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REVIEW

Reorienting research investments toward under-researched crops for sustainable food systems

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Abstract

The dominance of a few staple crops (maize, rice, and wheat) in most agricultural systems hampers the application of interventions to improve food security and nutrition. Research and development attention has focused on improving the production and utilization of these crops, leaving other crops under-researched and underutilized. Subsequently, there have been high malnutrition rates due to poor diet diversity, yet there are "opportunity crops" that remain under researched. The opportunity crops can unlock solutions to food insecurity, malnutrition, a lack of biodiversity, and indeed poor climate adaptation. The study explored diversification in agricultural systems to analyze whether reorientation of research investment to include under-researched crops can increase nutrient gain and enhance dietary diversity. Research outputs benchmarked as the number of publications from three leading African universities, Nairobi, Pretoria, and Ghana, were related to crop diversity and nutrition of crops in five clusters: cereals, vegetables, legumes, roots and tubers, and nuts. The findings show that maize was the predominantly researched crop across the three institutions. Low research outputs were observed for pearl millet, finger millet, and yam across the three institutions: amaranth and nightshade (Pretoria), sweet potatoes (Pretoria and Ghana), Marama bean (Nairobi), and soya bean (Nairobi and Ghana). There was nutrient gain across all five clusters, particularly from under-researched indigenous crops such as finger millet, amaranth, nightshade, yam, sweet potatoes, Marama bean, and soybean. Nutrient gain was contributed more by cereals and root and tuber crops from Pretoria, vegetables and nuts (Ghana), as well as legumes (Nairobi). The findings demonstrate that incorporating research on the least researched crops with successful integration of other research and development initiatives (policy and dissemination) can increase nutrition and improve dietary diversity. The nutrient gain will positively affect food security and nutrition, contributing to the achievement of Africa Agenda 2063, the United Nation's Sustainable Development Goals,

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and reducing food imports. The findings can inform research investment and decision across different institutions within the African continent. Research investment targeting crops such as finger millet, amaranthus, sweet potatoes, soya beans, and cashew nuts is needed considering the nutritional contribution, climate change adaptability, market potential, and biodiversity contribution. Further analysis should explore production, socio-economic (marketability and income generation), and environmental gains (adaptive ability to climate change) for specific crops. The development of frameworks to guide the analysis of the nature and scope of factors affecting the contribution of these crops to food security and nutrition, as well as research on specific crops considering geographic distribution and institutional involvement, is also needed.

KEYWORDS
crop diversity, food systems, indigenous crops, research institutions

1 | INTRODUCTION

The lack of food system sustainability at local, national, regional, and global levels is of concern. Emerging pandemics, climate change, dwindling natural resources, and sporadic wars have exposed food systems' vulnerabilities in delivering healthy, adequate, and safe foods (Cottrell et al., 2019; Rivera-Ferre et al., 2021). With the global population expected to reach 10 billion people by 2050, the mounting pressure for food systems research to deliver solutions that ensure food and nutrition security has led to studies focusing on different aspects of the food system.

Studies on food systems have increasingly involved biotechnology and genomics (Agarwal et al., 2021; Welgemoed et al., 2020), crop improvement and sustainable production (Quaye et al., 2021; Wahab et al., 2020), plant pathogens (Livoi et al., 2021; Nguetti et al., 2019), and crop modeling (Adisa et al., 2018; Ogbazghi et al., 2019). Other studies have looked at gender (Akrong et al., 2020; Torvikey, 2021), climate change, and policy (Beinah & Kunyanga, 2020; Bii et al., 2020) to enhance food system sustainability. These studies have generalized African food systems without considering the various types, geographic distribution, structure, or governance and their unique role in contributing to resilience and sustainable nutrition security. Marshall et al. (2021) identified five types of global food systems—rural and traditional, informal and expanding, emerging and diversifying, modernizing and formalizing, and industrial and consolidated—with specific roles in ensuring sustainable food security and nutrition in different geographic regions. Food systems also exist at different scales: global, regional, national, and local (von Braun et al., 2021). Regional and national disparities in, for example, socio-economic and biophysical conditions affect the contribution of food systems to sustainable food and nutrition security. Food systems also differ with regard to structure, governance, and supply chains. The recognition of these unique features that characterize different food systems is important, and there have been recommendations to consider territorialized studies in the analysis of food systems (Gasselin et al., 2020; López-Estébanez et al., 2022).

Promoting territorialized food systems research is the United Nations policy to transform food systems (OECD/FAO/UNCDF, 2016). However, few territorial studies on food systems exist as of yet. Gasselin et al. (2020) studied food systems' spatial dimensionality (urban, peri-urban, and rural typologies) to understand the interaction between territorial agriculture and food models. Rochefort et al. (2021) reviewed the impact of territorialized food systems on health, food security, and the environment. The multifunctionality and territoriality of peri-urban areas have been analyzed to identify the factors needed to re-territorialize food systems and improve their socio-ecological resilience (López-Estébanez et al., 2022). Territorial studies can facilitate policy design considering all four food security dimensions: availability, access, utilization, and stability. For example, localized policies that improve access to natural resources and agroecology, secure land tenure, and preserve agricultural land could be developed. A territorial perspective in food system analysis promotes social participation, allows policymakers to close information gaps and make better-informed decisions across different sectors, and strengthens local institutions, placing them at the forefront of tackling food insecurity (OECD/FAO/UNCDF, 2016).

The dominance of a few crops (maize, rice, and wheat) in most African food systems hampers the application of interventions to improve food and nutrition security at a territorial level because research has focused on improving the production and utilization of these crops (Oyange et al., 2020; Roodt, 2021; Roux et al., 2019). Statistics show that 58% of research funding between 2012 and 2016 related to maize, rice, and wheat (Ickowitz et al., 2022), implying that measures to improve food and nutrition security and research investments revolve around these crops. Subsequently, Africa has become a museum for malnutrition due to poor diet diversity, yet it has "opportunity crops" that have been under researched. Recent discussions on crop diversification have focused on improving dietary diversity and nutritional stability (Nicholson et al., 2021). Quantifying the nutritional quality and quantity of the indigenous crops in relation to crop diversity can contribute to unleash their potential and improve territorial food systems. These opportunity crops can unlock solutions to food insecurity and contribute to the achievement of Africa Agenda 2023 priority areas, which are the elimination of hunger, stunting by 10%, and underweight prevalence by 5% (AU, 2014).

Crop diversification within African communities can significantly contribute to sustainable food systems at a territorial and global level due to its diversity of crops, including cereals (sorghum, pearl millet, finger millet, teff, and African rice), roots and tubers (cassava, yams, sweet potato, and taro), pulses (cowpea, lablab beans, pigeon pea, and chickpea), fruits and vegetables (guava, loquats, baobab, amarula, nightshades, spider plant, amaranth, pumpkin, and moringa), and nuts seeds and spices (macadamia, cashew nuts, Bambara groundnuts, cumin, saffron, and rosemary), ginger, and nutmeg (Pichop et al., 2016). The scientific names of the crops are shown in Table A1. These crops are loaded with nutritional components, such as carbohydrates, proteins, energy, carotenoids, vitamin B complex, vitamin C, vitamin K, and antioxidants (Chandrasekara & Josheph Kumar, 2016; Maina & Mwangi, 2008; Pradhan et al., 2021; Ramashia et al., 2021; Suárez-Martínez et al., 2016). Other multi-dimensional benefits of these crops include economic and social development, resilience to climate change, improved livelihoods and rural development, biodiversity conservation, cultural diversity and heritage, adaptation to harsh environments, and low-input agriculture (Bokelmann et al., 2022). However, these crops remain undocumented, and their potential has not been exploited to improve food and nutrition security (Mabhaudhi et al., 2017; Pichop et al., 2016).

Unleashing the potential of Africa's indigenous or traditional crops to transform food systems in different territories has raised interest among many proponents, with recommendations to shift research to target these crops and improve their contribution toward sustainable food and nutrition security (Mabhaudhi et al., 2017; Manners & Van Etten, 2018). Research investment is merited, given the multiple benefits of indigenous food crops on the African continent. Manners & Van Etten, 2018 examined the global relationship between crop-specific research output in terms of the number of publications, total nutrient output available, and recommendations for human consumption. Mabhaudhi et al. (2017) developed a road map to promote the production and utilization of underutilized indigenous crops, underpinned by knowledge management, adaptive research, and priority setting. As discussions to reorient research investments continue, multi-country and institution mapping studies that show the dietary and economic value of Africa's indigenous crops are needed (Alarcon et al., 2021). This study contributes to this current debate on reorienting research investments by quantifying nutrient gain from under-researched crops in three leading African universities: Nairobi, Pretoria, and Ghana. The study examines how research outputs translate to nutritional quality and quantity when reoriented to include under-researched crops.

2 | MATERIALS AND METHODS

2.1 | Study institutions

A stratified sampling design employing a three-step procedure was used to select regions, countries, and institutions within the African continent. Three African regions—Southern, Eastern, and Western—were considered for benchmarking research outputs on crops grown in Africa. The regional classification was necessary for research and development, decision-making, and implementation. Three universities were selected to benchmark research outputs (number of publications) on research on crops grown in Africa: the University of Pretoria (Southern), the University of Nairobi (Eastern), and the University of Ghana (Western). The university selection was based on the higher quantity of research produced by these institutions compared to other institutions within the respective regions (Cloete et al., 2018; Kpolovie & Dorgu, 2019), which broadly represents the status of research on crops in institutions across Africa. The three universities also carry out collaborative research with institutions both at national (other universities, National Agricultural Research Systems, among others) and international levels (universities at the international level, Consortium of International Agricultural Research Centres) and have wider scope with regard to crop s of focus and geographic reach (CGIAR - IEA, 2017; Cloete et al., 2018).

2.2 | Benchmarking research outputs

A mapping exercise to synthesize the information from publications on crops grown in Africa was conducted across the three institutions, adopting and customizing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Figure 1) (Tawfik et al., 2019). The method is robust and ensures the transparent and complete reporting of systematic reviews and meta-analyses (Liberati et al., 2009). The method has four key stages: identification, screening, eligibility, and inclusion (Adu et al., 2018; Ali & Dahlhaus, 2022).

