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Meta-analysis of legumes and groundnut production trends and variability in the Global South

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ABSTRACT

This study examined the production trends and variability of grain legumes in the Global South from 2000 to 2022, with a particular emphasis on groundnut yields and regional differences. From 2000 to 2022, global legume production in the Southern Hemisphere increased by approximately 20–30 %, driven by rising demand for plant-based proteins and expanded cropping areas in countries like Brazil and Argentina. Improved agricultural practices have further enhanced yields. In contrast, groundnut production experienced a more moderate growth of around 10–15 %, influenced by favourable conditions and expanded cultivation in regions such as Argentina and South Africa. While demand for groundnuts remains strong, market fluctuations and competition with other crops continue to shape its production dynamics. The analysis covered a range of legumes, including common beans (*Phaseolus vulgaris*), cowpeas (*Vigna unguiculata*), pigeon peas (*Cajanus cajan*), groundnuts/peanuts (*Arachis hypogaea*), soya beans (*Glycine max),* bambara groundnuts (*Vigna subterranea*), chickpeas (*Cicer arietinum*), lentils (*Lens culinaris*), mung beans (*Vigna radiata*), black gram (*Vigna mungo*), faba beans (*Vicia faba*), lablab beans (*Lablab purpureus*), tepary beans (*Phaseolus acutifolius*), African yam beans (*Sphenostylis stenocarpa*), Kersting's groundnut (*Macrotyloma geocarpum*), lima beans (*Phaseolus lunatus*), black beans (*Phaseolus vulgaris*), adzuki beans (*Vigna angularis*), moth beans (*Vigna aconitifolia*), horse gram (*Macrotyloma uniflorum*), broad beans (*Vicia faba*), winged beans (*Psophocarpus tetragonolobus*). Regional data revealed significant differences in legume production. In Sub-Saharan Africa, cowpeas and groundnuts are vital, with cowpeas grown over 11.4 million hectares on average yielding 450 kg ha^{-1}, and groundnuts covering 9.1 million hectares with an average yield of 1007 kg ha^{-1}. Chickpeas and pigeon peas dominate South Asia's production, whereas Latin America features prominent soya bean and groundnut cultivation. Oceania's legume farming is less extensive, focusing on chickpeas and mung beans. Descriptive statistics revealed that Egypt led in groundnut production with an average yield of 3279.1 kg ha^{-1} and a low coefficient of variation (CV) of 4.89 %, indicating stable production. Conversely, Mozambique had the lowest average yield at 322.9 kg ha^{-1}, with a high CV of 30.23 %, reflecting greater variability. The Principal Component Analysis (PCA) identified five principal components explaining 70.9 % of the total variance, with the first two components (PC 1 and PC 2) accounting for 51 %. Bangladesh and Brazil were major contributors to PC 1, while Algeria and Senegal influenced PC 2. These findings highlight the considerable regional variability in yields and stability in legume production. Future research should address these disparities and enhance resilience through targeted agricultural practices and policy interventions.

1. Introduction

The term "Global South" broadly refers to regions and countries that are considered to be less economically developed, often characterized by lower income levels, greater economic inequality, and historical colonial ties [1,2]. This classification encompasses a diverse group of countries that share common developmental challenges (i.e., socio-economic and politics), rather than a strictly geographical location

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[3].

In Africa, almost all countries are considered part of the Global South [4]. This includes both Sub-Saharan Africa and parts of North Africa, where economic development levels vary but generally align with the characteristics of the Global South [1]. Latin America and the Caribbean, include all countries in South America, Central America, and the Caribbean [2]. In Asia, these include South Asia, Southeast Asia, and parts of East Asia. Countries like India, Pakistan, Bangladesh, Indonesia, Vietnam, and the Philippines form part of the Global South [5]. However, highly developed regions in East Asia, such as Japan and South Korea, are usually excluded from this classification. Oceania also has countries that are part of the Global South, primarily the island nations in the Pacific, such as Fiji, Papua New Guinea, the Solomon Islands, and other Pacific Islands [6]. In contrast, Australia and New Zealand, which are highly developed, are typically excluded from the Global South [7]. The Middle East includes many countries considered part of the Global South, especially those outside the high-income Gulf States [8].

While the global population was estimated to be approximately 8 billion in 2023 and is projected to reach around 9.7 billion by 2050 [9], the Global South is experiencing even more pronounced growth. The Global South is home to about 6.5 billion people, representing approximately 81 % of the world's population [10]. By 2050, the population in the Global South is expected to grow substantially. For instance, Sub-Saharan Africa is projected to double its population from around 1.35 billion to approximately 2.7 billion [11,12]. Similarly, Asia's population is anticipated to rise from about 4.7 billion to around 5.2 billion [13,14]. Latin America and the Caribbean populations are expected to increase from approximately 650 million to about 850 million [15], while Oceania's population is projected to grow from 44 million to 60 million [16,17].

The rapid demographic expansion in the Global South highlights the urgent need for increased food production to address nutritional needs and combat malnutrition, directly aligning with the Sustainable Development Goal (SDG) 2: Zero Hunger [18]. As the population grows, particularly in areas already facing food security challenges, there will be a higher demand for sustainable agricultural practices. This links to SDG 12: Responsible Consumption and Production, which emphasizes the need for sustainable food systems and practices [19]. The impacts of climate change further complicate this situation by affecting crop yields and food availability, connecting to SDG 13: Climate Action [20–22]. In this context, guided agriculture practices that prioritize environmental sustainability become essential. Grain legumes, in particular, offer a promising solution for climate adaptation and resilience, supporting SDG 15: Life on Land, which focuses on managing land sustainably and combating land degradation [23]. Legumes can fix atmospheric nitrogen in the soil, improving soil fertility and reducing the need for synthetic fertilizers. This supports more sustainable farming practices and enhances crop yields and nutritional quality, addressing SDG 3: Good Health and Well-being by improving dietary quality and reducing malnutrition. The integration of legumes into agricultural systems, not only helps meet the food security needs but also contributes to mitigating the environmental impact of conventional farming, thereby advancing multiple SDGs simultaneously.

To ensure food and nutritional security for the growing population, food production must increase by 50 % by mid-century [24–26]. This goal is complicated by challenges such as land degradation, water scarcity, and climate change, which disrupt efforts to achieve food security [27]. Grain legumes present an important array of food for the human population throughout the world, with diverse species grown in the Global South [28]. In Africa, smallholder farmers cultivate a wide range of grain legumes that are vital for food security and agricultural sustainability. Among the most commonly grown are common beans (*Phaseolus vulgaris*), which are a staple in many African diets. Cowpeas (*Vigna unguiculata*) and pigeon peas (*Cajanus cajan*) are also widely grown, particularly in semi-arid regions due to their drought tolerance. Groundnuts/peanuts (*Arachis hypogaea*) are a crucial source of protein and oil. Soya beans (*Glycine max*) are increasingly cultivated for both local consumption and export. Other important legumes include bambara groundnuts (*Vigna subterranea*), chickpeas (*Cicer arietinum*), lentils (*Lens culinaris*), mung beans (*Vigna radiata*), and black gram (*Vigna mungo*). Additionally, African farmers grow faba beans (*Vicia faba*), lablab beans (*Lablab purpureus*), tepary beans (*Phaseolus acutifolius*), African yam beans (*Sphenostylis stenocarpa*), and Kersting's groundnut (*Macrotyloma geocarpum*), each adapted to specific agro-ecological niches.

In Latin America and the Caribbean, smallholder farmers are known for their cultivation of common beans, a crop deeply rooted in the region's culture and cuisine [28]. Soya beans are also extensively grown, particularly in countries like Brazil and Argentina, for both domestic use and international markets. Lentils and chickpeas are less common but still important in certain areas. Cowpeas and pigeon peas are grown primarily in the Caribbean and parts of Central America. Groundnuts are another significant crop, used both for direct consumption and as an ingredient in various traditional dishes. Additionally, farmers in the region grow lima beans, black beans, mung beans, faba beans, and lablab beans.

In Asia, smallholder farmers cultivate a diverse array of grain legumes that are integral to the region's agriculture and diet [28]. Soya beans are widely grown across East and Southeast Asia, while mung beans and black gram are staple pulses in South Asia. Chickpeas and lentils are particularly important in India and neighbouring countries, forming the basis of many traditional dishes. Pigeon peas are another crucial legume in South Asia, especially in India and Myanmar. Common beans and groundnuts/peanuts are also significant crops across the continent. Other important legumes include adzuki beans, moth beans (*Vigna aconitifolia*), horse gram (*Macrotyloma uniflorum*), faba beans, broad beans (*Vicia faba*), lablab beans, tepary beans (*Phaseolus acutifolius*), each adapted to various climatic and soil conditions across the region.

In Oceania, including the Pacific Islands and Fiji, smallholder farmers grow several key grain legumes. Common beans are widely cultivated, as are cowpeas and pigeon peas, which are well-suited to the region's tropical and subtropical climates. Mung beans and Ground nuts are also significant crops in Oceania, providing essential sources of protein and income. Soya beans are grown on a smaller scale compared to other regions but are still important in certain areas. Additionally, winged beans (*Psophocarpus tetragonolobus*), faba beans, lablab beans, adzuki beans (*Vigna angularis*), and lentils are cultivated, reflecting the region's diverse agricultural practices and the adaptability of these legumes to different environments.

In the Middle East, grain legumes are a critical component of agricultural systems, with chickpeas and lentils being among the most commonly grown [28]. These legumes are staples in Middle Eastern diets and have been cultivated in the region for millennia. Faba beans are another important crop, especially in countries like Egypt. Mung beans and Soya beans are grown on a smaller scale. Ground nuts, pigeon peas and common beans are cultivated in some parts of the Middle East. Broad beans and lablab beans round up the list, with each legume contributing to the region's rich agricultural heritage and food security.

The significance of grain legumes in addressing food security and sustainable agricultural practices has been a focal point in agrarian research over the past two decades. The works of Smith and Breen [29,30] have emphasized the pivotal role of legumes in enhancing soil fertility and reducing dependency on synthetic fertilizers, thereby promoting environmentally sustainable farming. This meta-analysis aims to build upon these insights by synthesizing existing literature on grain legumes' production trends and variability in the Global South, particularly focusing on groundnut yields. The importance of legumes extends beyond mere crop production; they are integral to the socio-economic fabric of many communities, serving as vital sources of protein and income for smallholder farmers. Breen et al. [30] pointed out that in regions like Sub-Saharan Africa and South Asia, the cultivation of legumes not only supports food security but also contributes significantly to local economies. By examining historical data and regional differences, this study aims to understand how various agronomic practices and climate factors influence legume yields, thereby addressing gaps in previous research.

