Discover Agriculture

Research

Analysing rice (*Oryza sativa* L.) production trends—area harvested, quantity and yield stability in Tanzania

Aneth Japhet Magubika[1] · Francis Kloh Fukah[2,3] · Eliakira Kisetu Nassary[3] · George Muhamba Tryphone[1]

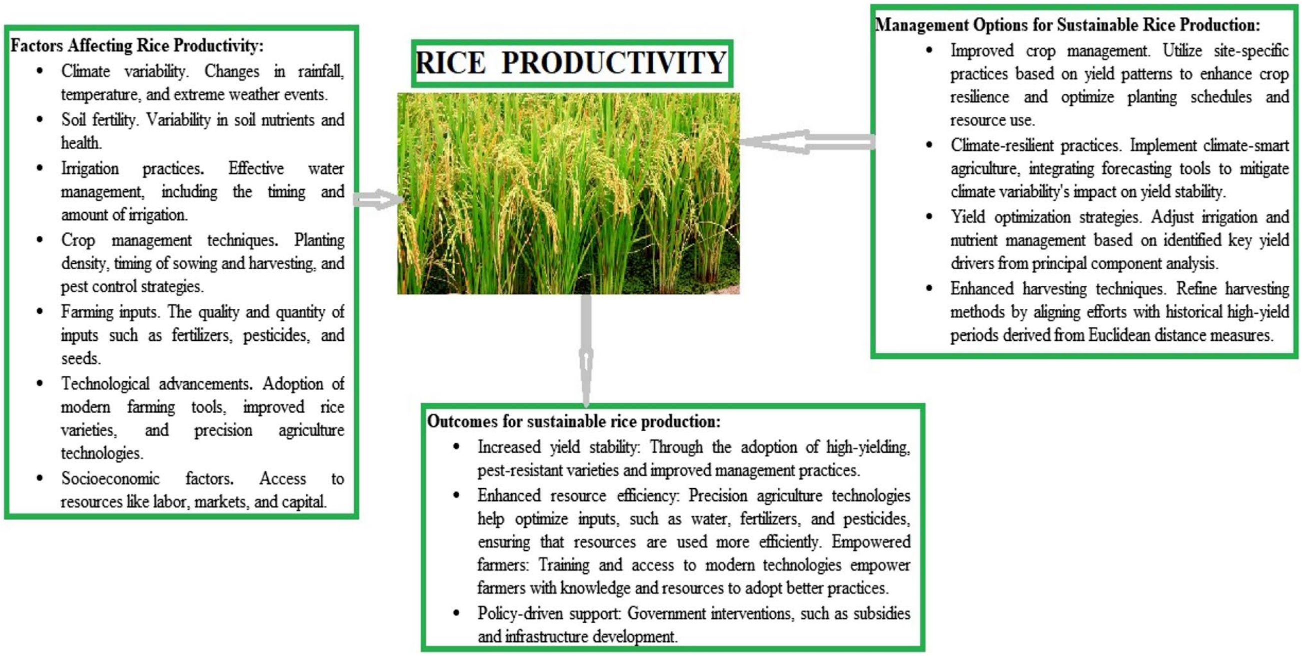
Received: 8 November 2024 / Accepted: 1 April 2025

Abstract

This study examined the trends in rice (*Oryza sativa* L.) production and yield stability in Tanzania, with a focus on harvested area, total production, and yield per unit land area. We utilized data from FAOSTAT (https://www.fao.org/faostat/en/#home), focusing on the "Production Domains (Crop and Livestock Products)" for the "United Republic of Tanzania." Filters were applied for "Area harvested," "Yield," and "Production Quantity" under "Items (Crops, Primary)" for the period 2000–2022. Other data and information were obtained from literature and government official reports. Mixed statistical analyses (Univariate and Multivariate) were performed. The univariate was performed to assess harvested area, total production, and grain yield through descriptive statistics, while multivariate analysis examined relationships among these variables and yield stability using Generalized Linear Models (GLMs) and Principal Component Analysis (PCA). The results revealed a significant increase in the area harvested, peaking at 481,000 hectares in 2020, compared to 250,000 hectares in 2000. Yield fluctuations were notable, with a significant decline in 2008 (– 729.29 kg ha^{-1}) followed by a recovery in 2018 (791.28 kg ha^{-1}). A strong positive correlation was confirmed between harvested area and production (0.00035791) and yield (0.0013233). PCA results demonstrated that the first three principal components accounted for 87% of the total variance. Statistical tests showed substantial yield differences between 2000 and 2010, reaching 720,690.1 kg ha^{-1}, with yield stability between 2021 and 2022 noted, resulting in a minor difference of 18,802.6 kg ha^{-1}. The findings reveal that harvested area significantly affects rice production, but yield variability remains a challenge. While expanding cultivated areas has increased output, yield stability is a concern. This emphasizes the need for targeted strategies to optimize cultivation and enhance food security amid changing agricultural conditions.

✉ Aneth Japhet Magubika, anethjmagu@gmail.com | [1]College of Agriculture, Department of Crop Science and Horticulture, Sokoine University of Agriculture, Chuo-Kikuu, P. O. Box 3005, Morogoro, Tanzania. [2]Faculty of Agriculture, Department of Soil Science, William V. S. Tubman University, P. O. Box 3570, Harper, Maryland, Liberia. [3]College of Agriculture, Department of Soil and Geological Sciences, Sokoine University of Agriculture, Chuo-Kikuu, P. O. Box 3008, Morogoro, Tanzania.

Graphical Abstract



Factors Affecting Rice Productivity:

- Climate variability. Changes in rainfall, temperature, and extreme weather events.
- Soil fertility. Variability in soil nutrients and health.
- Irrigation practices. Effective water management, including the timing and amount of irrigation.
- Crop management techniques. Planting density, timing of sowing and harvesting, and pest control strategies.
- Farming inputs. The quality and quantity of inputs such as fertilizers, pesticides, and seeds.
- Technological advancements. Adoption of modern farming tools, improved rice varieties, and precision agriculture technologies.
- Socioeconomic factors. Access to resources like labor, markets, and capital.

RICE PRODUCTIVITY

Management Options for Sustainable Rice Production:

- Improved crop management. Utilize site-specific practices based on yield patterns to enhance crop resilience and optimize planting schedules and resource use.
- Climate-resilient practices. Implement climate-smart agriculture, integrating forecasting tools to mitigate climate variability's impact on yield stability.
- Yield optimization strategies. Adjust irrigation and nutrient management based on identified key yield drivers from principal component analysis.
- Enhanced harvesting techniques. Refine harvesting methods by aligning efforts with historical high-yield periods derived from Euclidean distance measures.

Outcomes for sustainable rice production:

- Increased yield stability: Through the adoption of high-yielding, pest-resistant varieties and improved management practices.
- Enhanced resource efficiency: Precision agriculture technologies help optimize inputs, such as water, fertilizers, and pesticides, ensuring that resources are used more efficiently. Empowered farmers: Training and access to modern technologies empower farmers with knowledge and resources to adopt better practices.
- Policy-driven support: Government interventions, such as subsidies and infrastructure development.