2.3 | Eligibility criteria

The eligibility phase included defining the inclusion and exclusion criteria. The inclusion criteria were; (1) articles on research on crops grown in Africa conducted between 2010 and 2021; (2) articles with geographic coverage within Africa; and (3) online articles in the universities of Nairobi, Pretoria, and Ghana repositories. A manual screening of research on African crops, including theses and dissertations was conducted at the universities of Nairobi, Pretoria, and Ghana repository. Abstract-only articles and pay-to-access journals were excluded. The key search terms included "Food systems" OR "Sustainable Food Systems" OR/AND "Food and Nutrition Security" OR/AND "Agri-food Systems." To improve the search criteria and include relevant articles, the search term included descriptors "AND," "OR," and specific crops such as maize, wheat, rice, beans, sorghum, millet, cassava, African leafy vegetables, bananas, fruits, green leafy vegetables, Indigenous African Crops, and finger millet, among others. The crops were then classified into five clusters—cereals, vegetables, roots and tubers, legumes, and nuts—to necessitate decision-making and the implementation of research toward sustainable food systems. The data were then extracted and entered into Excel. Descriptive statistics were done to summarize the collected data.

2.4 | Nutrient composition data

Nutrient composition data for each crop were obtained from existing literature: cereals (Ramashia et al., 2021), vegetables (Maina & Mwangi, 2008), legumes (Kamboj & Nanda, 2018; Suárez-Martínez et al., 2016), roots and tubers (Chandrasekara & Josheph Kumar, 2016), and nuts (Pradhan et al., 2021). The nutrient compositions for

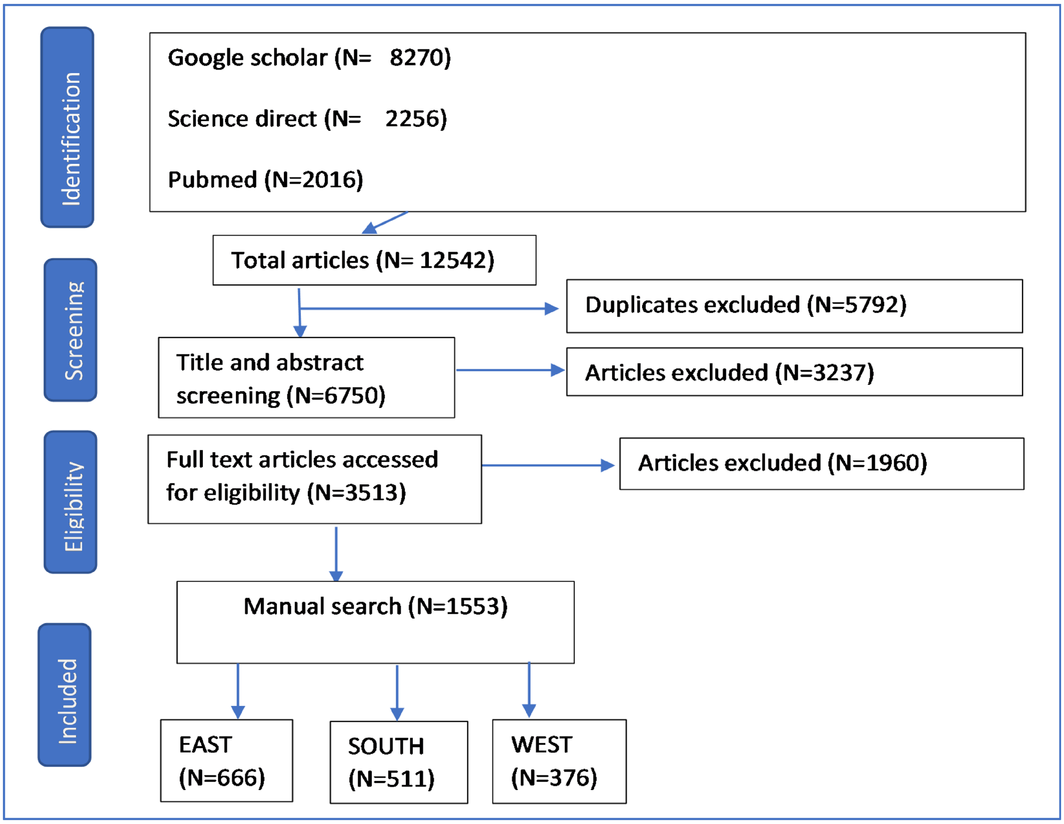

FIGURE 1 The review process showing the number of articles included in the study.

crops in each cluster are in Tables A2, A3, A5, A6, and A8 (cereals, vegetables, roots and tubers, legumes, and nuts, respectively).

2.5 | Nutrients related to research outputs

The study assumed two scenarios: (1) nutrients for each crop were quantified from current research outputs collected as the number of publications; and (2) a case reorientation in research investment involving the summation of research outputs for each crop in each cluster, with the average computed. In each case, an adoption rate of 30% was applied to the research outputs, according to Arslan et al. (2022), Magambo et al. (2020), Musa et al. (2022) and Teklewold et al. (2013).

2.6 | Scenario 1: Computation of nutrients from current research outputs

The number of research units (R) for each crop in each cluster was computed. The actual research outputs for each food crop, applying the 30% adoption rate, were computed as follows:

$$Y^{\Lambda} = \frac{30}{100} \times Y \tag{1}$$

where Y^{Λ} is the number of research outputs after applying the adoption rate and Y is the actual number of research outputs.

Total nutrients resulting from Y^{Λ} was computed as follows:

$$N_Y Z = Y^{\Lambda} \times \mathrm{NE}_L \tag{2}$$

where $N_Y Z$ is the nutrient added by Z crop, Y^{Λ} is the adopted research outputs computed in Equation 1, and NE_Z is the nutrient equivalent to nutritional component L, that is, K, Ca, P, protein, or carbohydrate.

This computation was done for each nutritional component, as shown in Tables A4, A7, and A9.

The nutrients calculated for each nutritional component within a crop were then summed as follows:

$$\mathrm{TN}_Y Z_{C1} = \sum_{i=1}^{n} N_Y Z\mathrm{i} = N_Y Z_1 + N_Y Z_2 + N_Y Z_3 + N_Y Z_4 + N_Y Z_5 \ldots . N_Y Zn \tag{3}$$

where $\mathrm{TN}_Y Z_{C1}$ is total nutrients for nutritional component Z and $N_Y Z_1 \cdots N_Y Zn$ are the nutrients calculated for each crop.

2.7 | Scenario 2: Computation of nutrients assuming a case of reoriented research

In each food cluster, the total number of adopted research outputs Y were divided by the number of crops in each cluster to find the number of units, assuming research was reoriented:

$$\mathrm{Bal} = \frac{Y^{\Lambda}}{K} \tag{4}$$

where K is the number of crops in each cluster.

The total nutrients assuming research was reoriented to compensate for under-researched food crops was computed as follows:

$$N_{\mathrm{Bal}} Z = \mathrm{Bal} \times \mathrm{NE}_L \tag{5}$$

where $N_{\mathrm{Bal}} Z$ is the nutrients for Z crop, Bal is research, and NE_L is nutrient equivalent to nutritional component L, that is, K, Ca, P, protein, or carbohydrate.

The nutrients calculated for each nutritional component were then summed as follows:

$$\mathrm{TN}_{\mathrm{Bal}} Z_{C1} = \sum_{i=1}^{n} N_{\mathrm{Bal}} Z\mathrm{i} = \begin{array}{l} N_{\mathrm{Bal}} Z_1 + N_{\mathrm{Bal}} Z_2 + N_{\mathrm{Bal}} Z_3 \\ + N_{\mathrm{Bal}} Z_4 + N_{\mathrm{Bal}} Z_5 \cdots N_{\mathrm{Bal}} Zn \end{array} \tag{6}$$

where $\mathrm{TN}_{\mathrm{Bal}} Z_{C1}$ is total nutrients for nutritional component Z and $N_{\mathrm{Bal}} Z_1 \cdots N_Y Zn$ are nutrients calculated for each crop, assuming a case of balanced research.

Nutrient gain was computed as the difference between the nutrient from actual and balanced research as follows:

$$\mathrm{NG} = \mathrm{TN}_{\mathrm{Bal}} Z_{C1} - \mathrm{TN}_Y Z_{C1} \tag{7}$$

2.8 | Crop diversity and nutrients

In each cluster, the contribution of each crop to nutrient gain was computed as a percentage of the total nutrient for each nutritional component across the three regions.

3 | RESULTS

3.1 | Review findings

The search database produced an initial search of 12,542 articles. After the screening exercise, which removed duplicates and checked titles and abstracts, a total of 6750 articles went through the eligibility stage. A total of 3515 articles went through full text screening for eligibility where they were assessed according to inclusion criteria which included; research articles on crops grown in Africa conducted between 2010 and 2021, in Africa, and within the universities of Nairobi, Pretoria, and Ghana repositories. Duplicate articles were also removed at this stage. A total of 1960 articles did not meet the criteria and were removed. In total, the review identified 1553 articles relevant for the study. Figure 1 shows the distribution of articles in each of the regions.

3.2 | Nature and type of research articles

More than 50% of the research articles had carried out collaborative research involving both international and national institutions as shown in Table 1. The collaborating institutions were diverse and included; other universities, National Agricultural Research Systems (NARS), Consortium of International Agricultural Research Centers (CGIAR), and Think Tanks. The institutions were distributed within Africa (East, West, South, and Central Africa) and globally (Europe, North America, South America, and Asia).