In the context of the Global South, the interrelationship between population growth, climate change, and agricultural production becomes increasingly critical. Muhie [31] emphasizes the urgent need for sustainable agricultural practices to meet the nutritional demands of a rapidly growing population. This demographic pressure is particularly acute in regions like Sub-Saharan Africa and South Asia, where food insecurity remains a pressing challenge. Groundnut production, for instance, has seen moderate growth despite rising demand, as highlighted by studies like those of Das et al. [32], which illustrate the challenges posed by market fluctuations and climatic variability. Moreover, understanding the variability in legume yields across different regions can offer valuable insights into potential adaptations and innovations that may enhance resilience in agricultural systems. Therefore, this meta-analysis not only aims to synthesize existing knowledge but also seeks to inform policy-making and agricultural strategies, fostering a deeper understanding of the complexities surrounding legume production in the Global South.

2. Methodology of the study

2.1. Literature and data acquisition

A systematic search was conducted following PRISMA guidelines [33]. This search encompassed multiple electronic databases including Web of Science, Scopus, PubMed, and Agricola, as well as gray literature, institutional repositories, and reports from relevant organizations to ensure comprehensive coverage of pertinent studies. The search strategy utilized a combination of keywords and phrases such as "climate change," "grain legumes," "adaptation strategies," "genetics grain legumes," "agronomy grain legumes," and "resilience," along with specific legume species names. For instance, a Scopus search filter was applied with the terms TITLE-ABS-KEY (impact AND climate AND change AND on AND agriculture AND grain AND legumes AND Global AND South) AND PUBYEAR >2000 AND PUBYEAR ≤2024. This approach aimed to capture studies relevant to the adaptation and resilience of grain legumes in response to climate stress.

Eligibility criteria for inclusion required studies to be published between 2000 and 2024, focusing on agronomic and genetic adaptation strategies for grain legumes. Eligible studies had to provide quantitative data on grain yield, temperature rise, precipitation decrease, and yield loss under climate stress conditions. Additionally, yield data for grain legumes was obtained from FAOSTAT [28] via their website (https://www.fao.org/faostat/en/#home). The data retrieval process involved selecting "Production Domains (Crop and Livestock Products)," filtering by "Country," applying filters for "Yield," choosing "Items (Crops, Primary)," and setting the time range to "Years (2000–2022)."

The meta-analysis employed statistical methods to integrate data and assess the effectiveness of adaptation strategies. Random-effect models were utilized to address variability across studies. Additionally, subgroup analyses were conducted to examine how specific adaptation strategies affected different legume species and regions (See Eq. (1) and Eq. (2)).

$$\text{Effective size}_{\text{Monoculture}} = \text{Potential yield}_{\text{Monoculture}} - \text{Current yield} \tag{1}$$

$$\text{Effective size}_{\text{Intercropping}} = \text{Potential yield}_{\text{Intercropping}} - \text{Current yield} \tag{2}$$

2.2. Statistical data analysis

All statistical analyses were performed using PAST.4.03.exe and Orange3-3.37.0-Miniconda-x86_64.exe software. The study employed a rigorous statistical approach to analyze legume production data, focusing on trends, variability, and influential factors across the Global South from 2000 to 2022. The dataset, sourced from FAOSTAT, included production metrics for 17 types of legumes across 54 countries, with a focus on groundnuts, reported by 47 countries and comprising 87 % of the data.

To evaluate heterogeneity within the dataset, the study utilized the I^2 statistic and Cochran's Q test. The I^2 statistic was used to quantify the percentage of total variation across studies that were due to heterogeneity rather than chance (Eq. (3)). The Cochran's Q statistic was used to assess the extent of heterogeneity by summing the weighted squared deviations of each study's effect size from the overall effect size (Eq. (4)).

$$I^2 = \frac{Q-(k-1)}{Q} \times 100 \tag{3}$$

Where, Q is the Cochran's Q statistic, which measures the total variation in effect sizes across studies; k is the number of studies included in the meta-analysis.

$$Q = \sum_{i=1}^{k} \frac{(E_i - \widehat{E})^2}{Var(E_i)} \tag{4}$$

Where, E_i is the effect size for study i; $\hat{E}$ is the overall effect size (or pooled effect size); $\text{Var}(E_i)$ is the variance of the effect size for study i. The degree of freedom for the Q statistic is $k-1$, and k is the number of studies. If Q is less than $k-1$, then I^2 is set to 0 %, indicating no observed heterogeneity.

For the analysis of groundnut production data, various descriptive statistics were computed, including the minimum, maximum, sum, arithmetic mean, standard deviation, and coefficient of variation. Principal Component Analysis (PCA) was then performed to manage the complexity of the data. PCA was instrumental in reducing the dataset to principal components (PCs) that are uncorrelated and ordered by their significance. This approach allowed for the extraction of key components that encapsulate the majority of the variation in groundnut production data. To visualize the results, two-dimensional scatter plots were created using the first two principal components. These components were selected because they collectively accounted for the majority of the variance in the groundnut production data, offering a clear representation of the underlying patterns and trends in the dataset. This visualization was important for revealing patterns and relationships within the data, enabling a clearer understanding of how production levels varied across different countries and years.

3. Results

3.1. Regional contributions to grain legume production

The distribution of grain legumes in the global south presents high variation [28]. The types of grain legumes commonly produced in the Global South are presented in Fig. 1. The data provides a broader perspective on global agricultural patterns for the period 2010–2022. In the Global South, the production trends of grain legumes reveal significant regional variations that highlight their importance in different agricultural systems.

In Sub-Saharan Africa, cowpeas and groundnuts are particularly vital. Cowpea, grown over 11.4 million hectares with a yield of 450 kg ha^{-1}, accounts for 84 % of the world's cowpea production in the region. Groundnut cultivation spans 9.1 million hectares with a yield of 1007 kg ha^{-1}, producing 8.9 million metric tons and representing 40 % of global production. These figures show the important role of these legumes in the region's agriculture and food security. In contrast, soybean and lentil production is minimal in Sub-Saharan Africa, with Soya beans contributing only 1.3 % and lentils 2 % to world production from the region.

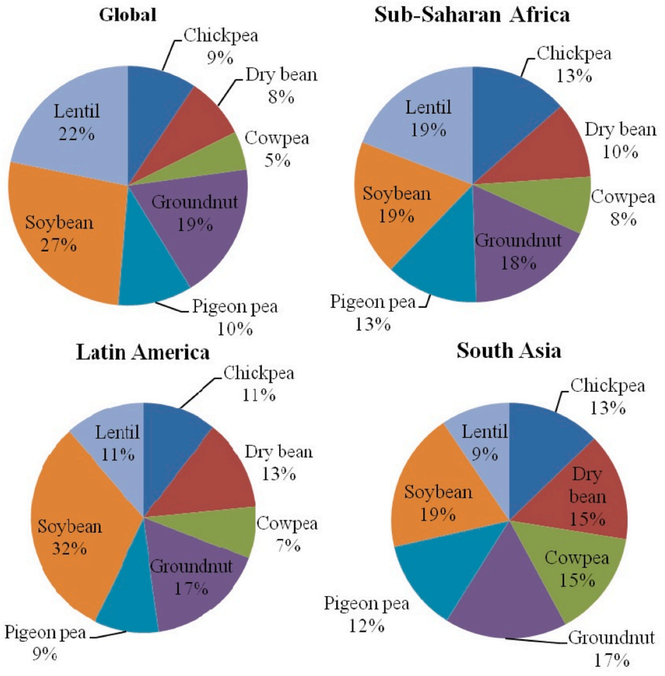

Fig. 1. Regional contributions to grain legume production in the Global South.

In South Asia, chickpeas and pigeon peas dominate. Chickpeas, cultivated on 8.3 million hectares with a yield of 855 kg ha^{-1}, produce 6.8 million metric tons, accounting for 76 % of global production in the region. Pigeon peas, grown over 4.1 million hectares with a yield of 840 kg ha^{-1}, result in 3.1 million metric tons, representing 88 % of world production in South Asia. Groundnuts and dry beans also show significant production, with groundnuts contributing 31 % and dry beans 30 % of global production in the region. However, cowpeas and soya beans have a relatively minor presence, with cowpeas contributing only 3 % and soya beans 9.2 % to global production.

In Latin America, the data presents a diverse picture. Groundnut is a major crop with 2.5 million hectares cultivated and a yield of 1330 kg ha^{-1}, resulting in 3.3 million metric tons of production. This highlights its importance in the region, particularly in countries like Argentina and Brazil. Soybean cultivation is also significant, with 49.8 million hectares and a yield of 2355 kg ha^{-1}, leading to 117.8 million metric tons of production. This underscores Latin America's crucial role in global soybean production, especially in Brazil and Argentina, which are major exporters. Other legumes, such as chickpeas and dry beans, have more modest production figures, reflecting varying agricultural priorities and climatic conditions in the region.

In Oceania, legume cultivation is less extensive compared to other regions. For instance, chickpea cultivation spans around 0.1 million hectares with a yield of 900 kg ha^{-1}, resulting in a modest production of 90,000 metric tons. Dry beans and groundnuts have even smaller production scales in Oceania, reflecting the region's lower emphasis on these crops. The focus in Oceania often shifts towards other crops and livestock, making legume production a smaller part of the overall agricultural landscape.

3.1.1. *Potential contributions to quantity production in the global south*

The results on the substantial potential for increasing grain legume yields are presented in Table 2. In Latin America, the data reveal considerable opportunities for enhancing productivity. For example, in Brazil, soya beans could see an increase from 3.2 t ha^{-1} to a potential yield of 5 t ha^{-1} under monoculture and 4.2 t ha^{-1} under intercropping. Similarly, common beans in Brazil have the potential to rise from 1.2 t ha^{-1} to 2.5 t ha^{-1} under monoculture and 2 t ha^{-1} under intercropping. This potential for yield improvement suggests that optimizing intercropping could significantly benefit food security and economic stability in the region. In Argentina, groundnuts and chickpeas also show potential for yield increases, which could further bolster food production. Mexico's black beans and lentils present similar potential for higher yields, highlighting the opportunity to enhance productivity and support local farmers.