Research Highlights

- Rice production in Tanzania showed high variability over 23 years.
- Significant external shocks affected yield fluctuations in 2008.
- Statistical analysis confirmed year-to-year production differences.
- Positive trends in rice yield were noted from 2010 onward.
- Sustainable practices could enhance long-term rice productivity.

Keywords Agricultural Practices · Crop Yield · Production Variability · Statistical Analysis · Sustainable Development

1 Introduction

Rice (*Oryza sativa* L.) is one of the important staple crops, supporting the food security and livelihoods of more than half of the world's population [1]. It thrives in diverse agro-ecological conditions, from the fertile plains of Asia to the expansive floodplains of Africa [2]. In 2022, global rice production reached nearly 520 million metric tons, with Asia being the dominant producer, particularly in China, India, Indonesia, and Vietnam [3]. The increasing global demand for rice, driven by rising populations and changing dietary preferences, especially in developing regions, shows the crop's critical role as a primary source of daily caloric intake [4, 5].

In Africa, rice production has experienced substantial growth in recent decades, largely as a response to food security initiatives and a push to decrease reliance on imports. The continent produced approximately 37.3 million metric tons of paddy rice in 2022, with high contributions from countries like Nigeria, Egypt, and Madagascar [6]. However, productivity of rice in Africa lags behind global averages, primarily due to challenges such as limited access to improved varieties, inadequate irrigation infrastructure, and vulnerability to climatic variability [7, 8]. These challenges are exacerbated by climate change, which introduces more frequent and intense weather events, impacting agricultural systems and increasing the risks associated with rice cultivation [9, 10]. However, the rapid growth in rice consumption across the continent necessitates a concerted effort to boost both production and yield stability.

Tanzania, recognized as one of the largest rice producers in Africa, plays a critical role in meeting the continent's escalating demand for rice [11]. The agricultural sector is a cornerstone of the Tanzanian economy, with rice being a key crop for food security and a vital source of income for smallholder farmers [12, 13]. Over the last two decades, the country has made significant advancements in rice cultivation, particularly in regions such as Mbeya particularly in the Usangu Plains [14], Tabora particularly in low-lying areas suitable for irrigation [15], Morogoro especially within the Kilombero Valley [16], Ruvuma particularly in districts like Songea [17], Mwanza around Lake Victoria [18], Kigoma leverages its proximity to Lake Tanganyika [19], and Shinyanga known for both rain-fed and irrigated rice farming [20]. Rice production in Tanzania has increased from approximately 1.3 million metric tons in 2000 to over 2.2 million metric tons in 2022, facilitated by the adoption of improved varieties and enhanced agronomic practices. Despite these advancements, Tanzania faces considerable challenges in achieving consistent yield stability. Erratic rainfall patterns, pest infestations, and soil fertility concerns contribute to fluctuations in rice yields across different regions and seasons.

Rice production in Tanzania plays a critical role in the nation's economy and food security, contributing directly to several Sustainable Development Goals (SDGs). As a staple food, it addresses SDG 2 (Zero Hunger) by ensuring a reliable food supply for the population and helping to alleviate hunger and malnutrition [21]. It is also a significant source of income for millions of smallholder farmers, thus contributing to SDG 1 (No Poverty) by improving livelihoods and reducing rural poverty [22]. The sector fosters rural employment and agricultural development, supporting SDG 8 (Decent Work and Economic Growth) by creating jobs and enhancing value chains, particularly through agro-processing and local markets [23]. Moreover, increasing rice production through sustainable practices can promote SDG 12 (Responsible Consumption and Production) by optimizing resource use and minimizing environmental impacts [24]. Lastly, innovations in rice farming can boost productivity and resilience, aligning with SDG 13 (Climate Action) by helping farmers adapt to climate change and ensuring long-term agricultural sustainability [25].

In light of the challenges posed by climate change, such as altered precipitation patterns and rising temperatures, Tanzania faces an increasing need to adopt resilient agricultural practices to mitigate risks and enhance adaptability. This includes focusing on climate-smart techniques, improving irrigation infrastructure, and promoting the cultivation of rice varieties better suited to changing conditions [26]. This study analyses the stability and variability of rice yields in Tanzania from 2000 to 2022 using meta-analysis techniques. Synthesizing data from various sources, it aims to provide insights into yield trends, the factors influencing performance, and their implications for future rice production in the country. Understanding yield stability is essential for developing improved strategies that boost rice production, ensure food security, and strengthen resilience against climatic variability and population growth. Therefore, the objective of this study is to improve food security and livelihoods of farmers through an enhanced understanding of rice production trends and yield stability. This can be achieved by assessing variability across years and identifying factors influencing these trends, including the evaluation of harvested area, yield, and production quantities, as well as synthesizing agricultural practices, environmental conditions, and policy interventions impacting rice yield fluctuations over time.

2 Materials and methods

2.1 Physiography and climate of Tanzania

Geographically, the country lies between 1°S and 12°S and 29°E and 41°E, encompassing a range of environmental zones ideal for rice cultivation [27]. The topography varies from low-lying coastal plains to the elevated regions of the Southern Highlands and the slopes of Mount Kilimanjaro, which rise over 2,000 m above sea level [28].

Rice is predominantly cultivated in lowland areas such as the coastal regions and river valleys, including the Rufiji, Kilombero, and Wami basins. These areas benefit from fertile soils and relatively favorable rainfall patterns, which support stable rice production. The northern and eastern regions of the country experience bimodal rainfall with long rains from March to May and short rains from October to December, providing two cropping seasons [29]. This rainfall pattern is beneficial for rice farmers in regions such as Kilimanjaro, Arusha, and Tanga, allowing for increased yield potential and production stability. Conversely, the southern and central regions, particularly the Southern highlands and the central plateau, experience unimodal rainfall, limiting rice cultivation to one season [30]. The central plateau, with its drier conditions and annual rainfall often below 400 mm, presents significant challenges for rain-fed rice farming [31]. Soil types vary widely across Tanzania, from the fertile volcanic soils in the highlands around Kilimanjaro and Arusha, ideal for rice farming, to the sandy and acidic soils in the central and western regions, where lower fertility and acidity can affect yield stability [32].

2.2 Data collection

The data for this study was obtained from FAOSTAT (2024) via https://www.fao.org/faostat/en/#home. The retrieval process began with the "Production Domains (Crop and Livestock Products)" section, where the focus was set on the "United Republic of Tanzania." Filters were applied for "Area harvested," "Yield," and "Production Quantity," while selecting "Items (Crops, Primary)" and establishing the time range from 2000 to 2022. Additionally, information was collected from various prior studies and reports, which provided extensive details on rice production in Tanzania. The dataset encompassed variables, including harvested areas, production quantities, and grain yields, thereby offering an overview of rice cultivation dynamics for the period spanning 23 years.

Data on improved trends in rice production were collected using a variety of methods, including literature reviews and government reports. Academic articles were reviewed to gather information on agricultural practices, yield improvements, and socio-economic factors affecting rice farming. Details on advancements in cultivated areas and the effects of improved seed varieties and pest management strategies were sourced to complement these findings. Government reports, such as the National Agricultural Sample Surveys and agricultural censuses, provided essential quantitative data on household involvement in rice farming and land use. Additionally, reports from the Ministry of Agriculture offered information on relevant policies, fertilizer subsidies, and production statistics. To further enhance the data collection process, internet surveys and phone calls with local farmers and agricultural extension officers were conducted, gathering qualitative data on current farming practices, market dynamics, and environmental challenges.