3.3 | Crop diversity in relation to research outputs

The number of research outputs varied between regions in the respective cluster crops. Across the three institutions, maize (*Zea mays*) was the predominant crop (Table 2). Other commonly researched crops in the cereal cluster included sorghum (*Sorghum bicolor*), rice (*Oryza sativa*), and wheat (*Triticum aestivum*). Finger millet (*Eleusine coracana*) and pearl millet (*Pennisetum glaucum*) had the fewest research outputs. In the vegetable cluster, amaranthus (*Amaranthus* spp.), nightshade (*Solanum nigrum*), and kale (*Brassica oleracea*) had the highest research outputs in Nairobi and Ghana. In Pretoria, kale, cabbage (*Brassica oleracea*), and spinach (*Spinacia oleracea*) had the highest research outputs.

TABLE 1 The percentage of collaborations, nature, and type of collaborating institutions and geographic reach.

	Description	%
Collaborations	Yes	53
	No	47
Nature of collaborating institutions	International	61
	National	39
Type of collaborating institutions	University	46
	NARS	28
	CGIAR	24
	Think Tank	2
Geographic reach	East Africa	39.0
	West Africa	16.0
	Europe	15.8
	South Africa	14.1
	North America	8.1
	Asia	4.6
	Central Africa	1.4
	South America	1.1

Abbreviations: CGIAR, Consortium of International Agricultural Research Centers; NARS, National Agricultural Research Systems.

In the root and tuber cluster, white and red-fleshed potatoes (*Solanum tuberosum* L.), cassava (*Manihot esculenta*), and sweet potato (*Ipomoea batatas*) had the most research outputs in Nairobi. A similar trend occurred in Pretoria, except for sweet potato. In Ghana, cassava had the highest research outputs, sweet potato and yam had a few, while white and red fleshed potatoes had none. In the legume cluster, common bean (*Phaseolus vulgaris L.*), soybean (*Glycine max*), and cowpea (*Vigna unguiculata*) had the most research outputs. In the nuts cluster, peanuts (*Arachis hypogaea* L.) had the most research outputs across the three institutions, with macadamia (*Macadamia integrifolia*) also studied in Ghana.

Some crops had no research outputs, including yam, cashew, and tiger nut in Nairobi, green gram and cashew in Pretoria, and white and red fleshed potatoes in Ghana.

The balanced research scenario showed that cereal crops had high research outputs across the three regions. In Nairobi and Ghana, vegetable crops ranked second for research outputs, followed by roots and tubers. In Pretoria, roots and tubers ranked second for research outputs after cereals, with vegetables third.

3.4 | Nutrient density and diversity in relation to research outputs for cereals, vegetables, root and tubers, legumes, and nuts

Table 3 shows the nutrient gain for cereals crops, which was positive for all nutritional components, except for fat in Nairobi and Pretoria, indicating nutrient gain. In contrast, Ghana had negative values for Potassium (K), Sodium (Na), Magnesium (Mg), Zinc (Zn), fat, and carbohydrates, indicating nutrient loss. Pretoria ranked best in nutrient gain for K, Na, Mg, Fe, Mn, Zn, and carbohydrate. Nairobi ranked best in nutrient gain for the thiamin, nicotinic acid, protein, and dietary fiber. In the vegetable cluster, the nutritional components had positive values in Ghana, as did Nairobi, except for protein, and Pretoria, except for Zn and Thiamin (Table 3). Nairobi ranked best in nutrient gain for Ca, Mg, Fe, Zn, thiamin, carotene,

TABLE 2 Number of research outputs for actual, actual after adoption, and balanced for different crops across Nairobi, Pretoria, and Ghana.

		Nairobi			Pretoria			Ghana		
Cluster	**Crop**	**Actual**	**After adoption**	**Balanced**	**Actual**	**After adoption**	**Balanced**	**Actual**	**After adoption**	**Balanced**
Cereals	Maize	149	44.7	12.4	177	53.1	14.52	67	20.1	5.8
	Sorghum	25	7.5	12.4	32	9.6	14.52	7	2.1	5.8
	Wheat	8	2.4	12.4	22	6.6	14.52	1	0.3	5.8
	Rice	22	6.6	12.4	4	1.2	14.52	37	11.1	5.8
	Finger millet	2	0.6	12.4	2	0.6	14.52	2	0.6	5.8
	Pearl millet	2	0.6	12.4	5	1.5	14.52	2	0.6	5.8
Vegetables	Amaranth	50	15	11.6	5	1.5	3.42	22	6.6	4.86
	Nightshade	42	12.6	11.6	4	1.2	3.42	16	4.8	4.86
	Kale	22	6.6	11.6	18	5.4	3.42	10	3.3	4.86
	Cabbage	19	5.7	11.6	15	4.5	3.42	8	2.4	4.86
	Spinach	19	5.7	11.6	16	4.8	3.42	6	1.8	4.86
Root and Tubers	White flesh	31	9.3	6.24	44	13.2	5.64	0	0	1.9
	Red flesh	21	6.3	6.24	30	9	5.64	0	0	1.9
	Sweet potato	20	6	6.24	3	0.9	5.64	4	1.2	1.9
	Cassava	32	9.6	6.24	16	4.8	5.64	22	6.6	1.9
	Yam	0	0	6.24	1	0.3	5.64	5	1.5	1.9
Legumes	Common bean	41	12.3	3.6	6	1.8	2.4	2	0.6	1.14
	Green gram	1	0.3	3.6	0	0	2.4	2	0.6	1.14
	Pea	3	0.9	3.6	1	0.3	2.4	1	0.3	1.14
	Soybean	5	1.5	3.6	21	6.3	2.4	6	1.8	1.14
	Cowpea	10	3	3.6	10	3	2.4	8	2.4	1.14
	Marama bean	0	0	3.6	10	3	2.4	10	3	1.14
Nuts	Peanuts	3	0.9	0.5	2	0.6	0.6	5	1.5	1.65
	Macadamia	2	0.6	0.5	2	0.6	0.6	2	0.6	1.65
	Cashew	0	0	0.5	0	0	0.6	2	0.6	1.65
	Tiger nut	0	0	0.5	4	1.2	0.6	10	3	1.65

Note: Actual are research outputs from published work; after adoption are research outputs after applying an adoption rate of 30%; balanced are research outputs, assuming reoriented research investment to compensate for under-researched crops.

TABLE 3 Nutrient gain in cereal and vegetable crops across three African regions.

	Cereals			Vegetables		
Nutritional components	Nairobi	Pretoria	Ghana	Nairobi	Pretoria	Ghana
Ca (mg)	1955*	1902	597	1197*	658	730
P (mg)	19,724	23776*	2133	–	–	–
K (mg)	16,758	21762*	−2661	–	–	–
Na (mg)	151	206*	−64	–	–	–
Mg (mg)	3878	5138*	−593	315*	185	165
Fe (mg)	557	657*	177	20*	2	12
Mn (mg)	205	277*	26	–	–	–
Zn (mg)	125	183*	−27	8*	−2	5
Thiamin (mg/100 g)	6*	5	3	6*	−1	4
Riboflavin (mg/100 g)	2	2	1	–	–	–
Nicotinic acid (mg/100 g)	42*	31	15	–	–	–
Carotene (mg/100 g)	–	–	–	12634*	7810	6911
Vitamin A	–	–	–	43*	29	23
Vitamin C	–	–	–	395	424*	312
Protein (g/100 g)	144*	141	31	–	–	–
Fat (g/100 g)	−154	−202	−63	9	1	5
Dietary fiber (g/100 g)	155*	126	66	–	–	–
Carbohydrates (g/100 g)	887	937*	−60	32	56	27
Energy	–	–	–	2030	72	1357

Note: The nutrient gain was based on computation of the research outputs-actual versus balanced (Table 1) and nutrient composition for each (Tables A2 and A3). The actual computation is shown in Table A4. The * shows highest in nutrient gain, – indicate not applicable or insufficient data for computation.

Abbreviations: Ca, calcium; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; Na, sodium; P, phosphorus; Zn, zinc.

energy, and Fat. Pretoria ranked best in nutrient gain for Vitamin C and carbohydrates.

In the root and tuber cluster, nutrient gain occurred under balanced research outputs for most nutritional components except for Mg, Na, ascorbic acid, protein, niacin, and folate in Nairobi, P, ascorbic acid, protein, niacin, folate, and vitamin K in Pretoria, and Ca, ascorbic acid, energy, lipid, carbohydrates, folate, and vitamin E in Ghana (Table 4). Pretoria ranked best in nutrient gain for Ca, Mg, Na, thiamin, riboflavin, lipid, carbohydrate, fiber, niacin, vitamin B6, and vitamin A, as were K, thiamin, vitamin E for Nairobi and P, protein, and folate for Ghana.

In the legume cluster, nutrient gain occurred for most nutritional components except for carbohydrates, K, Mn, and thiamine in Nairobi, fat, Mg, K, Na, Zn, and folic acid in Pretoria, and carotene, energy, iron, riboflavin, and folic acid in Ghana (Table 4). Nairobi ranked best in nutrient gain for Ca, Mg, P, Na, Zn, Fe, protein, riboflavin, niacin, folate, carotene, and choline, as were with thiamin, energy, carbohydrate, and fiber for Pretoria and K and Mn for Ghana.

In the nut cluster, there was nutrient gain for most nutritional components except for Ca, niacin, and folate in Nairobi, thiamin, riboflavin, and niacin in Pretoria, and folate and niacin in Ghana (Table 4). Ghana ranked best in nutrient gain for Ca, Mg, K, P, Na, Zn, Fe, ascorbic acid, thiamin, riboflavin, energy, carbohydrate, folate, vitamin K, vitamin A, pantothenic acid, and pyridoxine, as were protein and lipid for Pretoria.

3.5 | Nutrient contribution from different crops in cereal, vegetables, root and tuber, legume, and nuts

In the cereal cluster, the highest percentage of nutrient contribution came from finger millet for most nutrients, which included P, K, Na, Fe, thiamin, riboflavin, protein, and dietary fiber; rice for Mg, Zn, and carbohydrates; wheat for Ca, and maize for fat (Figure 2). Rice had the lowest percentage contribution for most nutrients, which included thiamin, riboflavin, nicotinic, protein, fat, and dietary fiber.