In Africa, as detailed in Table 1, there is notable potential for increasing legume yields. For instance, in Nigeria, cowpeas could increase from 0.7 t ha^{-1} to 1.5 t ha^{-1} under monoculture, while groundnuts in Kenya could rise from 1 t ha^{-1} to 2.5 t ha^{-1}. In Ethiopia, chickpeas and faba beans show considerable potential for yield increases, which could improve food security and resilience. Similarly, in Tanzania, common beans and groundnuts have the potential for higher yields, indicating that better agricultural practices could have a significant impact on productivity and farmer incomes in these regions.

In Asia, Table 1 highlights clear benefits from potential yield improvements. Chickpeas in India, for example, could see an increase from 1 t ha^{-1} to 2.8 t ha^{-1} under monoculture. Soya beans in China could rise from 1.8 t ha^{-1} to 3.5 t ha^{-1}. These potential yield improvements are crucial for addressing food security challenges and supporting economic growth. Additionally, lentils and mung beans in Bangladesh and Vietnam demonstrate the potential for higher yields, further underscoring the importance of optimizing agricultural practices in the region.

In Oceania, Table 1 shows the potential for increased legume yields. In Fiji, cowpeas could increase from 0.8 t ha^{-1} to 2 t ha^{-1} under monoculture, and Soya beans in Papua New Guinea could rise from 1.2 t ha^{-1} to 3 t ha^{-1}. These improvements suggest that enhancing agricultural practices could significantly benefit food security and resilience in Oceania. Mung beans and winged beans also show potential for higher yields, indicating that targeted interventions could effectively improve productivity in this region.

3.1.2. *Heterogeneity results*

The heterogeneity results for legume yields, as presented in Table 2, indicate varying levels of consistency across different legume species and cropping systems. For soya beans, the effect size estimate under monoculture is 1.5 t ha^{-1} with a moderate heterogeneity ($I^2 = 55$ %; $p = 0.1$). This suggests that while there is variability in yield improvement, it is not highly significant. In contrast, the effect size estimate for soya beans under intercropping is slightly lower at 1.2 t ha^{-1} with a higher degree of heterogeneity ($I^2 = 60$ %; $p = 0.07$), indicating a moderate variability in yield improvement.

For common beans, the effect size under monoculture is 1.3 t ha^{-1} with significant heterogeneity ($I^2 = 70$ %; $p = 0.03$). This shows notable variability in yield improvements among studies. Similarly, under intercropping, the effect size is 1.1 t ha^{-1} with significant heterogeneity ($I^2 = 65$ %; $p = 0.05$), indicating variability in yield improvements. Ground nuts and chickpeas exhibit moderate heterogeneity in both monoculture and intercropping systems, with effect sizes ranging from 1.4 t ha^{-1} to 1.5 t ha^{-1}. This moderate variability in yield improvement suggests that while potential benefits are evident, there is some inconsistency across different studies. The results for black beans and lentils show moderate heterogeneity with effect sizes ranging from 1.2 t ha^{-1} to 1.6 t ha^{-1}. This variability highlights the need for region-specific adaptations to fully realize the potential yield improvements.

3.1.3. *Regional reflection in legume heterogeneity*

The regional breakdown of heterogeneity results for grain yields, as outlined in Table 3, provides insights into the variability of yield improvements across different regions. In Latin America, Soya beans under monoculture have an effect size estimate of 1.8 t ha^{-1} with moderate heterogeneity ($I^2 = 60$ %; $p = 0.08$), indicating variability in yield improvements. Under intercropping, the effect size is 1.5 t ha^{-1} with a similar level of heterogeneity ($I^2 = 62$ %; $p = 0.07$). Common beans in Latin America show significant heterogeneity, with effect sizes of 1.4 t

Table 1
Grain yields by regions and legume species.

Region	Country	Legume	Grain yield (t ha^{-1})		
			Current	Potential monoculture	Potential intercropping
Latin America	Brazil	Soya beans	3.2	5	4.2
		Common beans	1.2	2.5	2
	Argentina	Ground nuts	2	3.5	3
		Chickpeas	1.1	2.5	2
	Mexico	Black beans	1	2.2	1.8
		Lentils	0.8	2	1.6
	Colombia	Common beans	1.1	2.4	2
		Cowpeas	0.9	2	1.7
Africa	Nigeria	Cowpeas	0.7	1.5	1.2
		Groundnuts	1	2.5	2.1
	Kenya	Pigeon peas	0.9	2.2	1.8
		Common beans	1.3	3	2.5
	Ethiopia	Chickpeas	1.2	2.8	2.3
		Faba beans	1.4	3.5	2.9
	Tanzania	Common beans	1	2.5	2
		Groundnuts	1.2	2.8	2.3
	South Africa	Soya beans	2.2	4	3.5
Asia	India	Chickpeas	1	2.8	2.3
		Pigeon peas	0.8	2.5	2
	China	Soya beans	1.8	3.5	3
		Adzuki beans	1	2.2	1.8
	Bangladesh	Lentils	1	2.5	2
		Mung beans	0.7	1.8	1.5
	Vietnam	Black gram	1.2	2.8	2.3
		Soya beans	1.5	3	2.5
Oceania	Fiji	Cowpeas	0.8	2	1.6
		Pigeon peas	0.7	2.2	1.8
	Papua New Guinea	Soya beans	1.2	3	2.5
		Winged beans	0.9	2.5	2
	Solomon Islands	Mung beans	0.7	1.8	1.4
		Cowpeas	0.6	1.7	1.3

Table 2
Heterogeneity results for grain yields of legume species under monoculture and intercropping systems.

Species	Cropping system	Effect size estimate (t ha^{-1})	I^2 Statistic (%)	Q-Test p-value
Soya beans	Monoculture	1.5	55	0.1
	Intercropping	1.2	60	0.07
Common beans	Monoculture	1.3	70	0.03
	Intercropping	1.1	65	0.05
Ground nuts	Monoculture	1.5	50	0.15
	Intercropping	1.4	55	0.12
Chickpeas	Monoculture	1.4	60	0.08
	Intercropping	1.2	62	0.06
Black beans	Monoculture	1.6	58	0.09
	Intercropping	1.3	63	0.07
Lentils	Monoculture	1.3	57	0.11
	Intercropping	1.2	60	0.09
Cowpeas	Monoculture	1.4	62	0.07
	Intercropping	1.1	64	0.05
Faba beans	Monoculture	1.5	59	0.09
	Intercropping	1.3	60	0.08
Winged beans	Monoculture	1.2	54	0.14
	Intercropping	1.1	56	0.13
Mung beans	Monoculture	1.1	53	0.16
	Intercropping	1	55	0.15

ha^{-1} under monoculture ($I^2 = 65$ %; $p = 0.04$) and 1.2 t ha^{-1} under intercropping ($I^2 = 67$ %, $p = 0.03$). This significant variability shows the importance of tailored interventions to optimize yield improvements.

In Africa, the effect size for cowpeas under monoculture is 1.2 t ha^{-1} with moderate heterogeneity ($I^2 = 62$ %; $p = 0.06$). Under intercropping, the effect size is 1.1 t ha^{-1} with significant heterogeneity ($I^2 = 64$ %; $p = 0.05$). Groundnuts and pigeon peas also show moderate to significant heterogeneity, indicating variability in yield improvements across different studies. In Asia, chickpeas exhibit moderate heterogeneity with an effect size of 1.4 t ha^{-1} under monoculture ($I^2 = 60$ %; $p = 0.08$) and 1.3 t ha^{-1} under intercropping ($I^2 = 62$ %; $p = 0.07$). Soya beans in Asia show similar patterns with effect sizes of 1.6 t ha^{-1} under monoculture and 1.4 t ha^{-1} under intercropping, both with moderate heterogeneity. In Oceania, cowpeas and Soya beans show moderate heterogeneity in yield improvements, with effect sizes of 1.1 t ha^{-1} to 1.3 t ha^{-1}. This variability highlights the need for region-specific strategies to effectively enhance yield potential.

3.1.4. Advancements in genetic improvements of grain legumes for enhanced climate resilience

Efforts to enhance the climate resilience of grain legumes have focused on developing varieties that can withstand drought, heat, and diseases, particularly in the Global South (e.g., Refs. [26,34–36]. These genetic improvements aim to stabilize crop yields and ensure productivity under changing climatic conditions (See Table 4).

Common beans have seen significant advancements in climate adaptation. In Brazil, the drought-resistant variety ‘DAB 295’ has been developed to maintain yield stability during dry spells [29]. India has introduced heat-tolerant varieties of chickpeas, groundnut, and pigeon peas specifically bred to enhance pod setting and grain filling under high-temperature conditions [37,38]. For chickpeas, varieties such as JG 11 and JAKI 9218 have been developed to improve yield and resilience against heat stress. In groundnut, varieties like ICGV-00350 and R2001-02 have been bred for their adaptability to elevated temperatures while maintaining high yields. Pigeon pea varieties, including Asha and LRG-41, have similarly been introduced to thrive in warmer climates, improving both yield and resistance to environmental stresses. In Kenya, disease-resistant common bean varieties such as KMR 11 (Angaza), Kat X56, UN6-Nakholo, UN2-Darkgreen, Enclave, Manakelly, and MU#13 have been developed to combat rust and anthracnose [39–42]. Soy beans have been genetically improved to enhance climate resilience. Argentina in Pampas region has selected heat-tolerant soybean varieties based on genetically modified (GM) soybeans that maintain stable yields

Table 3
Regional breakdown of heterogeneity in grain yield for different legume types.

Region	Species	Cropping system	Effect size estimate (t ha^{-1})	I^2 Statistic (%)	Q-Test p-value
Latin America	Soya beans	Monoculture	1.8	60	0.08
		Intercropping	1.5	62	0.07
	Common beans	Monoculture	1.4	65	0.04
		Intercropping	1.2	67	0.03
	Ground nuts	Monoculture	1.5	55	0.12
		Intercropping	1.4	57	0.1
	Chickpeas	Monoculture	1.6	58	0.11
		Intercropping	1.3	60	0.09
Africa	Cowpeas	Monoculture	1.2	62	0.06
		Intercropping	1.1	64	0.05
	Groundnuts	Monoculture	1.3	58	0.09
		Intercropping	1.2	60	0.08
	Pigeon peas	Monoculture	1.4	57	0.1
		Intercropping	1.2	59	0.09
	Common beans	Monoculture	1.3	65	0.04
		Intercropping	1.1	67	0.03
Asia	Chickpeas	Monoculture	1.4	60	0.08
		Intercropping	1.3	62	0.07
	Soya beans	Monoculture	1.6	57	0.09
		Intercropping	1.4	59	0.08
	Lentils	Monoculture	1.2	55	0.11
		Intercropping	1.1	57	0.1
Oceania	Cowpeas	Monoculture	1.1	50	0.14
		Intercropping	1.0	52	0.13
	Soya beans	Monoculture	1.3	55	0.12
		Intercropping	1.2	57	0.11
	Mung beans	Monoculture	1.1	52	0.13
		Intercropping	1.0	54	0.12

in high temperatures [43]. In Brazil, two cultivars (Embrapa 48 – early-maturing and BRS 134 – medium-maturity group) with enhanced nitrogen fixation have been developed to reduce fertilizer reliance, promoting more sustainable farming practices ([44–47].