2.3 Statistical data analysis

Statistical analyses were performed using the Past4.03.exe software, designed for paleontological statistics and data mining. The analysis employed mixed analyses methods to examine factors such as harvested area, total production, and grain yield. The univariate analysis was employed in calculating descriptive statistics, including the mean, median, variance, standard deviation, and minimum and maximum values. Kurtosis and skewness were calculated to describe the distribution shape, showcasing any extremity or asymmetry in the analysed variables. Kurtosis shows the shape of the distribution beyond its central tendency (mean) and variability (variance), as shown (Eq. 1).

$$\text{Kurtosis} = \frac{n(n+1)\sum_{i=1}^{n}(x_i - \text{Mean})^4}{(n-1)(n-2)(n-3)\left(\sum_{i=1}^{n}(x_i - \text{Mean})^2\right)^2} - \frac{3(n-1)^2}{(n-2)(n-3)} \tag{1}$$

where n is number of observations in the dataset, x_i is each individual data point.

Skewness measures the third standardized moment after kurtosis, reflecting the asymmetry of the data distribution. A positive skewness suggests a longer tail on the right side of the distribution, while a negative value indicates a longer tail on the left side (Eq. 2).

$$\text{Skewness} = \frac{n}{(n-1)(n-2)} f(x) = a_0 + \sum_{i=1}^{n} \times \left(\frac{x_{i-\bar{x}}}{S}\right)^3 \tag{2}$$

where n is number of observations, x_i is each individual data point, $\bar{x}$ is sample mean, S is sample standard deviation.

Furthermore, inferential statistical tests were conducted, including analysis of variance (ANOVA) to compare means for area harvested, production quantities, and yields across years. The Kruskal–Wallis H test was applied as an alternative to meet the situations when the assumptions of normality required for ANOVA were violated (Eq. 3).

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \left(\frac{R_i^2}{n_i}\right) - 3(N+1) \tag{3}$$

where H is the test statistical, R_i is the sum of ranks for group i, n_i is the number of observations in group i, and N is the total number of observations.

Multivariate analysis was employed to examine the yield stability, uncovering the relationships and patterns within the rice production data. Linear regression analysis was carried out using Scikit-learn in Python to evaluate trends in area harvested, quantity and yield stability over the study period. Generalized Linear Models (GLMs) were employed to analyse the stability of yield and to account for variability. Additionally, the Shapiro–Wilk test for normality was conducted, yielding p-values of 0.14, 0.11 and 0.08 for area harvested, quantity and yield, respectively, all of which are above the standard significance threshold of 0.05. These results confirmed that there were no significant departures from normality. Principal Component Analysis (PCA) was used to decompose the stochastic processes and identify the principal components driving the variance in data. Additionally, Euclidean similarity and distance indices were used to assess yield stability across different years, with data normalization performed to ensure that scale differences did not disproportionately influence distance calculations (Eq. 4).

$$\mathrm{d}(A,B)=\sqrt{\sum_{i=1}^{n}(x_i-y_i)^2} \tag{4}$$

where x_i and y_i are the individual data points for years A and B in the i^{th} dimension, n is the number of dimensions (frequency of annual rice yields).

3 Results

3.1 Rice production trends

The summary statistics in Table 1 for rice productivity show the area under rice cultivation has a broad range, with a minimum of 405,860 ha and a maximum of 1,370,000 ha, showing moderate variability (standard deviation of 285,657.9 ha). Production quantity, ranging from 78.15 to 452.75 t, demonstrates a higher relative variability, indicated by a coefficient of variation of 51%. In comparison, yield fluctuates less, with a minimum of 1,600.4 kg ha^{-1} and a maximum of 3,306 kg ha^{-1}, resulting in a coefficient of variation of 24.23%, suggesting more consistency in yield compared to production and area.

The negative skewness in area (– 0.08) and positive skewness in production (0.52) and yield (0.45) indicate that area distribution is fairly symmetrical, while production and yield are skewed toward higher values. The kurtosis values, all negative, suggest a flatter distribution than normal, particularly for area and yield. The geometric means for area, production, and yield are slightly lower than the arithmetic means, further reflecting the skewed distributions. The mean yield of 2,327.4 kg ha^{-1} aligns with the median yield (2,252.5 kg ha^{-1}), supporting the notion of consistency in yield performance over time.

Table 1 Summary statistics of rice production trends over 23 years from 2000–2022 in Tanzania

	Area (ha)	Production (t)	Yield (kg ha^{-1})
Years (N)	23	23	23
Min	405860	78.15	1600.4
Max	1370000	452.75	3306
Sum	2.04×10^{7}	4995.46	53530.2
Mean	888821.1	217.19	2327.4
Std. error	59563.79	23.10	117.5998
Variance	8.16×10^{10}	12268.31	318083.7
Stand. dev	285657.9	110.76	563.9891
Median	928273	219.48	2252.5
25 prcntil	620800	116.7692	1767
75 prcntil	1119324	297.99	2769.8
Skewness	– 0.08	0.52	0.45
Kurtosis	– 1.01	– 0.83	– 0.99
Geom. mean	840426.70	190.28	2264.05
Coeff. var	32.14	51.00	24.23

Table 2 Statistical tests for area, production and yield for rice (A) Univariate One-Way ANOVA for equal means and (B) Kruskal–Wallis test for equal medians from 2000–2022 in Tanzania

	Sum of sqrs	df	Mean square	F	p (same)
(A) Test for equal means					
Between groups (years):	1.21×10^{13}	2	6.04×10^{12}	222	4.93×10^{-30}
Within groups (area, production and yields):	1.80×10^{12}	66	2.72×10^{10}	Permutation p (n = 99,999)	
Total:	1.39×10^{13}	68	1.00×10^{-5}		
Components of variance (only for random effects):					
Var(group):	2.61×10^{11}	Var (error):	2.72×10^{10}	ICC:	0.905751
omega2:	0.865				
Levene´s test for homogeneity of variance, from means	p (same):	4.18×10^{-16}			
Levene´s test, from medians	p (same):	6.14×10^{-15}			
Welch F test in the case of unequal variances: F = 260.6, df = 30.42, p = $7.225 \times 10^{(-20)}$					
(B) Kruskal–Wallis test for equal medians					
H (chi2):	60.46				
Hc (tie corrected):	60.46				
p (same):	7.45×10^{-14}				

There is a significant difference between sample medians

The results from statistical analysis show significant differences for area, production and yield of rice across years (Table 2). In the test for equal means, the within-group (across years) sum of squares is 1.80×10^{12} with 66 degree of freedom and the mean square is 2.72×10^{10}. The permutation p-value with 99,999 iterations further supports this significance. Levene's test for homogeneity of variance results in p-values of $4.18 \times 10^{(-16)}$ (from means) and $6.14 \times 10^{(-15)}$ (from medians), indicating unequal variances. The Welch F-test for unequal variances gives F = 260.6, with 30.42 degrees of freedom, and a p-value of $7.225 \times 10^{(-20)}$, further confirming significant variation across the years.