In the vegetable cluster, the highest percentage contributions for most nutrients was from amaranth for protein, Ca, Mg, Fe, Zn, Vitamin A, and carbohydrates, kale for Vitamin C, energy, and fat, and spinach for Zn and thiamin (Figure 3). The lowest contribution for most nutrients

TABLE 4 Nutrient gain in root and tuber, legume, and nuts crops for Nairobi, Pretoria, and Ghana.

	Root and tuber			Legume			Nuts		
Nutritional components	**Nairobi**	**Pretoria**	**Ghana**	**Nairobi**	**Pretoria**	**Ghana**	**Nairobi**	**Pretoria**	**Ghana**
Ca (mg/100 g)	29.9	141*	−11.3	576*	326	167	−4.80	5.8	51.0*
Mg (mg/100 g)	−0.6	11*	8.9	571*	−135	68.9	124	128	372*
K (mg/100 g)	2917*	1435	926	−3087	−593	1118*	144	209	457*
P (mg/100 g)	71	−138	161*	1184*	420	80			
Na (mg/100 g)	−30	133*	40.9	340*	−16	59	6.80	10	20*
Zn (mg/100 g)	–	–	–	14*	−3.2	2.3	1.29	1.55	3.13*
Mn (mg/100 g)	–	–	–	−7.4	−4.6	2.4*	–	–	–
Fe (mg/100 g)	–	–	–	20.5*	2.6	−2.7	2.59	2.76	8.38*
Ascorbic acid (mg/100 g)	−6.1	−36	−34	–	–	–	0.33	0.20	2.09*
Thiamin (mg/100 g)	0.2*	0.2*	0.0	−1.6	1.1*	0.3	0.01	−0.12	1.08*
Riboflavin (mg/100 g	−0.1	0.2*	−0.1	1.0*	0.7	−0.1	0.01	−0.01	0.20*
Energy (Kcal)	2.5	406*	−380	121	794*	−65	233	686	1201*
Protein (g)	−0.6	−3.1	2.0*	141*	38	13	2.20	20*	5.205
Total lipid (g)	0.0	0.7*	−0.9	–	–	–	2.46	67*	63
Carbohydrate (g)	1.6	102*	−93	−134	94*	44	29	23	87*
Fiber (g)	13.9	15*	3.1	2.7	10*	0.8	–	–	–
Niacin (mg/100 g)	0.28	0.2*	0.0	35.9*	5.9	9.3	−2.00	−1.21	−4.73
Vitamin B6 (mg/100 g)	−0.1	0.28*	−0.1	–	–	–	–	–	–
Folate (ig)	−2.8	−5.9	0.8*	307*	−412	−226	–	–	–
Folate (mg/100 g)	–	–	–	–	–	–	−0.01	0.00	−0.05
Vitamin E (mg/100 g)	1.0*	0.6	0.6	–	–	–	1.00	0.98	3.30*
Vitamin K (μg)	−0.7	−0.7	−41	–	–	–	0.01	0.01	0.03*
Vitamin A (IU/IU)	1.6	3.2*	−0.5	–	–	–	0.44	0.52	1.44*
Carotene (ig)	–	–	–	1317*	644	−212	–	–	–
Choline (ig)	–	–	–	442*	408	86	–	–	–
Pantothenic (mg/100 g)	–	–	–	–	–	–	0.13	0.08	0.75*
Pyridoxine (mg/100 g)	–	–	–	–	–	–	0.13	0.08	0.50*

Note: The nutrient gain was based on computation of the research outputs-actual versus balanced (Table 1) and nutrient composition for each (ATables A5, A6, and A8). The actual computation is shown in Tables A7 and A9. The * shows highest in nutrient gain, − indicate not applicable or insufficient data for computation.

Abbreviations: Ca, calcium; Fe, Iron; K, potassium; Mg, magnesium; Mn, manganese; Na, sodium; P, phosphorus; Zn, zinc.

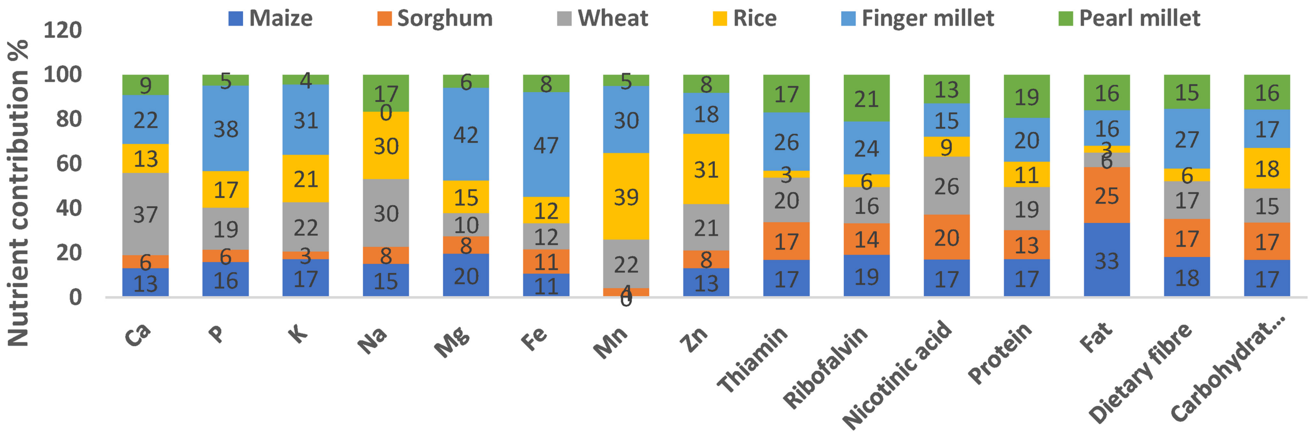

FIGURE 2 Contribution of nutrients for each food crop in the cereal cluster. Ca, calcium; K, potassium; Mg, magnesium; Na, sodium; P, phosphorus; Zn, zinc.

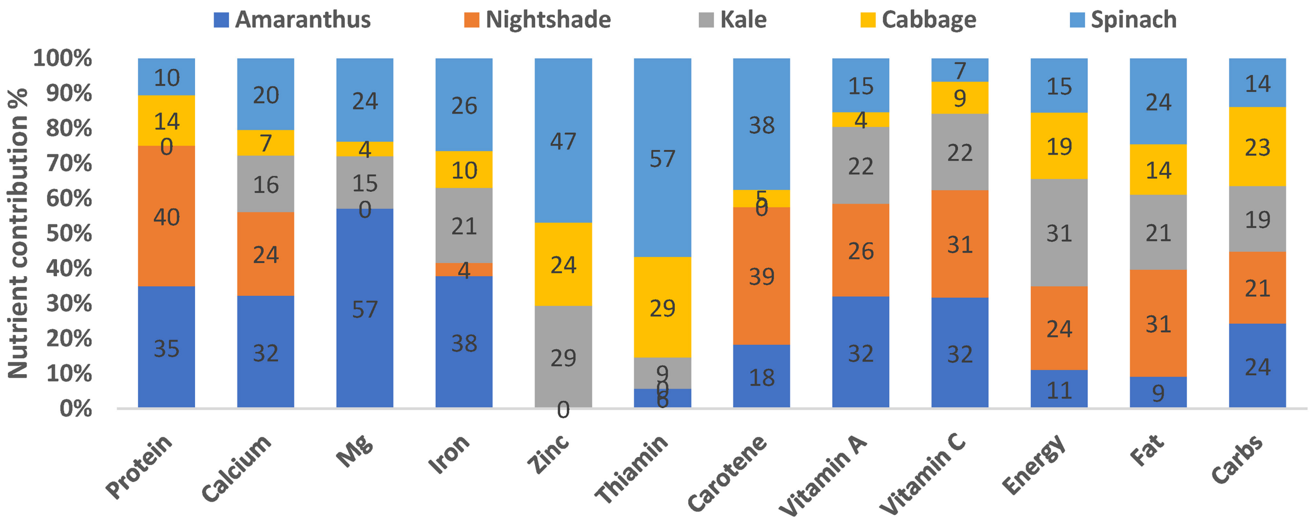

FIGURE 3 Contribution of nutrients for each food crop in the vegetable cluster. Mg, magnesium.

was from kale for Ca and vitamin A, kale for protein and carotene and nightshade for Mg and Zn.

In the root and tuber cluster, the highest contributions for most nutrients came from sweet potatoes for Ca, Mg, Na, thiamin, sugars, and Vitamin A; yam for K, energy, fiber, Vitamin B6, and Vitamin E; cassava for Vitamin C; total lipids, carbohydrates, and folate, and red-fleshed potatoes for P; protein, niacin, and vitamin K (Figure 4). The lowest contribution for most nutrients was from white-fleshed Irish potato for Ca, Mg, thiamin, riboflavin, energy, total lipid, carbohydrate, vitamin E, and vitamin A.

In the legume cluster, the highest contributions came from soybeans for protein, energy, Ca, P, Fe, Mg, and riboflavin; Marama bean for fat, Na, Zn, and niacin; cowpea for K, folic acid and choline; peas for moisture and crude; and common bean for thiamin (Figure 5). The lowest contribution for most nutrients came from fat, P, Fe, Mn, thiamin, and folic acid.

In the nut cluster, the highest contributions came from cashew for Fe, Zn, pantothenic acid, pyridoxine, cobalamin, and Vitamin K; macadamia for Mg, thiamin, riboflavin, Vitamin C, fat, and energy; peanut for Ca, K, and folate; and tiger nut for Vitamin E, Vitamin A, and carbohydrates (Figure 6). The lowest contribution for most nutrients was from tiger nut for thiamin, riboflavin, pantothenic acid, pyridoxine, folate, cobalamin, and vitamin A.