Chickpeas have also benefited from targeted breeding. In India, the short-duration variety 'ICC 4958' helps chickpeas avoid terminal drought conditions. Pakistan has developed heat-tolerant varieties such as 'BG 256', 'JG 412', and 'JG 218' that improve yields in hot regions. Myanmar has introduced drought-tolerant cowpeas like 'Yezin 6' to sustain yields during dry spells ([48–51]. Pigeon peas have been enhanced through focused breeding efforts. In Kenya, early-maturing varieties like 'MZ 2/9' and 'KAT 60/8' reduce water needs and improve drought escape. In India, breeding has produced varieties resistant to the sterility mosaic virus (SMV), reducing yield loss from viral infections. Thailand has developed heat-tolerant pigeon pea varieties that enhance yield performance under high temperatures ([37,52,53].

Cowpeas have been adapted for better climate resilience. In Brazil, the cowpea variety 'BRS Tumucumaque' is bred for improved drought resistance. Thailand's heat-tolerant cowpea varieties support flowering and pod filling under high temperatures. Additionally, Ethiopia has focused on breeding for efficient phosphorus use to enhance cowpea growth in low-phosphorus soils ([54–56]. Lentils have been improved to handle various climate stresses. Nepal's drought-tolerant variety 'ILL 6002' provides yield stability in water-limited environments. Pakistan has developed heat-tolerant varieties like AEL 23/40, which improve seed set during high temperatures. In Syria, disease-resistant lentils such as ILWL 79, ILWL 113, and ILWL 138 combat diseases like *Ascochyta* blight, contributing to more stable production [57–61].

Groundnuts have also seen genetic improvements for climate resilience. In Brazil, drought-tolerant varieties such as 'BR1' increase water use efficiency and yield under dry conditions. Thailand's heat-tolerant groundnut lines ensure stable pod development and kernel filling despite high temperatures. In India, varieties like GPBD 4 and ICGV86699 resistant to early and late leaf spots help reduce the need for chemical controls and enhance crop health [62–64]. Mung beans have been adapted through strategic breeding to manage climate stresses. In Myanmar, early-maturing varieties like Yezin 9 and Yezin 11 help avoid late-season drought stress. Thailand has developed high-temperature tolerant varieties that improve flowering and yield under hot climates. The Philippines has enhanced phosphorus uptake efficiency in mung beans to improve performance in phosphorus-deficient soils [65–70]. Faba beans have also been bred for climate resilience. In Morocco, drought-resistant varieties like 'REINA BLANCA' enhance yields under low rainfall conditions. In Egypt, breeding has produced varieties such as Maris Bead, which are resistant to chocolate spot disease, reducing disease incidence and improving plant health [59–61,71].

Lupins have been adapted for both drought and cold tolerance. In Ethiopia, drought-tolerant lupin varieties like "Gibto" support growth in dry climates. In Kenya, disease-resistant pea varieties help increase yield and reduce the need for fungicides [72]. Bambara nuts possess intrinsic drought tolerance and have been selected for improved yield in arid regions, particularly in Nigeria. In Ghana, enhanced nitrogen fixation in Bambara nuts has increased productivity in poor soils [73–75]. Tepary beans have been adapted for extreme conditions. In Mexico, high heat tolerance in tepary beans ensures productivity in hot environments [76].

Lablab beans have been improved for climate resilience through breeding. In Kenya, drought-resilient varieties like KAT/DL-1, KAT/DL-2, and KAT/DL-3 support production in semi-arid regions. In India, lablab varieties selected for high nitrogen fixation enhance soil fertility and crop yields [77,78]. Black gram has been targeted for climate resilience, with drought-tolerant varieties in India improving yields under limited water availability and heat-tolerant varieties in Sri Lanka boosting productivity during hot growing seasons [79,80]. Adzuki beans have been improved for consistent yields under climate stress. Drought-tolerant varieties in Thailand and disease-resistant varieties in Brazil help reduce crop losses [81].

3.2. *Trends in groundnut production in the region*

Based on data from FAOSTAT (2024) covering 23-year period (2000–2022), 17 types of grain legumes were identified across 54 selected countries in the Global South. These legumes include string beans, soybeans, dry pigeon peas, green peas, dry peas, various pulses

Table 4
Selected grain legumes with genetic improvements made to enhance their adaptation to climate change and resilience. Compiled from various studies.

Legume	Climate stress tolerance	Countries	References
Common Beans	Drought-resistant, heat-tolerant, disease-resistant	Brazil, India, Kenya	[39–42]
Soya beans	Heat-tolerant, enhanced nitrogen fixation	Argentina, Brazil	[45–47]
Chickpeas	Drought-tolerant, heat-tolerant	India, Pakistan	[48–50]
Cowpeas	Drought-tolerant, heat-tolerant, efficient phosphorus use	Myanmar, Brazil, Thailand, Ethiopia	[51,54–56]
Pigeon peas	Early-maturing, drought-resistant, heat-tolerant	Kenya, India, Thailand	[37,52,53]
Lentils	Drought-tolerant, heat-tolerant, disease-resistant	Nepal, Pakistan, Syria	[57–61]
Groundnuts	Drought-tolerant, heat-tolerant, disease-resistant	Brazil, Egypt, Thailand, India	[62–64]
Mung beans	Early-maturing, high-temperature tolerant, efficient phosphorus uptake	Myanmar, Thailand, Philippines	[65–70]
Faba beans	Drought-resistant, disease-resistant	Morocco, Egypt	[59–61, 712]
Lupins	Drought-tolerant, cold-tolerant	Ethiopia	[72]
Bambara nuts	Drought-tolerant, enhanced nitrogen fixation	Nigeria, Ghana	[73–75]
Tepary beans	Heat-tolerant	Mexico	[76]
Lablab beans	Drought-resilient, high nitrogen fixation	Kenya, India	[77,78]
Black gram	Drought-tolerant, heat-tolerant	India, Sri Lanka	[79,80]
Adzuki beans	Drought-tolerant, disease-resistant	Thailand, Brazil	[81]
Adzuki beans	Drought, disease	Thailand, Brazil	Specific references not provided in the original text

not elsewhere classified (n.e.c.), other beans, lupins, locust beans (carobs), dry lentils, groundnuts (unshelled), dry cowpeas, dry chickpeas, dry beans, dry bambara nuts, broad beans & dry horse beans, and broad beans & green horse beans. Groundnuts (unshelled) were found in 47 countries, accounting for 87 % of the data, necessitating a more focused statistical analysis of this legume type.

3.2.1. *Descriptive statistics*

The data on groundnut production from 2000 to 2022 highlights significant differences in productivity and stability across the Global South. Egypt emerges as the top producer with an average yield of 3279.2 kg ha^{-1}. This high mean value indicates Egypt's prominent role in global groundnut production. Furthermore, the low coefficient of variation (CV) of 4.89 % demonstrates exceptional stability in Egypt's production, suggesting that the country maintains consistent output with minimal fluctuations over the years.

In comparison, Brazil ranks as the second-largest groundnut producer, with an average yield of 2872.1 kg ha^{-1}. Although Brazil's production is slightly lower than Egypt's, it remains substantial. However, Brazil's CV of 23.34 % reveals a greater degree of variability in its production. This higher variability indicates that Brazil experiences more fluctuations in groundnut yields compared to Egypt, reflecting less stability in production levels.

At the other end of the spectrum, Mozambique reports the lowest average production of 322.9 kg ha^{-1}. This significantly lower yield underscores Mozambique's position as a minor producer in the global context. Additionally, Mozambique's CV of 30.23 % highlights a high level of variability in its production. This variability might be due to inconsistent agricultural practices or unstable environmental conditions affecting yield stability.

Examining the broader data from Table 5 provides further insights into groundnut production across different countries. Algeria and Morocco, for instance, exhibit relatively high average production values of 1625.2 kg ha^{-1} and 2314.8 kg ha^{-1}, respectively. Despite these high values, both countries experience considerable variability, with CVs of 42.61 % and 15.54 %, respectively. In contrast, Bangladesh and Argentina show high average production levels—1564.3 kg ha^{-1} and 2493.7 kg ha^{-1}—but with lower variability (CVs of 17.06 % and 24.48 %). The production trends for the leading producers, illustrated in Fig. 2, further reflect these dynamics. Egypt's production trend likely shows a stable or steadily increasing pattern, aligning with its low CV and high average yield. Brazil's trend, on the other hand, is likely more erratic, consistent with its higher CV, indicating greater fluctuations in production levels.

These variations in groundnut production across different countries illustrate the diverse challenges and successes in the sector. While Egypt demonstrates both high productivity and stability, Mozambique faces lower productivity and greater variability. Countries like Brazil, Algeria, and Morocco have significant production but experience varying levels of stability. Addressing these disparities is essential for improving agricultural practices and enhancing production stability across the region.

3.2.2. *Analyzing groundnut yield variability across countries in the global south*

Principal Component Analysis (PCA) was conducted to examine the groundnut production data from 47 countries over the period from 2000 to 2022, among 17 identified grain legumes (Fig. 3; Fig. 4). This analysis aimed to uncover the main factors influencing production levels and to understand the variability and stability of groundnut yields across different countries in the Global South.

The PCA identified five principal components (PCs) that together explained 70.9 % of the total variation in groundnut production. PC 1 emerged as the most significant component, accounting for 38.3 % of the variance (Table 6). It was followed by PC 2, which explained 12.7 % of the variance, PC 3 with 8.5 %, PC 4 with 5.9 %, and PC 5 with 5.6 %. These components were further analyzed for their impact, with PC 1 and PC 2 together accounting for 51 % of the total production variability. This highlights their substantial role in influencing production patterns. The eigenvalues and the percentage of variance for each component are detailed in Table 6, while Fig. 5 provides a visual representation through a scree plot, showing how each component contributes to the overall variability.