The results for equal medians also show a significant difference, with a chi-square (H) value of 60.46 and a tie-corrected Hc value of 60.46. The p-value of $7.45 \times 10^{(-14)}$ confirms that the medians are significantly different across years.

3.2 Yield stability of rice

3.2.1 Principal component analysis

The PCA results for rice area harvested, production quantities and yields over time are presented in Table 3. The first principal component (PC 1) factor scores show a distinct pattern of negative values during the early years. From 2000 to 2007, there is a clear decline in rice production-related factors, with the lowest score occurring in 2001 (– 483,000), highlighting a significant dip during that period. As the years progress, a notable shift occurs in 2010, where the factor scores become positive (247,000). This positive trend continues, with PC 1 peaking in 2020 at 481,000, suggesting a recovery or growth in rice production factors. The steady rise during these later years reflects an improvement in the conditions influencing rice production, which are primarily explained by this PC 1.

On the other hand, PC 2 presents a more irregular trend across the years. The early 2000s display moderate positive scores, such as in 2000 (181.41), followed by sharp fluctuations. Notably, 2008 exhibits a significant decline in PC 2, with a score of -729.29, indicating a marked drop in production factors associated with this component. Despite this, PC 2 shows a notable rebound in 2018, reaching 791.28, suggesting a recovery or an anomaly in the influencing factors during that period. The scores continue to fluctuate, showing some degree of variability in production factors tied to PC 2 throughout the analysis period.

The factor loadings provide further clarity on the variables driving each principal component. PC 1 is dominated by the area under cultivation, with a loading of 1, indicating that this variable is the primary contributor to the variability captured by PC 1. Meanwhile, PC 2 is heavily influenced by rice yield, with a loading of 0.99521. This suggests that, while area is the major factor influencing production trends overall, yield variations play a significant role in shaping the patterns observed in PC 2. Rice production, although contributing to both components, has a relatively minor impact compared to area and yield.

Table 3 The Principal Component Analysis for yield stability in rice over 23 years

	PC 1	PC 2
Factor scores		
2000	-4.73×10^5	181.41
2001	-4.83×10^5	451.59
2002	-3.23×10^5	− 158.43
2003	-2.68×10^5	− 205.88
2004	-2.76×10^5	− 236.39
2005	-1.87×10^5	− 418.05
2006	-2.55×10^5	− 86.898
2007	-3.31×10^5	516.19
2008	− 1162.1	− 729.29
2009	− 83192	− 563.1
2010	2.47×10^5	− 325.01
2011	2.31×10^5	− 628.15
2012	− 89,460	42.772
2013	39,452	− 16.39
2014	68,397	320.65
2015	2.66×10^5	− 98.651
2016	3.49×10^5	− 19.495
2017	2.08×10^5	− 371.74
2018	1.44×10^5	791.28
2019	1.64×10^5	760.62
2020	4.81×10^5	345.13
2021	4.62×10^5	56.518
2022	1.09×10^5	391.33
Factor loadings		
Area (ha)	1	− 0.00135
Production (t)	0.00035791	0.097736
Yield (kg ha^{-1})	0.0013233	0.99521
Eigenvalue	8.16×10^{10}	176885
% variance	100	0.000217

In terms of eigenvalues, PC 1 holds an overwhelming majority, with a value of 8.16×10^{10}, explaining nearly 100% of the total variance. In contrast, PC 2 has a much smaller eigenvalue (176,885), contributing only 0.000217% of the variance. This indicates that the trends in rice production over the years are primarily driven by the area under cultivation, while yield and other factors, though relevant, play a much smaller role in explaining the overall variation in rice production.

3.2.2 Production/yield and area relationships

The GLM results for rice production and yield indicate significant relationships with the area harvested. For production, the positive slope coefficient of 0.00035791 suggests that increasing the area cultivated is associated with a corresponding increase in production quantity (Fig. 1). Conversely, the negative intercept of -100.93 indicates that if no area were harvested, the expected production quantity would be negative, serving as a statistical construct rather than a meaningful physical interpretation. The estimated dispersion parameter of 1901.5 reveals considerable variation in production data not accounted for by the model, and the log likelihood value of -10.5 reflects the model's fit to the data. The G statistic of 120.94, along with a p-value of $3.93\times10^{(-28)}$, provides strong evidence against the null hypothesis, indicating a significant relationship between area harvested and production.

Similarly, the yield model shows a positive slope coefficient of 0.0013233, suggesting that as the area cultivated increases, so does the yield per unit area (Fig. 2). The positive intercept of 1151.2 implies an expected yield baseline, although abstract, if no area were harvested. The standard errors for both the slope (0.0003198) and intercept (297.91)

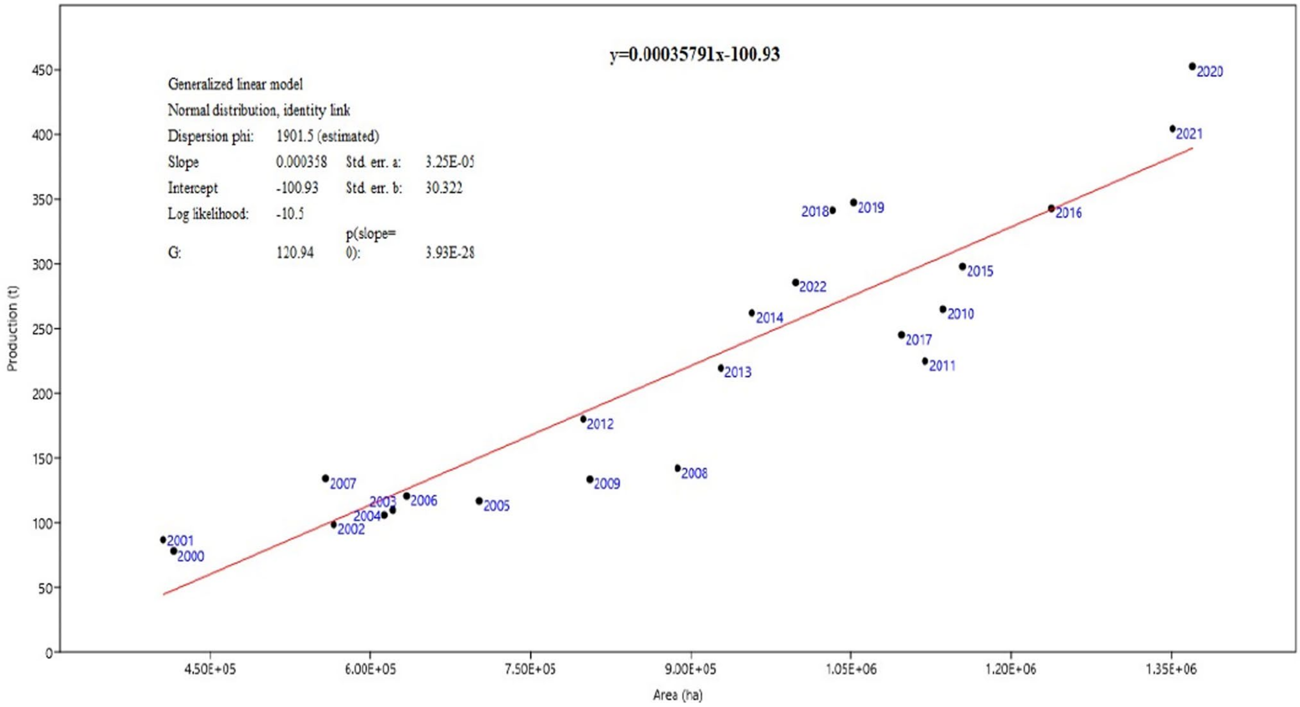


Fig. 1 Generalized linear model of rice based on area harvested and production quantity in Tanzania through 2000 to 2022