4 | DISCUSSION

4.1 | Research outputs in relation to crop diversity

Investment in research in cereal crops such as maize, wheat, and rice with less attention given to other crops has contributed to low crop and dietary diversity, leading

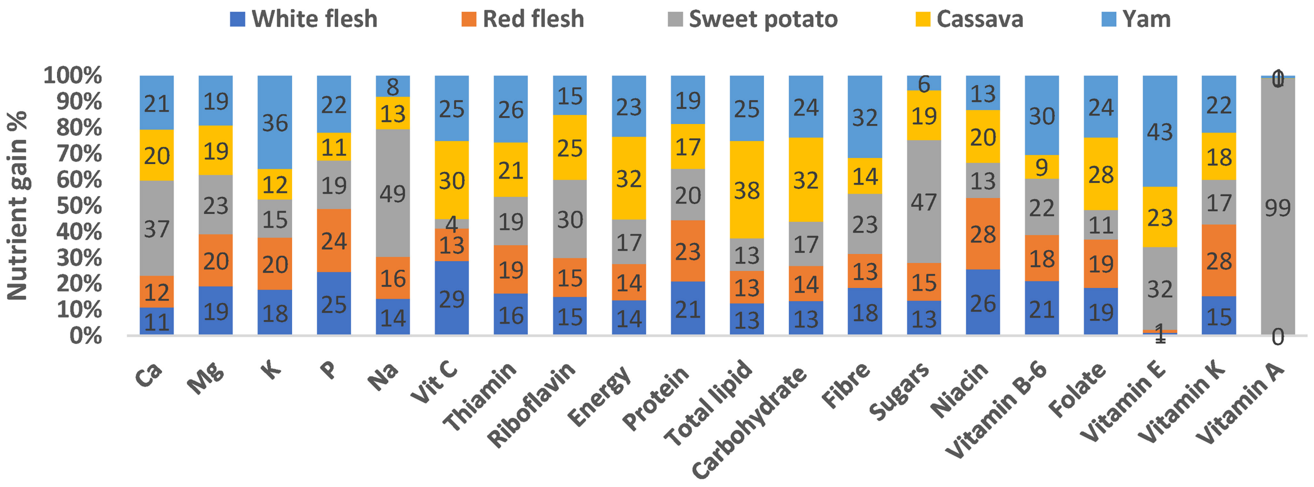

FIGURE 4 Contribution of nutrients for each food crop in the root and tuber clusters. Ca, calcium; K, potassium; Mg, magnesium; Na, sodium; P, phosphorus.

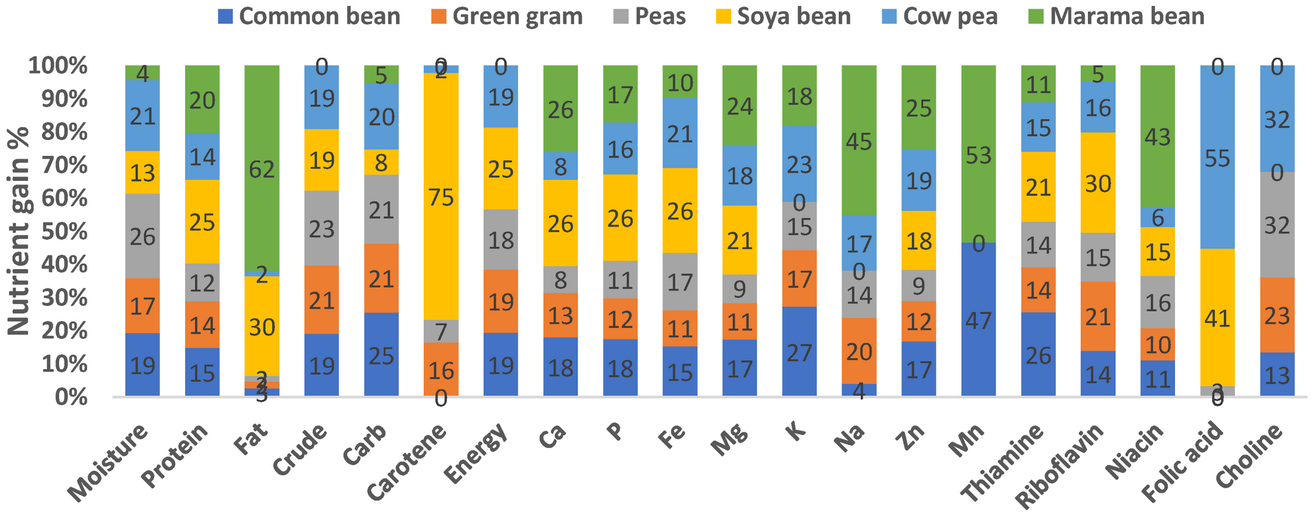

FIGURE 5 Contribution of nutrients for each food crop in legume cluster. Ca, calcium; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; Na, sodium; P, phosphorus; Zn, zinc.

to food insecurity (Akinola et al., 2021). The research investigated research outputs benchmarked as the number of publications in relation to crop diversity across three institutions: Nairobi, Pretoria, and Ghana, and its implication on food security. The high research outputs recorded for cereals (maize), as shown in Table 1, were an indication of more research investment in the crop compared to other crops such as vegetables, roots and tuber, nuts, and legumes, demonstrating low crop diversity. This can be attributed to the fact that for a long time, research investments have focused on of maize, wheat, and rice (Babele et al., 2022; Lynam et al., 2016; Munialo et al., 2023). Many investments, especially in seed production, are focused on staples and exports, leaving behind indigenous crops (Keatinge et al., 2015). This has limited the expected level of advancement in the production, commercialization, and utilization of these crops (Tadele, 2019).

The research outputs in each of the clusters were specific to each institution. In the vegetable, roots and tuber, legumes, and nuts clusters, the high research outputs recorded for amaranth and nightshade (Nairobi and Ghana), cassava across the three institutions, as well as common beans (Nairobi), Marama bean (Ghana and Pretoria), cowpea (Ghana), and tiger nut (Ghana), respectively, were an indication of a slow shift in research investment toward these crops. These can be attributed to increasing efforts to promote production and utilization of these crops. Initiatives such as the creation of awareness about the nutritional value of these crops and capacity enhancement in production are continuing to contribute to the prioritization of the crops in the research agenda

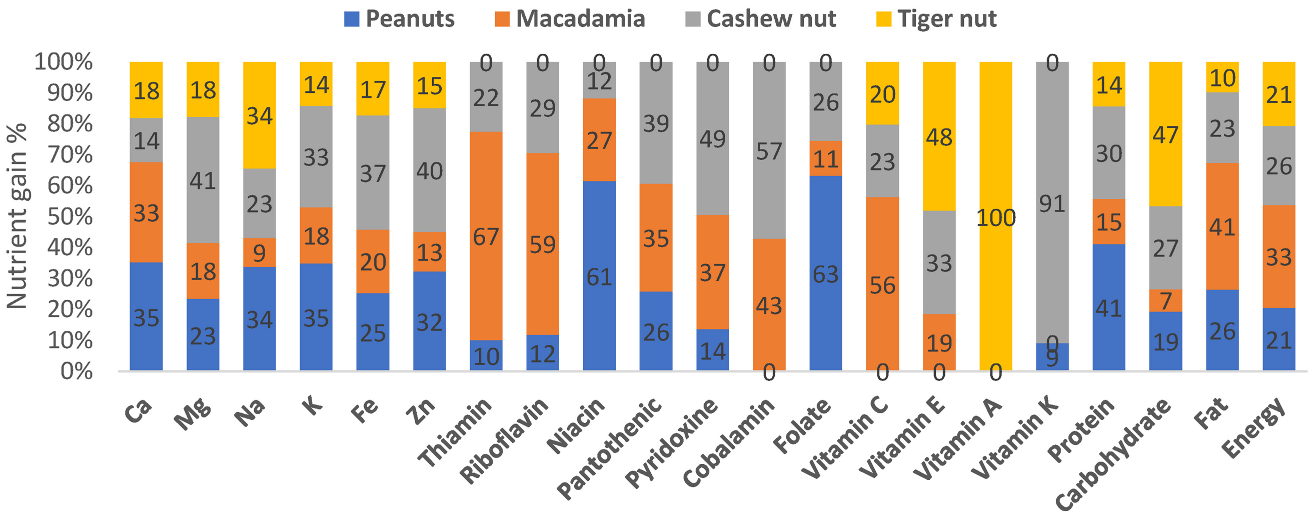

FIGURE 6 Contribution of nutrients for each food crop in nut cluster. Ca, calcium; Fe, iron; K-Potassium; Mg, magnesium; Na, sodium; Zn, zinc.

(Pichop et al., 2016). However, compared to maize, most indigenous crops still experience a large research deficit, as shown by the low research outputs in comparison to the nutrients the crops are contributing to the food system, resulting in food insecurity. Foyer et al. (2016) have shown the effects of neglecting grain legume crops on human health and sustainable production.

Low research for pearl millet, finger millet, and yam across the three institutions: amaranth and nightshade (Pretoria), sweet potatoes (Pretoria and Ghana), Marama bean (Nairobi), and soya bean (Nairobi and Ghana) is contributing to marginal yields and reduced production areas of these crops. Marginal yields and high yields gaps persist limiting the economic use of these crops (Akinola et al., 2021; Grovermann et al., 2018). Large yield gap (potential yield compared to actual yield) of 56% for pearl millet (Bastos et al., 2022), 55% for finger millet (Bastos et al., 2022), 300% for legumes (chick pea, soyabean and pigeon pea) (Foyer et al., 2016), 76% for root and tuber crops (Blomme et al., 2020), 72% for cashew nuts (Amanoudo et al., 2022), and 55% for groundnuts (Amanoudo et al., 2022) have been experienced. These yield gaps are large compared to the ones for maize, rice, and wheat which currently stands at 33%, 29%, and 20%, respectively (Awio et al., 2022; Silva et al., 2023, 2021). The area under cultivation for indigenous crops grown in Africa is low compared to maize, rice, and wheat. The combined area under millet (pearl millet, finger millet) is 10 million hectares, legumes (chick pea, pigeon pea, groundnuts, soya beans, common beans, and cowpea) is 36 million ha compared to maize, rice, and wheat which is 43, 10.2, and 10 million ha, respectively (Arouna et al., 2021; Cairns et al., 2021; Ojiewo et al., 2018; Rouamba et al., 2021).