The PCA results reveal that several countries had notable contributions to the different principal components. For PC 1, countries such as Bangladesh, Brazil, Côte d'Ivoire, the Democratic Republic of Congo (DRC), the Philippines, Sri Lanka, and Viet Nam showed strong loadings, indicating their significant impact on this component. In contrast, Algeria, Bhutan, Burundi, and Senegal were moderately associated with PC 2, with Colombia exerting the strongest influence on this component. The United Republic of Tanzania (URT) and Mali demonstrated strong negative correlations with PC 2, suggesting that the factors represented in PC 2 were more closely linked to the production dynamics in countries like Colombia, Algeria, Bhutan, Burundi, and Senegal.

For PC 3, Pakistan had the strongest influence, with Burkina Faso also showing a moderate loading. Conversely, Cambodia, Cameroon, Morocco, and Uganda exhibited negative correlations with PC 3. PC 4 saw Botswana as the leading contributor, with Zimbabwe, South Africa, and Namibia also playing significant roles. Zimbabwe was particularly influential in PC 5, followed by Gabon and Gambia, indicating that the parameters included in PC 5 were closely related to Zimbabwe's

Table 5
Descriptive statistics of groundnut production (2000–2022) for various countries in the Global South.

	N	Min	Max	Sum	Mean	Stand. dev	Coeff. var
Algeria	23	968.7	2913.2	37379.5	1625.20	692.45	42.61
Angola	23	285.4	797.7	11443.9	497.56	173.62	34.89
Argentina	23	1412.2	3498.9	57354.5	2493.67	610.43	24.48
Bangladesh	23	1042.5	1910.2	35978.2	1564.27	266.85	17.06
Benin	23	850.1	1050.3	21349.6	928.24	59.20	6.38
Bhutan	23	0	2827.4	10638.5	462.54	806.50	174.36
Botswana	23	137	1209.6	11350.4	493.50	302.67	61.33
Brazil	23	1790.3	3896.1	66057	2872.04	670.44	23.34
Burkina Faso	23	589.9	944.6	18418	800.78	105.50	13.17
Burundi	23	442.8	806.5	14763.5	641.89	97.41	15.18
Cambodia	23	729.2	1751.3	30544.7	1328.03	285.43	21.49
Cameroon	23	726.3	1747.4	28833.4	1253.63	280.13	22.35
CAR	23	1000	3095.2	47217.8	2052.95	961.75	46.85
Chad	23	819.4	1410.7	23865.8	1037.64	136.84	13.19
Colombia	23	797.2	2026.4	31428.1	1366.44	297.80	21.79
Congo	23	529.6	600	12846.3	558.53	25.87	4.63
Côte d’Ivoire	23	899.3	1565.5	27194.7	1182.38	237.02	20.05
DRC	23	778	953.7	19187.1	834.22	58.30	6.99
Egypt	23	3039.2	3710.5	75420.1	3279.14	160.22	4.89
Ethiopia	23	828.6	1806.5	31756.1	1380.70	336.87	24.40
Fiji	23	750	1000	19853.2	863.18	56.44	6.54
Gabon	23	900	1088.9	23511.7	1022.25	34.16	3.34
Gambia	23	575.1	1168.5	20804.9	904.56	165.91	18.34
Ghana	23	883.3	1838.8	29907.9	1300.34	282.27	21.71
India	23	694.3	2062.5	30996	1347.65	345.16	25.61
Kenya	23	564.7	5434.2	35311.8	1535.30	980.15	63.84
Malawi	23	568.2	1057.2	20274.9	881.52	134.47	15.25
Mali	23	589.7	1541.2	22722.5	987.93	242.35	24.53
Mexico	23	1203.7	1985.9	37362	1624.44	168.88	10.40
Morocco	23	981.9	2737.6	53240.5	2314.80	359.61	15.54
Mozambique	23	201.8	580.1	7426.6	322.90	97.61	30.23
Myanmar	23	1167.5	1598.2	33546.3	1458.54	120.24	8.24
Namibia	23	87.7	518.1	8766.7	381.16	87.68	23.00
Nigeria	23	905.5	1719.9	30355	1319.78	189.44	14.35
Pakistan	23	608.7	1121.5	20958.8	911.25	128.47	14.10
Philippines	23	970	1330.8	25838.1	1123.40	103.27	9.19
Rwanda	23	370	698.9	12520.9	544.39	93.63	17.20
Senegal	23	320.4	1467.2	21682	942.70	275.37	29.21
S. Leone	23	499.8	2436.9	21241.4	923.54	442.25	47.89
S A	23	782.3	1824	31286.2	1360.27	282.60	20.78
Sri Lanka	23	578.2	1993.1	30925.3	1344.58	504.89	37.55
Thailand	23	1139.2	2267.3	39475.4	1716.32	294.32	17.15
Uganda	23	363.6	1018.5	17052.6	741.42	174.35	23.52
URT	23	444.4	1510.1	19085.6	829.81	213.34	25.71
Viet Nam	23	1450.8	2604.8	48243.1	2097.53	343.23	16.36
Zambia	23	381.8	1332.3	15110.9	657.00	183.60	27.95
Zimbabwe	23	218	823.3	10223.9	444.52	139.16	31.31

production characteristics.

The analysis, as depicted in Fig. 6, shows the correlation coefficients and contributions of each country to PC 1, providing insights into which nations had the most significant impact on this principal component. Fig. 7 presents a box plot of the principal components PC 1 and PC 2, illustrating the direction and magnitude of their contributions across the 47 countries.

In terms of production capacity, the data highlighted significant variations in groundnut yields over time. Kenya led in 2013 with a production of 5434.2 kg ha^{-1}. Other countries also demonstrated high production levels in specific years: the Central African Republic (CAR) in 2010 with 3095.2 kg ha^{-1}, Egypt in 2017 with 3210.5 kg ha^{-1}, Argentina in 2020 with 3498.9 kg ha^{-1}, and Brazil in 2021 with 3896.1 kg ha^{-1}. Fig. 8 illustrates these production trends, showcasing the leading producers in different years and highlighting the shifts in production capacity over the two-decade period.

4. Discussions

The analysis of legume production in the Global South, covering 17 types of grain legumes, reveals a diverse and complex landscape. While groundnuts (unshelled) represent a significant portion of the dataset, the trends in other legumes offer valuable insights into regional agricultural dynamics and challenges.

Among the various legumes studied, soya beans, dry pigeon peas, and dry lentils stand out due to their economic importance and diverse production patterns [82,83]. Soya beans, for instance, are important for both human consumption and animal feed, and their production reflects global agricultural trends [84,85]. The variability in soybean production across countries can be attributed to differences in climatic conditions, soil types, and agricultural practices [86]. Major producers such as Brazil and Argentina benefit from favourable conditions that support high yields [87], while other regions may struggle with lower productivity due to less optimal growing conditions or limited technological advancements.

Dry pigeon peas, another important legume, are predominantly grown in South Asia and East Africa [89]. The production trends for dry pigeon peas indicate a significant role in food security and local economies [90]. However, variability in yields across regions suggests factors such as pest pressures, rainfall patterns, and soil health impact production [91,92]. Countries like India and Kenya, which are major producers, face challenges related to climate change and resource management, affecting their ability to maintain stable production levels [93]. Dry lentils, primarily cultivated in regions like Canada, India, and

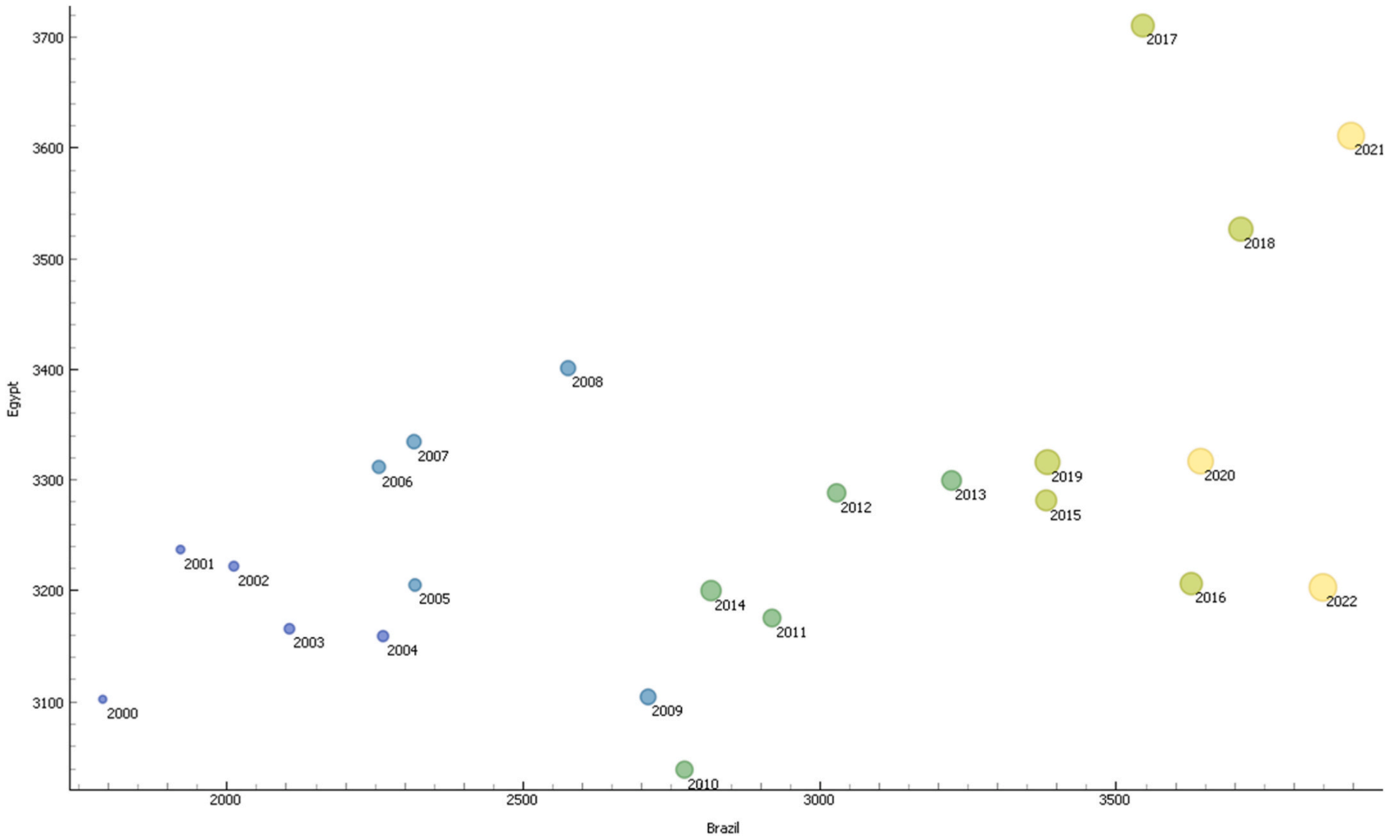

Fig. 2. Trends in groundnut production for Egypt and Brazil (2000–2022).

