2 to F4 based on controlled greenhouse conditions of optimal temperature and continuous light. In addition, marker-assisted selection, involving "tagged" genes of interest, can be utilized to cut the length of the breeding cycle. Individuals can be evaluated and selected based on genotype alone, eliminating wait times until the trait is manifested phenotypically and, in many cases, reducing field and labour resources required for phenotypic evaluation.

Advanced molecular approaches such as genomic selection utilize dense genome marker coverage to estimate genetic potential. Genomic selection facilitates faster identification of lines to serve as parents in the next breeding cycle, shortening cycle time [165]. In addition, genomic selection can be used to "predict" performance, replacing preliminary testing, as a means to advance progeny with greater genetic promise to advanced testing stages [165,166]. Furthermore, it can offer higher predictive ability when associated with modelling G×E interaction [167]. Estimated gain from genomic selection can be as much as 5-fold that of conventional breeding [168-170]. Although uptake of genomics-assisted breeding in Burkina Faso has been extremely low, as in many developing countries [68], due to the lack of human and infrastructure resources [69], nevertheless, opportunity for breeding programmes to embrace genomics-assisted breeding exists, using, where applicable, data available in partner institutions like ICRISAT where historical data on the performance of about 340 advanced breeding lines have been compiled [69].

8.3 *Modern approaches, technologies, and tools to support commercialization and release of improved cultivars*

Modern approaches and technologies are available to support production of volumes of quality seed for distribution of new improved groundnut cultivars to farmers. DNA-fingerprinting technologies ensure seed authenticity and purity [171]. Seed quality can be preserved using seed storage technologies, along with monitoring of relative humidity and seed moisture content with electronic meters or indicator papers [172]. Preserving seed quality is crucial for both the cultivar development process and the conservation of germplasm.

Data management tools that track materials through the entire breeding process facilitate traceability and document pedigree information. For example, the Breeding Management System (BMS; *https://www.integratedbreeding.net/breeding-management-system*) provides a comprehensive suite of mutually compatible software applications that work together to help breeders manage germplasm and collect, store and analyse their research data [173]. The BMS manages breeding data across all phases of the crop improvement cycle, keeping a safe, standardized and centralized record of data from one generation to the next in order to facilitate more economical and accelerated cultivar development. Such a system is not only crucial and foundational to breeding teams in their quest for selection accuracy, it supports breeding operations, resource allocation, and data analyses [174], and provides support services at every step of the breeding process, all the way through to cultivar release. Such tools are essential to integrate and support all aspects of the breeding pipeline, and to integrating efforts across team members.

A number of analytical and decision support tools for genomics-assisted breeding are freely available [175]. For example, CIMMYT offers several software packages to facilitate various specialized analyses (see. *https://data.cimmyt.org/dataverse/cimmytswdvn*). And other resources are available in the scientific literature to facilitate bioinformatics aspects of managing DNA-sequence data (e.g. GAPIT; Genome Association and Prediction Integrated Tool [176]). Use of publically-available tools such as these satisfies needs while avoiding license fees.

9. Research challenges in Burkina Faso

The implementation of a modern breeding programme requires expertise, infrastructure, equipment, all of which requires a higher level of investment. To assess the benefit and ultimate value of implementing a new approach, technology, or tool, a cost-benefit analysis can be performed to provide justification for the additional expenditures. Furthermore, with or without further investment, other factors can go a long way to build in greater efficiencies in cultivar development: outsourcing some activities requiring special equipment or expertise (e.g. genotyping), establishing research networks to better leverage available resources and data, and forging partnerships with the private sector.

The lack of sustained funding and over-dependency on donors [63] restrains possibilities to implement long term view and renders the programme vulnerable to funding inconsistencies and abrupt changes in research agenda and vision. Therefore, efforts must be put into igniting government commitment to research for food and nutritional security in the country. Policy makers and those in the groundnut value chain must be made aware of possibilities and challenges if groundnut production is to impact national nutrition and trade and draw support from the private sector.

Ultimately, private sector intervention is probably the way forward to dependably invest substantial funding in the crop breeding and bring better governance in the breeding programme. The groundnut industry could be inspired by successful examples of private agricultural research in Burkina Faso and elsewhere, driven by cash crops such as cotton, banana and oil palm [63,177,178].

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10. Conclusion

Groundnut production and genetic improvement in Burkina Faso has stagnated for too long. In the absence of a strong national program, research in the country has centred on evaluations of lines developed at international research institutes and programmes, such as IRHO, ICRISAT and Peanut CRSP. However, lines from international institutions may have limited alignment with domestic product targets and fail to deliver adaptation under local conditions required for high yield. For best adaptability of cultivars to local conditions and national stakeholder needs, a strong national breeding programme built on the foundation of local germplasm collection must be the driver.

Most of the issues discussed in this review are applicable to many other national agricultural research programmes in sub Saharan or West Africa. Scientific strength of breeding programmes requires expertise in plant breeding and genetics (i.e. at least two full-time PhD scientists per crop species [54]) ,as well as support in related disciplines important for groundnut improvement, viz. entomology, agronomy, weed science, pathology [54,68]. We contend that it is possible to significantly increase groundnut production and productivity through dedication of a strong local breeding programme, which takes advantage of improved lines from international research institutions and modern breeding approaches, technologies, and tools to develop locally adapted high-yielding varieties with desirable traits. To this extent, strategies to accelerate genetic gain need to be adopted, along with gender integration in the entire crop development and value chain. Building technical and infrastructure capacities of the national breeding programme, is needed to achieve such a research level, and to expedite delivery of improved groundnut varieties to both modern and smallholder farmers.

Authors' Contributions

M.K. wrote the first draft and incorporated the inputs from the co-authors and comments of editors. J.S., A.M., D.K.O., H.D., P.J. and R.H.M. reviewed the first draft and made inputs to improve the manuscript. All authors read and commented on the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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