The low research outputs have also affected the abundance and distribution of indigenous crops compared to maize, rice, and wheat. Although studies have shown that Indigenous Africa's Crops are suited for production in areas with dry to semi-arid areas and in areas with marginal fertilizer (Saxena et al., 2018), studies have shown limited concentration of these crops in these environments as most 60% is area under maize production (Orr et al., 2016; Santpoort, 2020). Chick pea is highly produced in Ethiopia, whereas it has been shown to suitably be grown in Kenya, Malawi, Niger, South Sudan, Sudan, Togo, Uganda, Tanzania, and Zimbabwe (Addisu et al., 2023; Fikre et al., 2020). Pigeon pea is mostly grown in a few places in Eastern Africa Fatokimi and Tanimonure (2021), while soya bean production is concentrated in the Southern part of Africa (Dlamini et al., 2014; Foyer et al., 2019). The impacts of the low research outputs have also contributed to reduced economic benefits within smallholder farms in spite of the high monetary value of sorghum, millet, groundnuts, cowpea, Bambara nut, pigeon pea, and pearl millet compared to maize (Abass et al., 2014; Orr et al., 2016).

Indigenous crops have multidimensional benefits, which include dietary provision, social development, resilience to climate change, improved livelihoods and rural development, biodiversity conservation, cultural diversity and heritage, adaptation to harsh environments, and low-input agriculture (Siddique et al., 2021). The low research outputs of indigenous crops indicated low productivity and utilization. Pichop et al. (2016) have also shown low production and utilization of indigenous crops in favor of exotic types. These have contributed to narrow the food base, resulting in food insecurity manifested as malnutrition, obesity, chronic diseases, and stunting in children across the African continent. Research investments that prioritize indigenous crops are needed to promote their production and utilization.

4.2 | Research outputs in relation to nutrition

Recent discourse in food systems has revolved around the need to refocus research on under-researched crops to achieve sustainable food and nutrition security (Mabhaudhi et al., 2017; Manners & Van Etten, 2018). The research investigated the nutritional gains by relating research outputs to nutritional quality and quantity in a case of research reorientation to include under-researched crops. Our study revealed that reorienting research toward under-researched crops will increase nutrition and improve dietary diversity (Tables 3 and 4), attributed to the nutrient contribution from each crop in five clusters: cereals, vegetables, legumes, roots and tubers, and nuts. The findings correspond to Manners & Van Etten, 2018, who have shown high nutrient contribution from under-researched indigenous crops. The nutrient gain mostly comes from under-researched and under-exploited indigenous crops. This can be attributed to the high micro and macro nutrients of these crops (Chandrasekara & Josheph Kumar, 2016; Kamboj & Nanda, 2018; Maina & Mwangi, 2008; Pradhan et al., 2021; Ramashia et al., 2021; Suárez-Martínez et al., 2016; Suleiman et al., 2018). For example, in the cereal cluster, finger millet adds more nutrients for most nutritional components than maize, rice, and wheat (Figure 2). This is due to the high nutrient content of calcium and iron in finger millet and sorghum compared to maize (Babele et al., 2022). In the vegetable cluster, amaranth and nightshade contribute more nutrients because of the high levels of protein, magnesium, calcium, iron, potassium, manganese, and zinc compared to spinach, kale, cabbage, and maize (Aderibigbe et al., 2022). Amaranth and nightshades have also been shown to have high levels of bioactive compounds such as phenolic acids, protocatechuic, hydroxybenzoic, caffeic, and ferulic acid, rutine, nicotiflorin, and isoquercetin to fight chronic disease, aging, oxidation, and memory loss (Aderibigbe et al., 2022). In the root and tuber cluster, sweet potatoes and yams add more nutrients, as do soybean and Marama bean in the legume cluster and cashew and macadamia in the nut cluster, reflecting the high and diverse nutrient level of these crops (Tables A2, A3, A5, A6, and A8). Reorienting research to include other crops will contribute to sustainable, resilient, diversified food systems, reaching sustainable development goals, agrobiodiversity conservation, climate change mitigation, reducing food imports, increasing commercialization, and soil and water conservation.

Realizing sustainable food systems through crop diversification is important for ensuring social, economic, and environmental stability into the future. The study showed nutrient gain across all clusters (cereals, vegetables, legumes, roots and tubers, and nuts), achievable with balanced research investments that allow for increased production of diverse underexploited crops. Climate change, emerging pandemics, and civil wars are current events contributing to unsustainable food systems, compounded by the predominance of a few crops (maize, rice, and wheat). Balanced research will allow for technological advances in crop diversity and productivity resulting in high yields. The production of a range of food crops will lead to diversified diets and sustainable food systems and contribute to overcoming global malnutrition. Food imports have increased the diversity of food supply in underperforming regions (Kummu et al., 2020), with economic and environmental effects on the importing and exporting countries, respectively (Nicholson et al., 2021). Countries with a high reliance on imports also suffer from food insecurity when subjected to trade wars, market shifts, and price shocks. Balanced research to allow the production of underproduced crops will increase production, improving food security and buffering countries and regions against the economic and environmental impacts of food imports. Food and nutrition insecurity across different regions hampers success in the sustainable development goals, particularly SDGs 1, 2, 5, 6, 12, 13, 15, and 17 (FAO, 2018). Cropping system diversification through reoriented research is one way to achieve food and nutrition security and expedite reaching the SDGs and achievement of Africa Agenda 2063 by eliminating all forms of food insecurity.

Many indigenous or traditional crops remain undocumented, and the documented few have not been fully exploited (Sibanda & Mwamakamba, 2021). Reoriented research will provide an opportunity to record undocumented indigenous crops to unleash their market and commercialization potential. Indigenous crops are well adapted to drought and heat stress, semi-arid and arid environments, resistant to pests and diseases, and do well in marginal soils (Keatinge et al., 2015). Increasing efforts to bring these crops back into the mainstream food system may render them susceptible to pests and diseases. Studies have even pointed out to pest and disease as one of the genetic and management constraints for these crops that needs focus (Dawson et al., 2019). Refocusing research to include under-research crops will also allow for advances in genetic capability of indigenous crops to pest and disease.

4.3 | Relevance and applicability of the findings

This study showed similarities and differences in crop diversity and nutrient gain across the three institutions.

Similarities in researched crops occurred predominantly in the cereal cluster. Differences in researched crops in the vegetable, legume, root and tuber, and nut clusters were observed across the three institutions. Differences also occurred in nutrient gain in the different cluster crops for reoriented research across the three regions. High nutrient gain occurred for cereals and root and tuber crops in Pretoria, vegetables and nuts in Ghana, and legumes in Nairobi. These findings are significant and can inform research investments and the designing of policies to improve research on under-exploited crops across different institutions within the African continent. Deficiency of certain elements such as zinc is of concern as statistics show that more than a third of the population suffer from shortage of this element (Tabrez et al., 2022).

The crops in this study equally contribute nutrients to the food systems as shown from the findings. Due to resource constraints, research investment to increase production and utilization on focus crops are needed to ameliorate nutrient deficiency. Considering nutritional contribution from each food group (cereals, vegetables, root and tuber, legumes, and nuts), research investment and implementation should be done on the following priority crops; finger millet, amaranthus, sweet potato, soya bean, and cashew nut. These crops are also adapted to climate change, for example, finger millet Luitel et al. (2019) have high market potential, for example, cashew nuts Monteiro et al. (2017) and contribution to soil conservation, for example, sweet potato and soya bean (Afzal et al., 2021; Karunakaran & Behera, 2015). Research investments considering geographic suitability could target cassava and peanuts in the West Africa region (Faye et al., 2018; Sanni et al., 2009), Marama bean in Southern Africa part (Cullis et al., 2023) as well as common bean (Katungi et al., 2010) and nightshade (Sangija et al., 2021) in East Africa. Considering under-researched crops research investments should target finger and pearl millet across the three institutions for the cereal cluster. In the vegetable cluster, investment in research should target amaranth and nightshade in Pretoria. In the root and tuber cluster, investment should target yam in Nairobi, sweet potato in Pretoria, and white and red fleshed potatoes in Ghana. In the legume cluster, research investment should target green gram and pea in all regions, Marama bean and soybean in Nairobi, and common bean in Pretoria and Ghana.

Transforming indigenous Africa's crops will require funding supported by the government within the respective regions. Government should consider designing packages that specifically target research on indigenous Africa's crops. Policy formulation should aim at un leashing the potential of Africa's crops along the food systems value chain. At the production level, indigenous crops are hampered by use of poor quality of seed and a lack of standard agronomic procedures (Akinola et al., 2021; Kansiime et al., 2018). Research investment that enhances the development of quality seed and standard agronomic practices applicable across the African continent are needed to improve production. Significant loss and waste occur at the postharvest and handling of indigenous crops. Inadequate processing also results in reduced commercialization of these crops (Thandeka et al., 2022). Research investment to identify methods that improve the shelf-life and commercialization of these crops is needed. These policies should aim at developing standard procedures in postharvest and handling and packaging of the indigenous crops. Low consumption of indigenous Africa's crops especially among the young generation and urban residents within certain region has resulted in low production and loss of biodiversity of indigenous crops (Zulu et al., 2022). Continuous creation of awareness on the nutritional value of these crops using targeted messages through media platforms is required to increase their utilization. The increased focus on maize, wheat, and rice could contribute to reduce biodiversity of indigenous crops. Policies, measures, and regulations to conserve and protect indigenous crops are needed. Such measures could include building of community protection hubs within the different geographic regions in the African continent and empowering communities on the benefits of conserving and preserving indigenous crops.