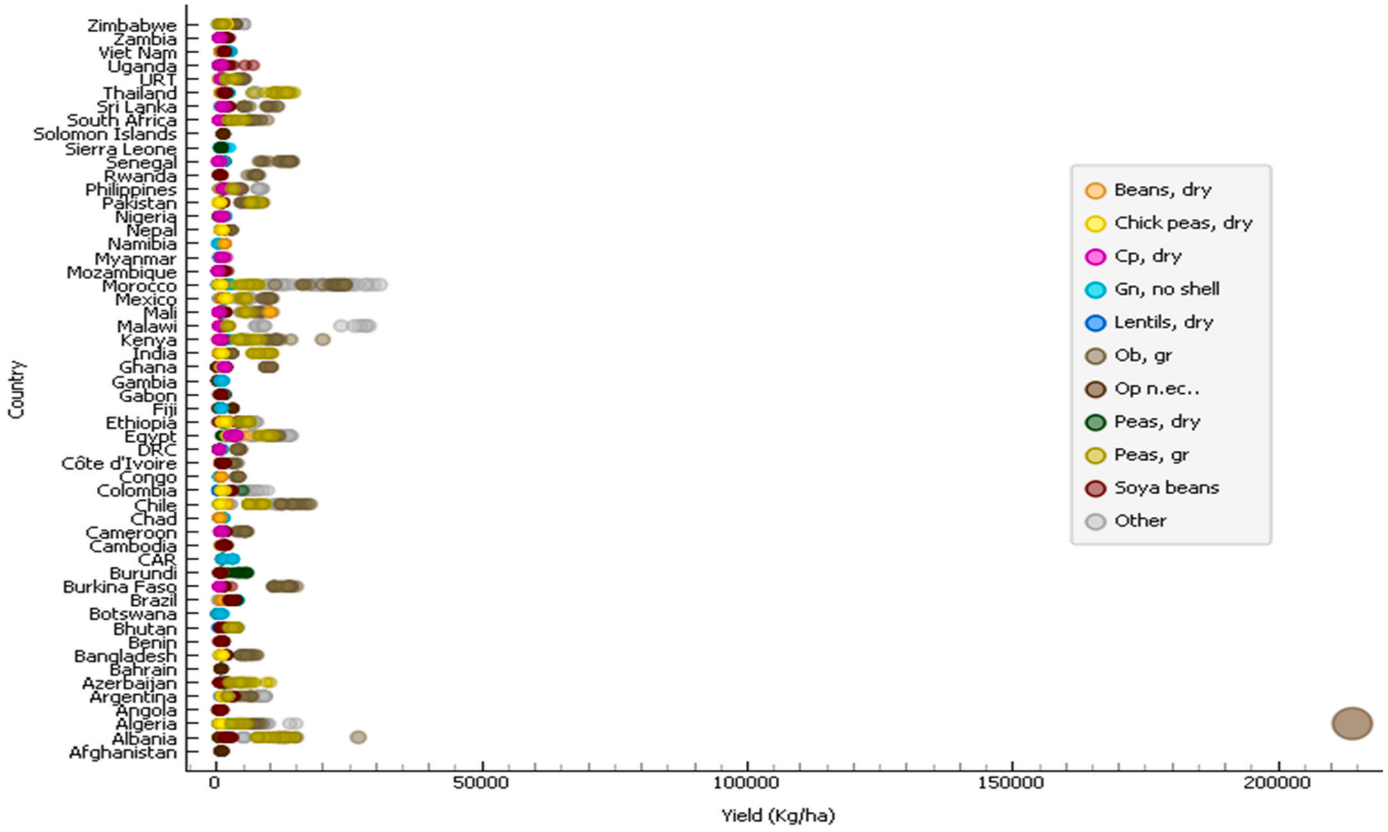

Fig. 3. Countries and their production output of 17 grain legumes over the 23 years.

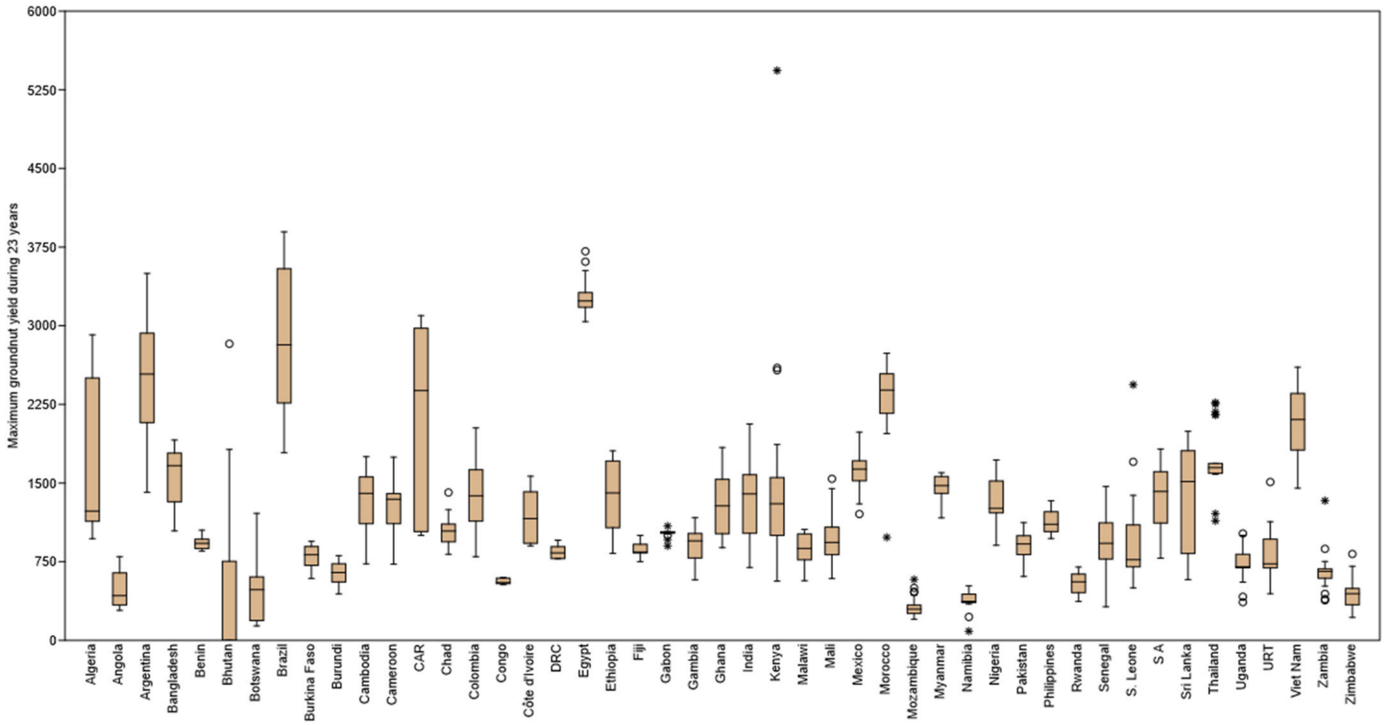

Fig. 4. Production output of groundnut (kg ha^{-1}) based on countries.

Turkey, also show diverse production patterns [94]. Lentils are valued for their nutritional content and as a key crop in crop rotation systems [95]. The trends in lentil production reveal both high-performing regions and areas facing challenges [96]. For example, Canada's high yields reflect advanced agricultural practices and favourable conditions [97], while other regions may experience variability due to climatic factors or pest outbreaks.

Yield increases in legumes under monoculture can be attributed to a combination of technological advancements and improved agricultural practices from 2000 to 2022. Our analysis highlights a significant increase in yields of grain legumes under both monoculture and intercropping systems compared to traditional farming practices. Monoculture, despite its critiques regarding soil nutrient depletion and heightened pest susceptibility, can provide yield consistency for certain legumes [98,99]. Innovations such as breeding for high-yielding seed varieties, precision farming techniques, and enhanced soil management strategies have played a significant role in increasing productivity, indicating that these gains are not only based on expanding farmland but rather a reflection of improved farming practices [100,101].

Conversely, intercropping presents complementary benefits by enhancing biodiversity, improving soil health, and optimizing land use. Research by Toker et al. [102] shows that intercropping can improve overall productivity and resilience especially under unfavourable climatic conditions. However, the challenge of converting intercrop yields into equivalent yields remains significantly complicated by variable market prices influenced by national policies and subsidies [103–105]. Despite these setbacks, recent advances in technological developments have equipped farmers in addressing these challenges, allowing for more effective management of intercropping systems [106–108].

Access to digital platforms and market information has improved the ability to standardize yield equivalences, even amidst fluctuating prices [109]. The evolution of agricultural technology over the past two decades has enabled farmers to maximize crop interactions and nutrient utilization, addressing the challenges of yield conversion and pricing [110,111]. Integrated strategies—such as combining crop rotation, cover cropping, and organic amendments—may offer greater long-term sustainability and yield stability than relying solely on monoculture or intercropping [23,112–114].

It is essential to recognize the variability in agricultural practices based on regional contexts, soil types, and climate conditions. While findings suggest that both monoculture and intercropping can outperform some conventional methods, they are not universally superior to all existing practices [115]. Future research should prioritize identifying context-specific best practices that align with agro-ecological conditions. This tailored approach will be vital for optimizing legume production in the Global South, ensuring both effectiveness and sustainability in agricultural practices.