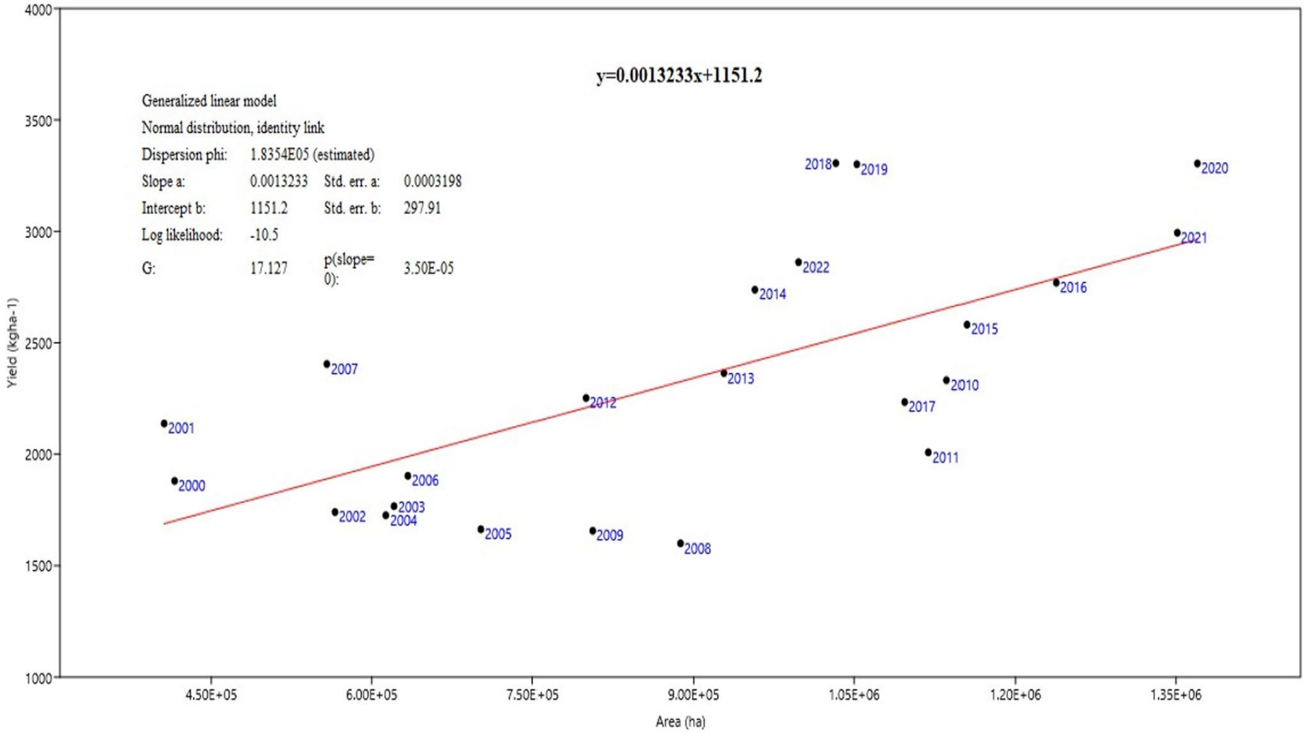


Fig. 2 Generalized linear model of rice based on area harvested and yield in Tanzania through 2000 to 2022

indicate the precision of these estimates, with a smaller standard error for the slope reflecting greater confidence in the yield estimate. The estimated dispersion parameter of 1.8354×10^5, points to substantial variability in the yield data, consistent with the production model. The log likelihood value of -10.5 indicates similar model fit for yield, and the G statistic of 17.127, paired with a p-value of $3.50 \times 10^{(-05)}$, provides strong evidence against the null hypothesis, confirming the statistical significance of the relationship between area harvested and yield.

3.2.3 Yield similarity and distance indices across years

The Euclidean similarity and distance index for rice yield across years (2000–2022) shows distinct variations in yield performance (Table 4). The diagonal values are all zero, indicating that the distance of each year from itself is always zero. Off-diagonal values reflect the Euclidean distance between yields of different years, with larger values signifying greater differences. For example, the distance between 2000 and 2001 is 9743.4 kg ha^{-1}, indicating a relatively small difference in yield. In contrast, the distance between 2002 and 2003 is 205200.0 kg ha^{-1}, highlighting a much larger discrepancy in yield. The highest distance value is between 2010 and 2000, amounting to 720690.1 kg ha^{-1}, which reflects a substantial increase in yield over that decade.

The distances between other year pairs also illustrate yield fluctuations over time. The yield distance between 2021 and 2022 is 18802.6 kg ha^{-1}, suggesting a moderate difference, while the distance between 2020 and 2021 is similar, indicating a relatively minor change in yield. Overall, the index provides insights into the temporal variability of rice yield, emphasizing periods of significant change and stability in yield performance throughout the analyzed years.

4 Discussion

4.1 Rice production trends in Tanzania 2000–2022

The study highlights variability in cultivated area, ranging from 405,860 ha to 1,370,000 ha, with a mean of 888,821.1 ha, and indicating significant engagement in rice farming but also reflecting the influence of factors such as climate, soil quality, and farming practices [33, 34]. The high standard deviation suggests notable fluctuations in land allocation, which Panneerselvam et al. [35] attribute to farming practices like residue management and microbial interventions that can enhance soil quality and stabilize yields. The findings on statistically significant differences in rice area, production, and yield across years emphasize the importance of aligning resource allocation and management strategies with temporal variations [36, 37]. These results point to the need for stakeholders, including policymakers and farmers, to implement targeted interventions that address these variations, such as improving access to agricultural inputs, adopting adaptive farming practices, and enhancing productivity measures [7, 38]. Such actions can help mitigate production inconsistencies and promote sustainable rice cultivation in Tanzania. Additionally, Anagha et al. [33] emphasize the impact of external factors like ozone pollution, which has doubled crop production loss in recent years, further contributing to yield variability. These show the importance of both improved agricultural practices and environmental management to reduce instability in rice production.

The average rice production of 217.19 tons per year, with a maximum of 452.75 tons, shows significant variability across regions, highlighted by a high standard deviation of 110.76 tons. This disparity can be linked to differences in resource availability, agricultural techniques, and pest management strategies, as also highlighted in previous studies, by Saberali and Darzi-Naftchali [39], who identified key factors such as fertilizer rates and transplanting dates that significantly influence yield gaps. Also, Maung and Charoenratana [40] emphasized the role of adaptive capacity (AC) among farmers, noting that those with higher AC, marked by better access to education, credit, and irrigation, achieved greater yields through practices like crop diversification and the use of climate-resistant varieties. The observed moderate positive skewness in production data suggests that many smaller-scale farmers face challenges that limit their access to advanced farming technologies, leading to lower yields. Collectively, these studies highlight the need for improved resource access and agricultural practices to optimize productivity and enhance food security.