5 | CONCLUSION

The study analyzed the potential benefits of balancing research by incorporating under-researched crops to advance food and nutrition security in three leading African institutions: Nairobi, Pretoria, and Ghana. Research outputs quantified as the number of publications were related to crop diversity and nutrients. The findings revealed that research biased toward under-researched crops could increase nutrients and improve dietary diversity. The nutrient increase resulted from indigenous crops, such as finger millet, amaranth, nightshade, yam, sweet potato, Marama bean, and soybean. This could have positive implications for food and nutrition security, achievement of sustainable development goals and Africa Agenda 2063. The findings also highlight similarities and differences in crop diversity and nutrient gain when reorienting research to under-researched crops. The study contributes to the ongoing debate on the need to refocus attention on under-researched and under-exploited crops. Considering nutritional contribution, adaptation to climate change, market potential, and contribution to soil conservation, research investment could focus on the following crops:

fingermillet, amaranthus, sweet potato, soyabean, and cashew nuts. Other rationales to merit investment include geographic coverage and institutional involvement. Further research should explore the, production, economic (marketability and income), and environmental gains (adaptive ability to climate change) related to research outputs for the specific crops. The development of frameworks to guide analysis of the nature and scope of factors affecting the contribution of indigenous crops to food security and nutrition is also needed.

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CONFLICT OF INTEREST STATEMENT

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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APPENDIX A

TABLE A1 Common and scientific names of indigenous crops found in Africa.

Common name	Scientific name	Common name	Scientific name
Sorghum	*Sorghum bicolor*	Sweet potato	*Ipomoea batatas*
Pearl millet	*Pennisetum glaucum*	Taro	*Colocasia esculenta*
Finger millet	*Eleusine coracana*	Cowpea	*Vigna unguiculata*
Teff	*Eragrostis tef*	Lablab beans	*Lablab purpureus*
African rice	*Oryza glaberrima*	Pigeon pea	*Cajanus cajan*
Cassava	*Manihot esculenta*	Chickpea	*Cicer arietinum*
Yams	*Dioscorea*	Guava	*Psidium guajava*
Loquats	*Eriobotrya japonica*	Macadamia	*Macadamia ternifolia*
Baobab	*Adansonia digitata L*	Cashew nuts	*Anacardium occidentale*
Amarula	*Sclerocarya birrea*	Bambara groundnuts	*Vigna subterranea*
Nightshades	*Solanum*	Cumin	*Cuminum cyminum*
Spider plant	*Cleome gynandra*	Saffron	*Crocus sativus*
Amaranth	*Amaranthus*	Rosemary	*Salvia rosmarinus*
Pumpkin	*Cucurbita*	Ginger	*Zingiber officinale*
Moringa	*Moringa oleifera*	Nutmeg	*Myristica fragrans*
Marama bean	*Tylosema esculentum*		

TABLE A2 Nutrient composition for selected cereal crops.

	Ca (mg)	P (mg)	K (mg)	Na (mg)	Mg (mg)	Fe (mg)	Mn (mg)	Zn (mg)	Thiamin (mg/100 g)
Maize	60	990	1200	10	470	11	0	5	0.38
Sorghum	27	350	240	5	188	11	1	3	0.38
Wheat	170	1170	1550	20	250	12	5	8	0.45
Rice	60	1030	1500	20	350	12	9	12	0.07
Finger millet	100	2400	2200	0	1000	48	7	7	0.59
Pearl millet	42	296	307	10.9	137	8	1.15	3.1	0.38

Source: Ramashia et al. (2021).

TABLE A3 Nutrient composition for selected vegetable crops.

	Protein (g/100 g)	Calcium (mg/100 g)	Mg (mg/100 g)	Iron (mg/100 g)	Zinc (mg)
Amaranthus	4	270	130	3	0
Nightshade	4.6	200	0	0.3	0
Kale (*Brassica oleracea*)	0	135	34	1.7	0.44
Cabbage (*Brassica oleracea*)	1.4	52	8	0.7	0.3
Spinach (*Spinacia oleracea*)	1.2	170	54	2.1	0.7

Source: Maina and Mwangi (2008).

TABLE A4 Nutrient gain between actual and balanced research outputs for cereals and vegetable crops for Nairobi, Pretoria, and Ghana.

	Cereals								
	Nairobi			Pretoria			Ghana		
Nutritional components	N-Bal	N-Actual	Gain	N-Bal	N-Actual	Gain	N-Bal	N-Actual	Gain
Ca (mg)	5728	3774	1955	6665	4762	1902	2662	2065	597
P (mg)	77,825	58,102	19,724	90,547	66,771	23,776	36,169	34,036	2133
K (mg)	87,323	70,564	16,758	101,596	79,835	21,762	40,583	43,243	−2661
Na (mg)	822	671	151	957	751	206	382	446	−64
Mg (mg)	29,890	26,011	3878	34,775	29,637	5138	13,891	14,484	−593
Fe (mg)	1273	716	557	1481	824	657	592	415	177
Mn (mg)	289	84	205	336	59	277	134	108	26
Zn (mg)	475	350	125	553	370	183	221	248	−27
Thiamin (mg/100 g)	28	22	6	33	28	5	13	10	3
Riboflavin (mg/100 g)	13	11	2	15	14	2	6	5	1
Nicotinic acid (mg/100 g)	265	222	42	308	277	31	123	108	15
Protein (g/100 g)	761	617	144	886	745	141	354	323	31
Fat (g/100 g)	392	546	−154	456	658	−202	182	245	−63
Dietary fiber (g/100 g)	926	771	155	1077	951	126	430	364	66
Carbohydrates (g/100 g)	5475	4588	887	6225	5288	937	2544	2604	−60
Carotene (mg/100 g)	–	–	–	–	–	–	–	–	–
Vitamin A	–	–	–	–	–	–	–	–	–
Vitamin C (mg/100 g)	–	–	–	–	–	–	–	–	–

Note: The nutrient gain was based on computation was based on N-Bal versus N-Actual represent nutrients for balanced and actual research outputs respectively.

Source: Own generation.

Abbreviations: Ca, calcium; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; Na, sodium; P, phosphorus; Zn, zinc.

Riboflavin (mg/100 g)	Nicotinic acid (mg/100 g)	Protein (g/100 g)	Fat (g/100 g)	Minerals (g/100 g)	Dietary fiber (g/100 g)	Carbs (g/100 g)
0.2	3.6	10.5	10.5	1.2	13.4	73
0.15	4.3	7.9	7.9	1.6	12.8	73
0.17	5.5	11.8	2	1.8	12.6	71.2
0.06	1.9	7	1	0.6	4.1	79
0.25	3.2	12	5	2.3	20	75
0.22	2.7	11.8	5	2.3	11.3	67.5

Thiamin (mg/100 g)	Carotene (mg/100 g)	Vitamin A	Vitamin C (mg/100 g)	Energy (kJ)	Fat (g/100 g)	Carbs (g/100 g)
0.07	1725	10.7	135	75	0.3	2.6
0	3700	8.8	131	163	1	2.2
0.11	0	7.3	93	209	0.7	2
0.3	385	1.2	33	109	0.4	2.9
0.7	3535	5.1	28	105	0.8	2.1

Vegetables								
Nairobi			**Pretoria**			**Ghana**		
N-Bal	N-Actual	Gain	N-Bal	N-Actual	Gain	N-Bal	N-Actual	Gain
9825	8628	1197	2828	2171	658	4214	3484	730
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
2685	2370	315	773	588	185	1128	963	165
93	73	20	27	24	2	41	29	12
–	–	–	–	–	–	–	–	–
17	9	8	5	6	−2	8	3	5
14	8	6	4	5	−1	7	3	4
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
133	134	−1	38	22	16	60	54	6
38	29	9	11	10	1	17	12	5
140	108	32	98	42	56	68	41	27
111,019	98,385	12,634	31,960	24,150	7810	46,857	39,946	6911
393	351	43	113	85	29	165	143	23
4990	4595	395	1436	1012	424	2165	1853	312

TABLE A5 Nutrient composition for selected tuber crops.

	Ca (mg)	Mg (mg)	K (mg)	P (mg)	Na (mg)	Ascorbic acid (mg)	Thiamin (mg)	Riboflavin (mg)	Energy (Kcal)	Protein (g)
White flesh and skin, raw	9	21	407	62	16	19.7	0.07	0.03	69	1.7
Red flesh and skin, raw	10	22	455	61	18	8.6	0.08	0.03	70	1.9
Sweet potato	30	25	337	47	55	2.4	0.08	0.06	86	1.6
Cassava	16	21	271	27	14	20.6	0.09	0.05	160	1.4
Yam	17	21	816	55	9	17.1	0.11	0.03	118	1.5

Source: Chandrasekara and Josheph Kumar (2016).

TABLE A6 Nutrient composition for selected legume crops.

	Moisture mg/100 g	Protein mg/100 g	Fat mg/100 g	Crude fiber mg/100 g	Carb mg/100 g	Carotene mg/100 g	Energy kcal	Ca mg/100 g	P mg/100 g
Common bean	9.6	24.9	1	3.8	54.5	0	323	134	573
Green gram	10.4	24	1.3	4.1	56.7	94	334	124	326
Peas	16	19.7	1.1	4.5	56.5	39	315	75	298
Soybean	8.1	43.2	19.5	3.7	20.9	426	432	240	690
Cowpea	13.4	24.1	1	3.8	54.5	12	323	77	414
Marama bean	2.67	34.71	40.06		14.07	0	0	241	454

Note: The units of measurement for Moisture, Protein, Fat, Crude fiber, Carb, Ca, P, Mg, Na, K, Fe, Zn, Thiamin, Riboflavin, Niacin, Choline are mg/100 g and for Folic acid and Carotene are ig.

Source: Common bean (Suárez-Martínez et al., 2016); green gram, pea, soybean, and cowpea (Kamboj & Nanda, 2018); Marama bean (Müseler & Schönfeldt, 2006).