Groundnuts are a major crop in the Global South [116], contributing to food security and economic stability in many countries. The production patterns of groundnuts offer insights into the broader agricultural landscape of these regions [117]. Egypt stands out as a leading producer, reflecting a well-established and stable production environment [118]. The low coefficient of variation indicates minimal fluctuations in production, suggesting that Egypt's agricultural practices and climatic conditions are highly conducive to consistent and high-yielding groundnut production. This stability is a testament to effective farming techniques and a supportive agricultural infrastructure [119]. Brazil, another significant producer, shows a high average yield but experiences greater variability. This higher variability indicates that Brazil faces challenges in maintaining stable production levels. Factors contributing to this variability may include fluctuating climatic conditions, market dynamics, and regional differences in agricultural practices [120]. Addressing these issues is important for Brazil to enhance its production stability and competitiveness in the global market.

Mozambique, in contrast, reports the lowest average yield with a high coefficient of variation. This low productivity and high variability highlight significant challenges in Mozambique's groundnut sector [121]. Factors such as inconsistent agricultural practices, limited access to resources, and unstable environmental conditions contribute to these issues [122]. Improving productivity in Mozambique requires targeted interventions, including better access to agricultural technology, improved farming practices, and support for overcoming environmental challenges [123].

In other regions, such as Algeria and Morocco, high average

Table 6
Principal component analysis (PCA) loadings for groundnut production (2000–2022).

Component*	PC 1	PC 2	PC 3	PC 4	PC 5
Algeria	0.191	**0.209**	-0.013	-0.098	0.013
Angola	0.188	-0.026	0.036	-0.202	0.074
Argentina	0.192	0.040	-0.101	0.104	-0.052
Bangladesh	**0.227**	-0.060	-0.009	-0.004	-0.034
Benin	0.100	0.175	-0.123	0.187	-0.117
Bhutan	0.163	**0.225**	0.005	-0.060	0.023
Botswana	-0.088	0.058	-0.105	**0.406**	0.081
Brazil	**0.227**	0.019	-0.013	-0.034	-0.005
Burkina Faso	0.017	0.055	**0.256**	-0.213	-0.090
Burundi	-0.108	**0.258**	-0.185	-0.142	0.127
Cambodia	0.093	-0.215	-0.265	-0.071	0.121
Cameroon	0.088	-0.118	-0.276	0.037	0.063
CAR	0.186	-0.141	0.093	-0.073	-0.003
Chad	0.135	-0.066	0.124	-0.132	0.142
Colombia	0.066	**0.308**	0.073	0.017	-0.086
Congo	-0.164	0.079	0.190	0.043	0.002
Côte d'Ivoire	**0.223**	0.011	0.030	-0.073	0.034
DRC	**0.222**	0.084	0.056	-0.068	0.020
Egypt	0.111	0.120	-0.119	-0.067	0.102
Ethiopia	0.199	-0.028	-0.021	0.008	0.070
Fiji	-0.176	0.140	-0.131	-0.112	0.105
Gabon	0.096	-0.053	-0.131	0.268	**0.343**
Gambia	-0.073	-0.095	0.006	-0.147	**0.339**
Ghana	0.180	0.113	0.092	0.081	-0.232
India	0.184	0.049	0.040	0.054	0.100
Kenya	0.024	-0.256	0.138	-0.132	0.208
Malawi	0.080	-0.164	0.094	0.348	-0.110
Mali	0.073	-0.293	-0.008	0.161	0.012
Mexico	0.124	-0.005	0.090	0.141	0.350
Morocco	0.144	0.036	-0.212	-0.056	-0.036
Mozambique	-0.006	0.046	0.266	0.145	0.019
Myanmar	0.146	-0.259	-0.144	0.084	-0.026
Namibia	-0.043	-0.023	0.340	**0.247**	-0.006
Nigeria	-0.176	0.127	-0.113	-0.174	0.016
Pakistan	-0.010	0.010	**0.339**	-0.053	0.133
Philippines	**0.225**	0.062	-0.046	0.011	0.024
Rwanda	-0.155	-0.062	0.040	0.145	-0.261
Senegal	0.146	**0.226**	0.016	0.107	0.166
S. Leone	0.120	0.128	0.081	0.015	-0.072
S A	-0.113	0.127	-0.160	**0.263**	-0.014
Sri Lanka	**0.218**	-0.066	0.019	0.122	-0.068
Thailand	0.109	**0.212**	0.060	0.080	-0.120
Uganda	-0.153	-0.074	-0.246	0.070	0.064
URT	0.011	-0.312	0.165	-0.053	-0.090
Viet Nam	**0.228**	0.016	-0.061	0.032	-0.040
Zambia	0.048	-0.070	-0.163	0.003	-0.351
Zimbabwe	-0.074	0.163	0.117	**0.257**	**0.344**
Eigenvalue	18.00	5.94	3.97	2.79	2.62
% variance	38.31	12.65	8.46	5.94	5.57
Cumulative variance %	38.31	50.96	59.42	65.36	70.93

**Bold indicates a positive correlation while bold and green indicates a very strong influence. Red indicates a strong negative correlation while light-shaded indicates a moderate negative correlation. Key: CAR= Central African Republic; DRC = Democratic Republic of Congo; S. Leone = Sierra Leone; URT = United Republic of Tanzania.*

production values are accompanied by considerable variability. The coefficients of variation recorded for Algeria and Morocco suggest that while these countries achieve significant production, achieving consistency remains a challenge. This variability could be influenced by factors such as fluctuations in weather conditions, agricultural practices, and market dynamics [124]. Bangladesh and Argentina, on the other hand, exhibit more stable production profiles with high average yields and lower coefficients of variation [125]. The yields recorded in Bangladesh and Argentina reflects consistent production environments. The lower variability in these countries suggests effective agricultural practices and favourable conditions that contribute to both high productivity and stability.

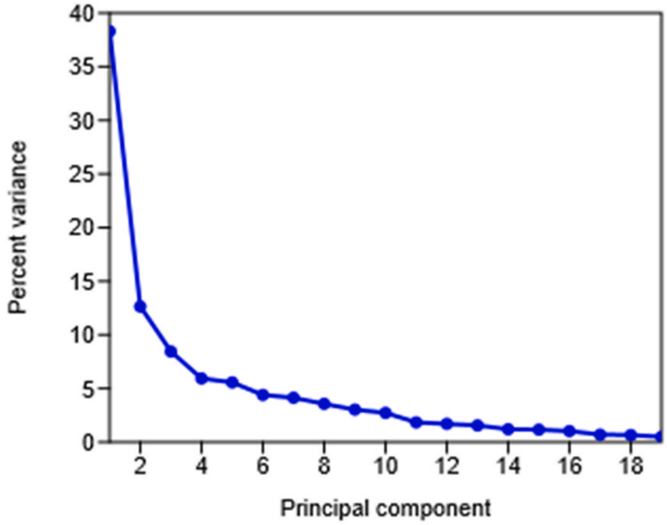

Fig. 5. Scree Plot of Principal Components for Groundnut Production (2000–2022). This scree plot illustrates the eigenvalues of the principal components identified through PCA. The plot shows the percentage of variance explained by each principal component, helping to visualize the relative importance of the components in explaining the variability in groundnut production.

The PCA provides a deeper understanding of the factors influencing groundnut production across the Global South. The PCA identified five principal components that together explain over 70 % of the variability in production. PC 1, the most significant component, captures 38.3 % of the variance and highlights the influence of countries such as Bangladesh, Brazil, and Côte d'Ivoire. This component reflects the key factors driving production patterns and illustrates the substantial role of major producers in shaping overall trends.

Countries like Tanzania and Mali, which show strong negative correlations with PC 2, indicate different production dynamics compared to those with positive contributions. This suggests regional variations in the factors affecting groundnut production and highlights the need for tailored approaches to address specific challenges in different countries. The diverse contributions of countries to various principal components reveal the complex interplay of factors influencing groundnut production. Understanding these dynamics is essential for developing targeted strategies to improve productivity and stability in different regions.

5. Conclusions and future directions

The study of legume production across the Global South highlights both the rich diversity and significant disparities in agricultural practices and outcomes. Analyzing various grain legumes, such as soybeans, dry pigeon peas, and dry lentils, reveals distinct production patterns influenced by regional factors, including climate, soil quality, and farming practices. Each legume presents unique challenges and opportunities, reflecting the varied agricultural landscapes of different countries. For instance, while soybeans and dry pigeon peas show stable and substantial production in certain regions, dry lentils exhibit considerable variability based on geographical and environmental conditions.

Focusing on groundnut production, Egypt stands out with its high productivity and stability, indicating effective agricultural practices and favourable conditions. In contrast, countries like Mozambique experience lower yields and higher variability, pointing to challenges such as inconsistent farming practices and environmental constraints. Principal Component 1, which explains a significant portion of the variance, highlights the contributions of major producers such as Bangladesh and Brazil, while other components reveal the diverse influences of different countries on production trends. This variability is crucial for understanding the broader context of agricultural productivity and stability.

Addressing the gaps in the current study, several areas require further investigation. Assessing the nutritional value of legumes produced under different systems, such as monoculture versus intercropping, could provide valuable insights beyond yield figures. Moreover, exploring the socio-economic implications of legume production will illuminate how various farming practices affect farmers' livelihoods, access to markets, and the role of gender in agriculture. Detailed assessments of environmental impacts—on biodiversity, soil health, and water usage—will further inform practices that minimize ecological footprints while maximizing productivity.

Investigation into the barriers preventing the adoption of new technologies across different regions is essential. Identifying challenges faced by farmers, such as knowledge gaps and access to resources, can help tailor interventions that promote innovation and sustainability. As climate patterns become increasingly unpredictable, research on

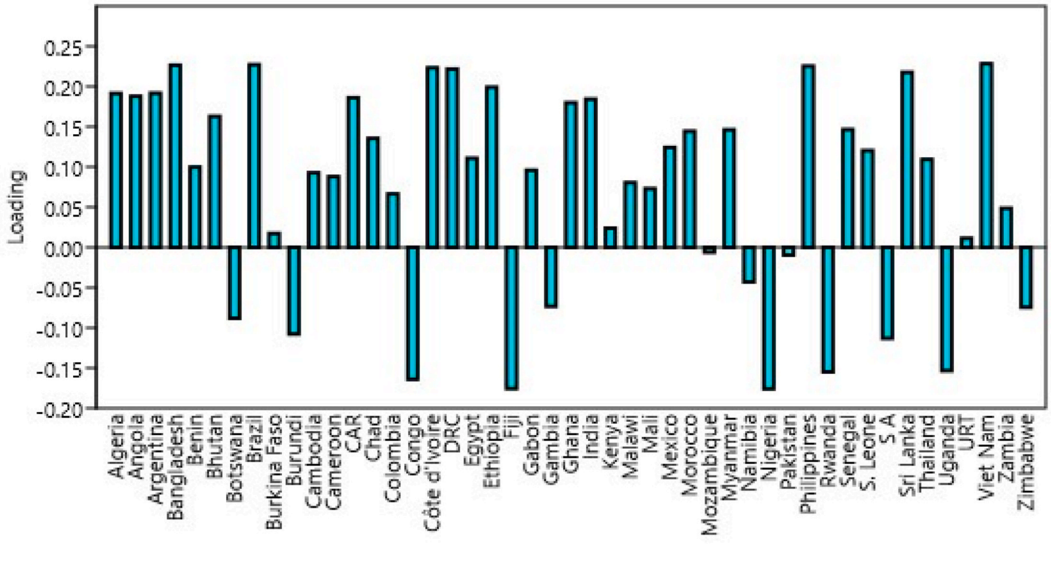

Fig. 6. Contribution and Correlation Coefficients of Countries to Principal Component 1 (PC 1). This figure shows the correlation coefficients and contributions of each country to PC 1. It highlights which countries had the most significant impact on this principal component, indicating their influence on the production patterns captured by PC 1.