Yield statistics emphasize the disparities in rice production efficiency, with an average yield of 2327.4 kg ha^{-1} and a range from 1600.4 kg ha^{-1} to 3306 kg ha^{-1}. This variability suggests that some farmers achieve significantly higher productivity due to better management practices, effective pest control, and access to quality seeds. Also, Rouf Sarkar et al. [41] demonstrated that using good-quality seeds from formal sources correlates with yield increases from 0.03 to 0.15 t ha^{-1} compared to informal sources, highlighting a 48% gap in access to quality seeds. The positive skewness indicates that many farmers may be producing below optimal levels, highlighting the need for targeted agricultural extension services to improve seed access and promote good practices, thereby enhancing overall agricultural efficiency.

Table 4 Euclidean similarity and distance index for yield (kg ha^{-1} of rice between cultivation years

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
2000	0																						
2001	9743.4	0																					
2002	150000.1	159740.5	0																				
2003	205,200.0	214940.3	55200.0	0																			
2004	197530.1	207270.4	47530.0	7670.1	0																		
2005	286390.1	296130.4	136390.0	81190.1	88860.0	0																	
2006	218170.0	227910.1	68170.2	12970.7	20640.8	68220.4	0																
2007	142382.0	152121.2	7647.9	62822.2	55153.2	144010.9	75790.7	0															
2008	472060.1	481800.3	322060.0	266860.1	274530.0	185670.0	253890.2	329680.0	0														
2009	390030.1	399770.3	240030.0	184830.0	192500.0	103640.0	171860.2	247650.1	82030.0	0													
2010	720690.1	730430.0	570690.3	515490.3	523160.4	434300.5	502520.2	578309.0	248631.1	330660.7	0												
2011	703724.0	713464.0	553724.1	498524.1	506194.1	417334.1	485554.0	561343.1	231664.4	313694.2	16969.1	0											
2012	383761.2	393501.0	233761.6	178561.7	186231.7	97372.8	165591.4	241380.1	88301.4	6297.2	336929.0	319963.1	0										
2013	512673.2	522413.1	362673.5	307473.6	315143.7	226284.1	294503.4	370292.0	40620.2	122645.0	208017.0	191051.3	128912.1	0									
2014	541618.7	551358.3	391619.3	336419.4	344089.5	255230.3	323449.1	399237.1	69567.3	151591.9	179072.5	162107.6	157857.8	28947.4	0								
2015	738867.3	748607.1	588867.6	533667.6	541337.7	452477.9	520697.4	596486.0	266808.8	348838.2	18178.7	35147.7	355106.2	226194.1	197249.1	0							
2016	822400.5	832140.2	672400.8	617200.8	624870.9	536011.1	604230.6	680019.1	350342.0	432371.4	101710.9	118678.4	438639.3	309727.3	280782.0	83533.2	0						
2017	681683.1	691423.0	531683.2	476483.2	484153.3	395293.4	463513.1	539302.0	209624.0	291653.6	39007.1	22042.2	297922.0	169010.1	140065.9	57185.1	140718.0	0					
2018	617303.7	627043.1	467304.6	412104.9	419775.0	330916.1	399134.5	474921.9	145252.0	227278.0	103392.6	86431.7	233543.4	104633.2	75686.1	121567.2	205098.7	64389.9	0				
2019	636948.6	646688.1	486949.5	431749.7	439419.8	350560.8	418779.3	494566.8	164895.8	246922.5	83748.6	66789.5	253188.2	124277.5	95330.7	101922.5	185453.8	44748.7	19645.0	0			
2020	954401.1	964140.7	804401.5	749201.6	756871.7	668012.0	736,231.3	812,019.5	482,343.0	564,372.4	233712.0	250679.4	570640.0	441728.0	412782.4	215534.2	132001.1	272719.1	337098.0	317453	0		
2021	935600.7	945340.4	785601.0	730401.0	738071.1	649211.4	717430.8	793219.2	463542.1	545571.6	214911.0	231878.1	551839.5	422927.5	393982.1	196733.4	113200.2	253918.1	318298.2	298653.2	18802.6	0	
2022	582400.8	592140.4	432401.5	377201.6	384871.7	296012.4	364231.3	440019.2	110347.2	192373.8	138291.0	121327.0	198639.9	69728.8	40782.2	156467.3	240000.0	99285.0	34904.8	54548.8	372000.3	353200.0	0

The results indicates outliers and a flatter distribution, suggesting that while most farmers achieve average production and yields, a few outliers attain exceptionally high results due to innovative practices or better resource allocation. This aligns with Li et al. [42], which highlights significant variability in rice yields, especially with Japonica rice facing severe declines under climate change. The high coefficient of variation for production (51.00%) compared to area (32.14%) and yield (24.23%) emphasizes that production is the important variable factor. Additionally, Wen et al. [43] shows that returning wheat straw and applying microbial agents like *Bacillus subtilis* and *Trichoderma harzianum* can enhance rice yield by 3.81–26.63% through improved root development and soil health. Together, these findings highlight the importance of targeted adaptation strategies and innovative practices to stabilize production and optimize rice yields in the face of external challenges.

The results show significant variation in rice area, production, and yield across years, with very low p-values indicating that these differences are unlikely due to chance. The high F-value (222) and extremely low p-value ($4.93 \times 10^{(-30)}$) suggest that changes in agricultural practices, environmental conditions, or policy interventions likely inifluenced rice production over time. This aligns with Chang et al. [24], who highlight the limited adoption of sustainable agricultural practices (SAPs) in Southeast Asia, contributing to variability in production. Also, Nguyen et al. [44] emphasize that factors such as government support, social influence, and the role of agricultural cooperatives significantly impact the adoption of precision agriculture technology, further affecting rice production outcomes.

Also results with highly significant means ($p = 4.18 \times 10^{(-16)}$) and medians ($p = 6.14 \times 10^{(-15)}$), suggest inconsistent variance in rice production across years, likely due to external shocks such as droughts, floods, or pest outbreaks. The Welch F-test for unequal variances supports this, indicating that certain years were disproportionately affected. Sivakumar [45] highlights the increasing frequency of extreme weather events and their direct and indirect impacts on rice production, reinforcing the idea that these shocks contributed to the variance. This points the importance of agro-meteorological strategies to mitigate these impacts and build resilience in rice farming.

4.2 Yield stability in rice

The PC 1 explains 100% of the variance, primarily influenced by the area of rice cultivation, showcasing its critical role in production trends. Negative factor scores in the early 2000s suggest a decline in land dedicated to rice farming, coinciding with the pressures outlined by Taer [46], who noted both natural and anthropogenic factors affecting rice lands in the Philippines. Conversely, the positive scores from 2010 onward, peaking in 2020, likely reflect policy changes, technological advancements, and favourable environmental conditions that expanded cultivated areas or improved productivity. This aligns with findings from Amnuaylojaroen and Chanvichit [47], which highlight the importance of understanding climate patterns in enhancing crop productivity. Therefore, interventions aimed at boosting rice output should focus on optimizing land use, expanding cultivation areas, and enhancing productivity through sustainable practices and informed decision-making.