Total lipid (g)	Carbs (g)	Fiber (g)	Sugars (g/g)	Niacin (mg)	Vit B6 (mg)	Folate	Vitamin E (mg)	Vitamin K (μg)	Vitamin A (IU/IU)
0.1	15.7	2.4	1.2	1.07	0.203	18	0.01	1.6	8
0.1	15.9	1.7	1.3	1.15	0.17	18	0.01	2.9	7
0.1	20.1	3	4.2	0.56	0.209	11	0.26	1.8	14,187
0.3	38.1	1.8	1.7	0.85	0.088	27	0.19	1.9	13
0.2	27.9	4.1	0.5	0.55	0.293	23	0.35	2.3	138

Fe mg/100 g	Mg mg/100 g	K mg/100 g	Na mg/100 g	Zn mg/100 g	Thiamine mg/100 g	Riboflavin mg/ 100 g	Niacin mg/100 g	Folic acid ig	Choline mg/100 g
3.4	168	1731		1.89	0.52	0.16	1.8	0	352
4.4	127	843	28	3	0.47	0.27	2.1	0	167
7.05	100	725	20	2.3	0.47	0.19	3.4	7.5	235
10.4	238	0	0	4.4	0.73	0.39	3.2	100	0
8.6	210	1131	23.4	4.6	0.51	0.2	1.3	133	202
3.95	274.5	895	63.75	6.2	0.38	0.06	9.21	0.14	0

TABLE A7 Nutrient gain between actual and balanced research outputs for cereals and vegetable crops for Nairobi, Pretoria, and Ghana

	Root and Tubers								
	Nairobi			**Pretoria**			**Ghana**		
Nutritional components	N-Bal	N-Actual	Var	N-Bal	N-Actual	Var	N-Bal	N-Actual	Var
Ca (mg/100 g)	511.7	481.8	29.9	462.5	320.7	141.8	155.8	167.1	−11.3
Mg (mg/100 g)	686.4	687.0	−0.6	620.4	609.0	11.4	209.0	200.1	8.9
K (mg/100 g)	14264.6	11347.2	2917.4	12893.0	11457.8	1435.2	4343.4	3417.0	926.4
P (mg/100 g)	1572.5	1500.6	71.9	1421.3	1559.9	−138.6	478.8	317.1	161.7
Na (mg/100 g)	698.9	729.6	−30.7	631.7	498.4	133.3	212.8	171.9	40.9
Thiamin (mg/100 g)	2.7	2.5	0.2	2.4	2.2	0.2	0.8	0.9	0.0
Riboflavin (mg/100 g)	1.2	1.3	−0.1	1.1	1.0	0.2	0.4	0.4	−0.1
Energy (Kcal)	3138.7	3136.2	2.5	2836.9	2430.6	406.3	955.7	1336.2	−380.5
Protein (g)	50.5	51.1	−0.6	45.7	48.7	−3.1	15.4	13.4	2.0
Total lipid (g)	5.0	5.0	0.0	4.5	3.8	0.7	1.5	2.4	−0.9
Carbohydrate (g)	734.4	732.8	1.6	663.8	561.7	102.2	223.6	317.4	−93
Fiber (g)	81.1	67.3	13.9	73.3	58.3	15.0	24.7	21.6	3.1
Niacin (mg/100 g)	2.7	2.5	0.2	2.4	2.2	0.2	0.8	0.9	0.0
Ascorbic acid (mg/100 g)	426.8	432.9	−6.1	385.8	422.3	−36.5	130.0	164.5	−34.5
Vitamin B6 (mg/100 g)	1.2	1.3	−0.1	1.1	1.0	0.2	0.4	0.4	−0.1
Folate	26.1	28.8	−2.8	23.6	29.5	−5.9	7.9	7.1	0.8
Vitamin E (mg/100 g)	6.0	5.0	1.0	5.4	4.9	0.6	1.8	1.3	0.6
Vitamin K (μg)	605.3	606.0	−0.7	547.1	547.8	−0.7	184.3	225.9	−41.6
Vitamin A (IU/IU)	5.1	3.5	1.6	4.6	1.5	3.2	1.6	2.1	−0.5
Carotene (ig)	–	–	–	–	–	–	–	–	–
Fe (mg/100 g)	–	–	–	–	–	–	–	–	–
Zn (mg/100 g)	–	–	–	–	–	–	–	–	–
Mn (mg/100 g)	–	–	–	–	–	–	–	–	–
Folic acid (ig)	–	–	–	–	–	–	–	–	–
Choline (ig)	–	–	–	–	–	–	–	–	–

Note: The nutrient gain was based on computation was based on N-Bal versus N-Actual represent nutrients for balanced and actual research outputs respectively.

Abbreviations: Ca, calcium; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; Na, sodium; P, phosphorus; Zn, zinc.

TABLE A8 Nutrient composition for selected nut crops.

	Ca mg	**Mg mg**	**Na mg**	**K mg**	**Fe mg**	**Zn mg**	**Thiamin mg**	**Riboflavin mg**	**Niacin mg**	**Pantothenic mg**
Peanuts	92	168	18	705	4.58	3.27	0.18	0.04	5.75	0.59
Macadamia	85	130	5	368	3.69	1.3	1.2	0.2	2.5	0.8
Cashew	37	292	12	660	6.68	4.06	0.4	0.1	1.1	0.9
Tiger nut	44	118	17	267	2.9	1.4	0	0	0	0

Note: The units of measurement for Ca, Mg, Na, K, Fe, Zn, Thiamin, Riboflavin, Niacin, Pantothenic, Pyridoxine, Cobalamin, Folate, Vit C, Vit E, and Vit K are in mg/100 g.

Source: Peanuts, macadamia, and cashew (Pradhan et al., 2021); tiger nut (Suleiman et al., 2018).

Legume								
Nairobi			**Pretoria**			**Ghana**		
N-Bal	N-Actual	Var	N-Bal	N-Actual	Var	N-Bal	N-Actual	Var
3326	2749	576	2217	1891	326	1053	886	167
4134	3562	571	2756	2891	−135	1309	1240	68
17,791	20,878	−3087	11,860	12,454	−593	5633	4515	1118
9522	8337	1184	6348	5928	420	3015	2934	80
507	166	340	338	354	−16	160	101	59
12.4	14.0	−1.6	8.3	7.2	1.1	3.9	3.6	0.3
4.6	3.7	1.0	3.1	2.4	0.7	1.5	1.5	−0.1
6267	6145	121	4178	3384	794	198	2049	−65
616	474	141	410	372	38	195	181	13
232	54	178	155.2	159	−3.9	73	51	22
978	1112	−134	652	558	94	309	265	44
71	69	2.7	47	37	10	22	21	0.8
77.8	41.9	35.9	51.9	46.0	5.9	24.6	15.4	9.3
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
2055	738	1317	1370	726	644	650	863	−212
146	125	20	97.5	95	2.6	46	49.0	−2.7
88	74	14	59	62	−3.2	28	25	2.3
12	19	−7.4	3.9	8.5	−4.6	3.9	1.5	2.4
867	560	307	578	991	−412	274	501	−226
2532	2090	442	1930	1522	408	801	715	86

Pyridoxine mg	**Cobalamin mg**	**Folate mg**	**Vitamin C mg**	**Vitamin E mg**	**Vitamin K mg**	**Protein mg**	**Carbs mg**	**Fat mg**	**Energy kcal**
0.11	0	0.062	0	0	0.003	24.8	21.5	49.6	444
0.3	0.0003	0.011	1.2	0.5	0	8.78	8	77	718
0.4	0.0004	0.025	0.5	0.9	0.03	18	29.9	43	553
0	0	0	0.4	1.2	0.87	0	8	48	17

TABLE A9 Nutrient gain between actual and balanced research outputs for nut crops across three institutions in Africa.

	Nairobi			Pretoria			Ghana		
Nutritional components	**N-Bal**	**N-Actual**	**Gain**	**N-Bal**	**N-Actual**	**Gain**	**N-Bal**	**N-Actual**	**Gain**
Ca (mg/100 g)	129.0	133.8	−4.80	112.0	106.2	5.8	425.7	374.7	51.0
Mg (mg/100 g)	354.0	229.2	124.80	306.8	178.8	128.0	1168.2	796.2	372.0
Na (mg/100 g)	26.0	19.2	6.80	24.2	13.8	10.4	85.8	65.7	20.1
K (mg/100 g)	1000.0	855.3	144.70	853.4	643.8	209.6	3300.0	2842.2	457.8
Fe (mg/100 g)	8.93	6.34	2.59	7.72	4.96	2.76	29.45	21.07	8.38
Zn (mg/100 g)	5.02	3.72	1.29	4.29	2.74	1.55	16.55	13.42	3.13
Thiamin (mg/100 g)	0.89	0.88	0.01	0.71	0.83	−0.12	2.94	1.86	1.08
Riboflavin (mg/100 g)	0.17	0.16	0.01	0.14	0.14	−0.01	0.56	0.36	0.20
Niacin (mg/100 g)	4.68	6.68	−2.00	3.74	4.95	−1.21	15.43	20.16	−4.73
Pantothenic (mg/100 g)	1.15	1.01	0.13	0.92	0.83	0.08	3.78	3.03	0.75
Pyridoxine (mg/100 g)	0.41	0.28	0.13	0.32	0.25	0.08	1.34	0.84	0.50
Cobalamin	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Folate (mg/100 g)	0.05	0.06	−0.01	0.04	0.04	0.00	0.16	0.21	−0.05
Vitamin C (mg/100 g)	1.05	0.72	0.33	0.92	0.72	0.20	3.47	1.38	2.09
Vitamin E	1.30	0.30	1.00	1.28	0.30	0.98	4.29	0.99	3.30
Vitamin A (mg/100 g)	0.44	0.00	0.44	0.52	0.00	0.52	1.44	0.00	1.44
Vitamin K (mg/100 g)	0.02	0.00	0.01	0.01	0.00	0.01	0.05	0.03	0.03
Protein (mg/100 g)	29.79	27.588	2.20	25.432	4.8	20.632	98.307	93.102	5.205
Carbohydrate (g)	53.7	24.15	29.55	52.56	28.8	23.76	177.21	89.64	87.57
Fat (g)	93.3	90.84	2.46	78.04	10.2	67.84	307.89	243.9	63.99
Energy (Kcal)	1064	830.4	233.60	933.8	247.8	686	3511.2	2310	1201.2

Note: The nutrient gain was based on computation was based on N-Bal versus N-Actual represent nutrients for balanced and actual research outputs respectively.

Abbreviations: Ca, calcium; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; Na, sodium; P, phosphorus; Zn, zinc.