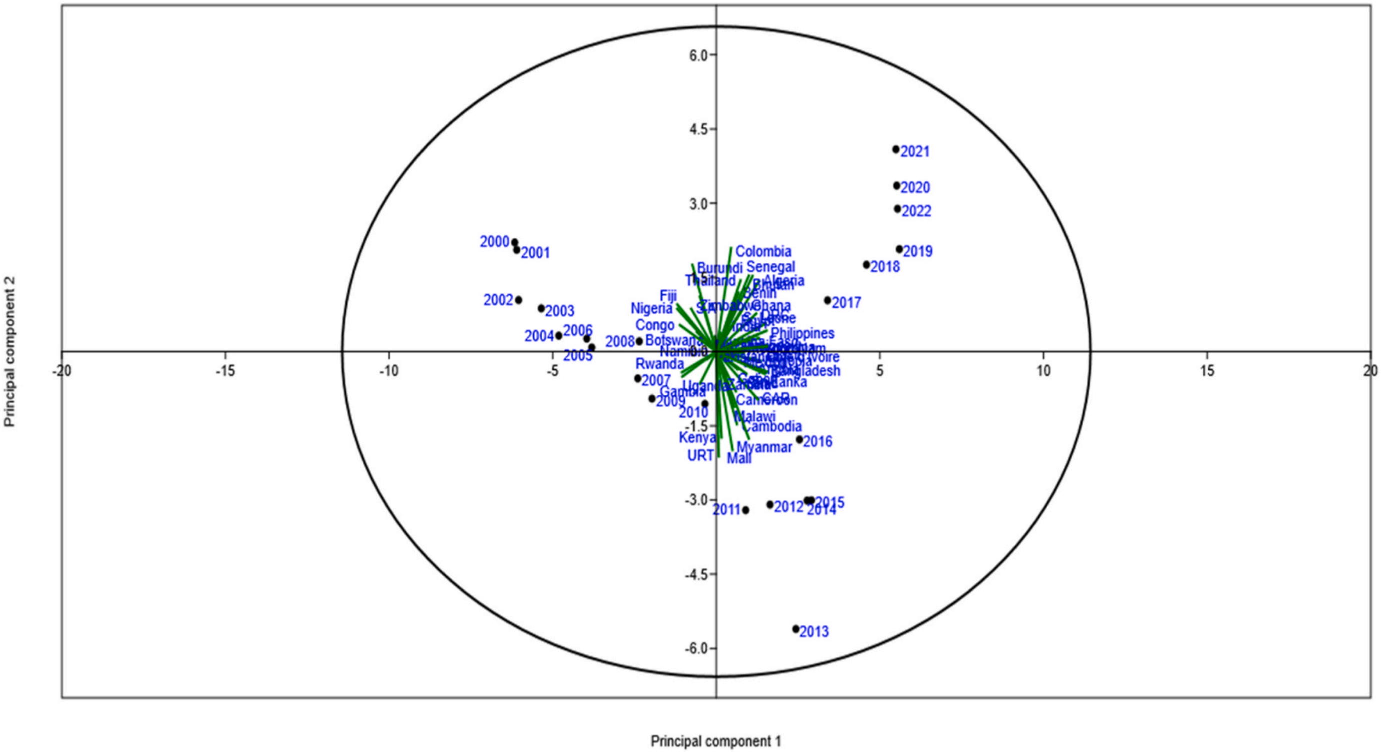

Fig. 7. Box Plot of Principal Components 1 and 2 (PC 1 and PC 2) for groundnut production (2000–2022). The box plot displays the contributions of PC 1 and PC 2 across the 47 countries. It illustrates the direction and magnitude of the impact of these principal components on groundnut production, providing insights into the variability and influence of these components.

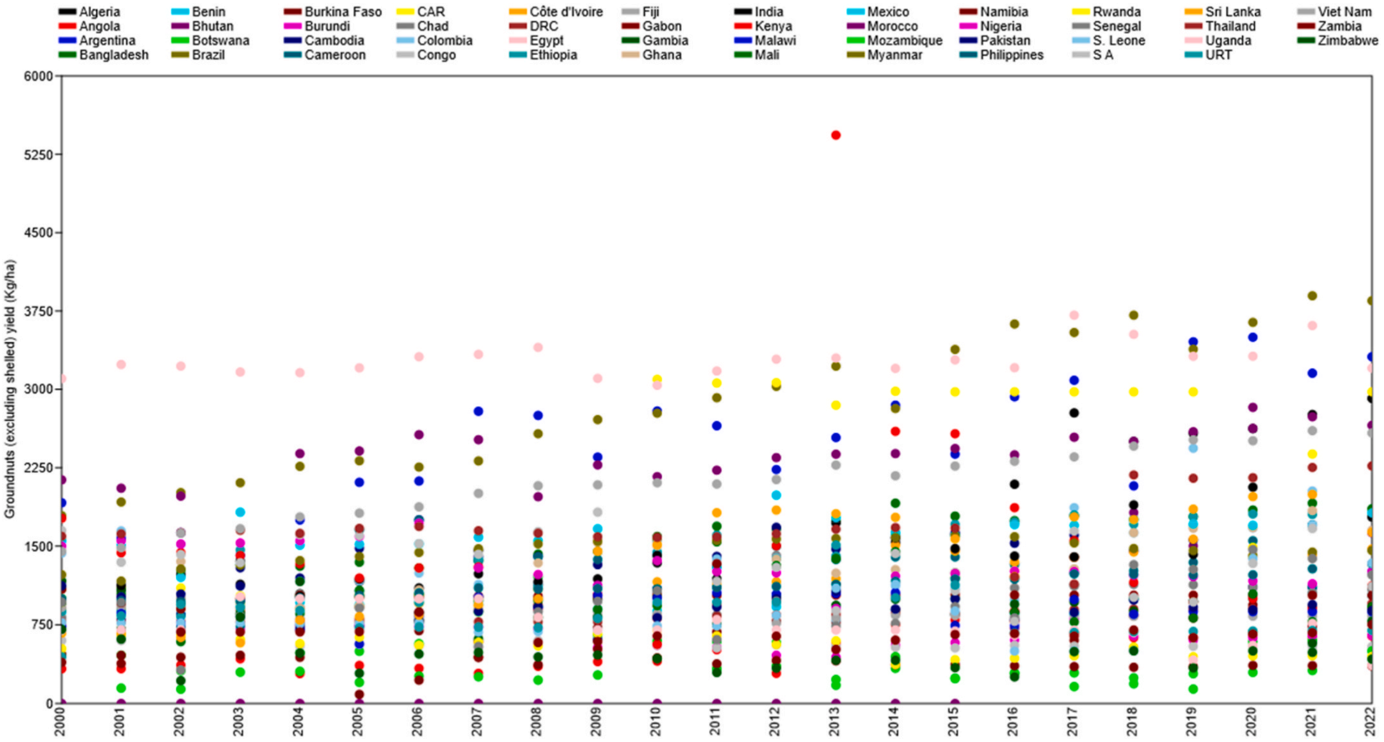

Fig. 8. Trends in groundnut production by leading countries (2000–2022). This graph shows the production levels of groundnuts (excluding shelled) for various leading countries over the period from 2000 to 2022. It highlights the top producers in different years and visualizes the changes in production capacity across these years.

adaptive strategies specific to legume cultivation is vital, including resilient varieties and sustainable practices capable of withstanding climatic stresses.

Developing metrics to evaluate the long-term sustainability of legume production systems will facilitate assessments of trade-offs between yield, soil health, and socio-economic outcomes. A critical examination of existing policies and subsidies related to legume production can reveal gaps and opportunities for improvement. Understanding how these policies influence farming decisions will help design more effective support systems for farmers.

Looking forward, enhancing agricultural support in low-yielding countries like Mozambique is vital. This could involve improving access to modern agricultural technology, enhancing soil management practices, and providing support for pest and disease management. Investing in local farmers through training and resources can help improve productivity and reduce yield variability. Additionally, adapting to climate change is essential for stabilizing production. Developing and implementing climate-smart agricultural practices, such as drought-resistant crop varieties and efficient irrigation systems, can mitigate the impacts of climate variability.

Regional collaboration plays a significant role in addressing agricultural challenges. Sharing appropriate practices and resources allows countries with similar agricultural conditions to work together to overcome common obstacles. Strengthening regional partnerships facilitates knowledge exchange and supports sustainable development in the legume sector. Policy development is another critical area for improvement. Formulating and implementing policies that support legume production, address regional disparities, and create favourable conditions for farmers can drive progress.

Continued research is necessary to gain deeper insights into the factors influencing legume production. Longitudinal studies can track changes over time, evaluate the effectiveness of interventions, and provide valuable information for future agricultural strategies. Overall, a multifaceted approach that encompasses agricultural practices, socio-economic factors, environmental sustainability, and policy development will be vital for optimizing legume production and enhancing resilience in the Global South.

CRediT authorship contribution statement

Francis Kloh Fukah: Writing – review & editing, Writing – original draft, Formal analysis, Software. **Aneth Japhet Magubika:** Writing – review & editing, Writing – original draft. **George Muhamba Tryphone:** Writing – review & editing. **Eliakira Kisetu Nassary:** Writing – review & editing, Writing – original draft, Conceptualization, Formal analysis.

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Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

Data will be made available on request.

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