4.3 Agro-environmental, socio-economic, and policy impacts on rice production in Tanzania

Rice production in Tanzania has shown an increasing trend over the past two decades, marked by significant growth in both the number of households engaged in farming and improvements in yield. The national agricultural sample survey conducted in 2007/08 revealed a 20% increase in the number of households involved in rice farming compared to the 2002/03 season (The United Republic of Tanzania—URT [48].

During the 2007/08 cropping season, the Shinyanga region emerged as the top producer in rice, with 19% of its land dedicated to rice farming, accounting for about 180,000 hectares. Other regions with notable proportions of land used for rice included Morogoro (18.7%), Mwanza (13.7%), and Tabora (11%). On a more localized scale, Morogoro had the highest percentage of land planted with rice at 31%, followed by Mwanza at 14.8% and Dar es Salaam at 11.8%. Conversely, several regions had less than 10% of their land planted with rice, with Arusha showing the lowest figures—only 2,300 households and ~ 900 hectares (or 0.1%) of land devoted to rice cultivation. The Rukwa region demonstrated the highest average area of rice planted per household, at 1.34 hectares, indicating limited land availability despite the importance of rice production in the region. From the 2002/03 Agricultural Census, which recorded average yields of 1.0 t ha^{-1}, there has been a remarkable increase in rice yields, with some surpassing 100%. The yield range varied significantly, with the lowest yield recorded in Dodoma at 0.7 t ha^{-1} and the highest in Manyara at 3.4 t ha^{-1}. Rukwa, notable for its average area planted per household, also recorded the second-highest average yield of 2.74 t ha^{-1} [48].

The upward trend in rice production continued in subsequent years. A report of URT [49] indicates that during the 2022/23 agricultural year, approximately 1.8 million households were involved in rice cultivation across Tanzania. The total area planted with rice reached 1.7 million hectares, comprised of 1,683,000 hectares by agricultural households and 17,000 hectares by large-scale farms. Notably, agricultural households harvested 1,076,100 hectares, representing 64% of the planted area, with all regions achieving harvest rates exceeding 70%. The total rice production for the 2022/23 season was 2.4 million tons, with agricultural households contributing 2,369,000 million tons and large-scale farms reaching 31,000 tons. Regionally, Morogoro led in production with 430,000 tons, followed by Mbeya with 350,000 tons and Tabora with 208,300 tons. The Njombe region reported the lowest production at 1,800 tons. The average national

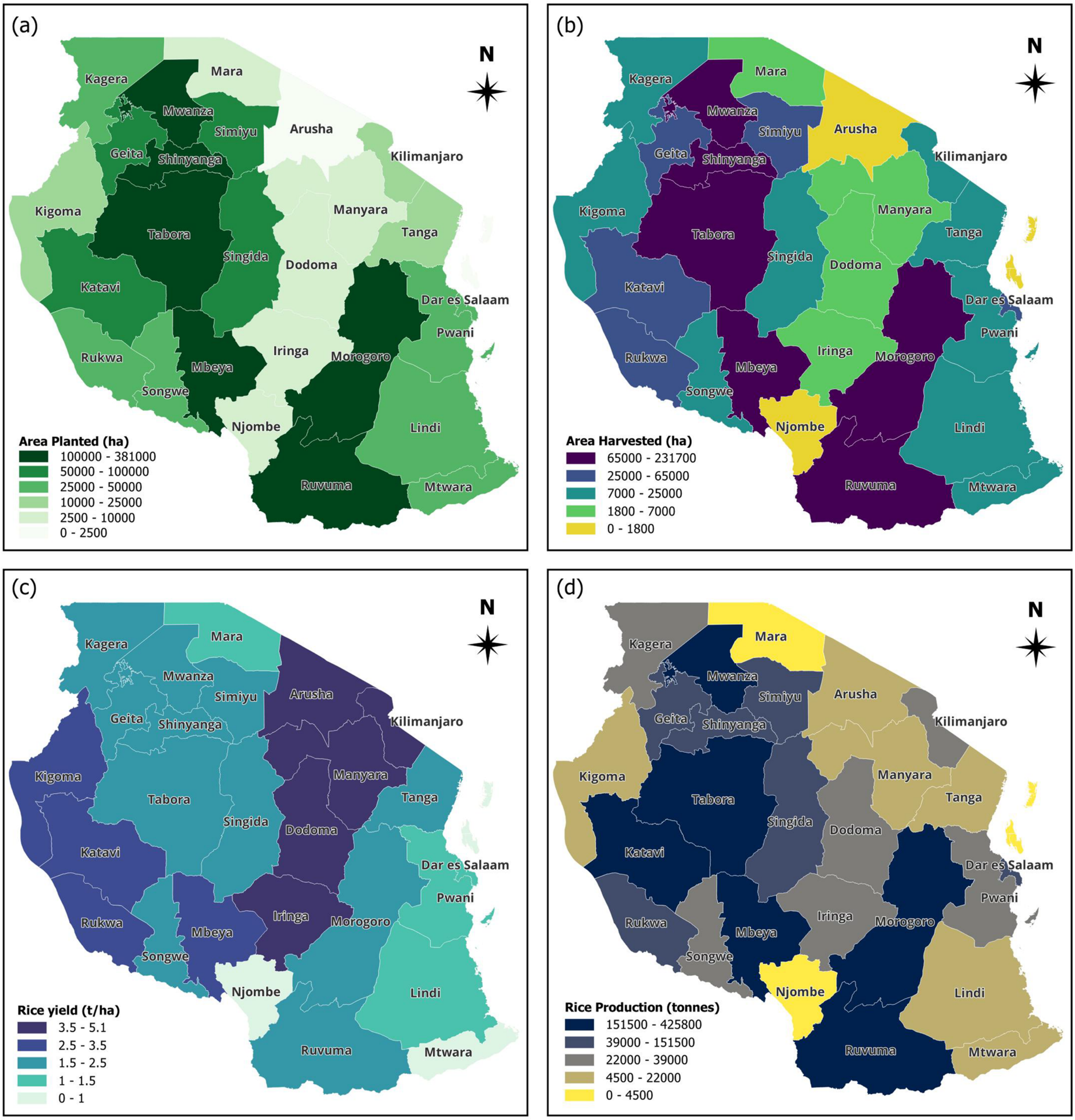


Fig. 3 Map illustrating rice production trends in Tanzania for the 2022/2023 cropping season. Created by the authors; data obtained from URT [49]

yield of rice was 2.2 t ha^{-1}, with Manyara achieving the highest yield at 4.5 t ha^{-1}, while Mtwara recorded the lowest at 0.7 t ha^{-1} (See Fig. 3).

Our study also highlights the significant improvements in rice production in Tanzania from 2000 to 2022, characterized by an increase in cultivated area from 405,860 ha to 1,370,000 ha. This growth reflects enhanced engagement in rice farming, driven by improved agricultural practices and adaptive capacity among farmers [50]. Average yields rose from approximately 1600.4 kg ha^{-1} to 2327.4 kg ha^{-1}, demonstrating the impact of factors such as access to quality seeds and effective pest management [41, 51]. Despite fluctuations due to environmental challenges, overall trends indicate that targeted interventions and innovative practices have been important in stabilizing and optimizing rice production, thereby contributing to improved food security in the rice industry.

The substantial increase in rice production between 2018 and 2022 could be attributed to several interrelated factors, including technological advancements in agronomic practices, societal preferences, awareness of environmental impacts, and supportive government policies [41, 52]. Significant strides in research and breeding have led to the development of improved rice varieties, such as 'TXD 306 – SARO 5', and 'SUPER BC', which are suited to local conditions [40]. Enhanced irrigation systems and the adoption of cover crops like lablab (*Lablab purpureus*), mucuna (*Mucuna pruriens*), and sunhemp (*Crotalaria juncea*) have significantly improved soil fertility [35]. The increased application of synthetic and bio-fertilizers, supported by government subsidies on various types, including NPS, NPK, UREA, CAN, TSP, and muriate of potash (MOP), has further contributed to productivity gains [34].

Societal consumption patterns have also played a critical role in rice production [53]. There has been a marked increase in rice consumption during social occasions, as well as dietary diversification tailored to specific groups, such as pregnant women, children under five years, and the elderly [54, 55]. The higher market value of rice relative to other cereal grains has incentivized farmers to allocate more resources toward rice cultivation, driving overall yield improvements [56, 57].

Farmers have also become more aware of environmental factors affecting rice production, leading to improved practices such as timing planting with the onset of the rainy season, utilizing supplemental irrigation, and implementing soil and moisture conservation techniques like mulching [58]. Crop rotation with drought-tolerant legumes during short rainy seasons has further enhanced resilience against climate variability [59].

The Tanzanian government's supportive policies have had a profound impact on rice production. The fertilizer subsidy program, which allows farmers to access three bags of fertilizers per acre (approximately 150 kg, with one bag applied during planting and two as topdressing), has significantly improved input accessibility [60]. Initiatives like the "guaranteed price" or "fixed price" (stakabadhi ghalani) program ensure that farmers have a guaranteed market for their produce, while the establishment of seed multiplication farms has bolstered production capabilities [60, 61]. The government has also prioritized the construction of irrigation dams for strategic crops, including rice, maize (*Zea mays*), and sunflower (*Helianthus annuus*), as part of its "Building Better Tomorrow – BBT" program. Additionally, crop protection initiatives targeting pests and diseases, such as the management of destructive birds and pests like Sudan doves (*Eudocimus albus*), rats (*Rattus spp*.), and fall armyworms (*Spodoptera frugiperda*), have helped mitigate yield losses, ensuring that farmers can achieve better outcomes [62, 63]. The crop protection program under the Tanzania Plant Health and Pesticides Authority (TPHPA) has been essential in addressing these challenges.

The study's reliance on secondary data sources, such as FAOSTAT and government reports, introduces limitations regarding the reliability and accuracy of the dataset. Potential biases may arise from uneven regional representation of data, as not all rice-growing areas in Tanzania may be equally documented. Additionally, variability in reporting methods and data collection techniques over the years could affect the consistency and comparability of the dataset. These factors may influence the interpretation of trends and highlight the need for caution when generalizing findings. Future research should consider integrating primary data collection and more regionally disaggregated analyses to address these limitations.

5 Practical implications of the study and future directions

The study highlights the fluctuations in rice yield performance, revealing both periods of stability and substantial change. This information is valuable for stakeholders in rice production, as it emphasizes the importance of understanding yield trends over time, which can guide decision-making in cultivation practices and resource allocation [64].

Practically, the study suggests farmers and agricultural planners should consider historical yield data when developing strategies for crop management and improvement. This data-driven approach can facilitate targeted interventions to enhance yield stability, such as adopting improved varieties, optimizing cultivation practices, or implementing soil and water management techniques [65]. Furthermore, extension services can leverage these insights to educate farmers about yield variability and promote adaptive practices to mitigate risks associated with fluctuating yields [66, 67].

Looking ahead, future research should focus on exploring the underlying factors contributing to yield variability in rice production. This could involve examining environmental conditions, such as climate variability and soil health, as well as agricultural practices that influence yield outcomes [42]. Additionally, integrating molecular techniques and advanced analytics can enhance understanding of the complex interactions between agronomic practices and yield performance [68, 69]. Ultimately, expanding this research can lead to the development of strategies that improve rice yield stability and sustainability in the face of changing environmental conditions.

Author contributions A.J.M: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing—original draft, Writing—review & editing. F.K.F: Supervision, Validation, Visualization, Writing—review & editing. E.K.N: Supervision, Validation, Visualization, Writing—review & editing. GMT: Supervision, Validation, Visualization, Writing—review & editing.

Funding This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability Data will be made available on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

1. Purba HJ, Azahari DH, Dani FZ, Alsyouf I, Masmoudi M, Obaideen K. Enhancing rice resilience and sustainability: a bibliometric analysis of innovations for food security and environmental conservation. BIO Web of Conf Sci. 2024. https://doi.org/10.1051/bioconf/202411905003.
2. Bhuyan GV, Deka N, Bhagabati AK. Rice farming in Assam (India): Ecology, tradition, and transformation. Singapore: Springer Nature; 2024.
3. Yadav S, Sharma A. Shortcomings in rice production: with special emphasis on salinity stress. Acta Sci Microbiol. 2024. https://doi.org/10.31080/ASMI.2024.07.1361.
4. Alam M, Lou G, Abbas W, Osti R, Ahmad A, Bista S, He Y. Improving rice grain quality through ecotype breeding for enhancing food and nutritional security in Asia-Pacific region. Rice. 2024;17(1):47. https://doi.org/10.1186/s12284-024-00725-9.
5. Ojo OO, Oladoyin OP, Ekundayo BP, Borokini EA. Food calorie consumption and vulnerability status of the rice farmers in Ekiti state, Nigeria: perspective for commercialized farming. Euro J Nut Food Safety. 2024;16(3):35–44. https://doi.org/10.9734/ejnfs/2024/v16i31396.
6. Kimwemwe PK. (2024). Genetic diversity and selection criteria for yield and aroma in rice (*Oryza sativa* L.) Germplasm of the Eastern Democratic Republic of Congo (Doctoral dissertation, JKUAT-CoANRE). Jomo Kenyatta University of Agriculture and Technology. Congo.
7. Touch V, Tan DK, Cook BR, Li Liu D, Cross R, Tran TA, Cowie A. Smallholder farmers' challenges and opportunities: implications for agricultural production, environment and food security. J Environ Manag. 2024. https://doi.org/10.1016/j.jenvman.2024.122536.
8. Tamekloe MK, Matsui K. Smallholder rice and vegetable farmers' constraints to adopt small-scale irrigation in South Tongu district, Ghana. Int J Agric Environ Res. 2024;10(4):513–34. https://doi.org/10.22004/ag.econ.345053.
9. Khatri P, Kumar P, Shakya KS, Kirlas MC, Tiwari KK. Understanding the intertwined nature of rising multiple risks in modern agriculture and food system. Environ Dev Sustain. 2024;26(9):24107–50. https://doi.org/10.1007/s10668-023-03638-7.
10. Lu M. Impact of climate change on rice and adaptation strategies: a review. Adv Resources Res. 2024;4(2):252–62. https://doi.org/10.50908/arr.4.2_252.
11. Tibamanya FY, Daudi CM, Utouh HM. Does information technology matter in adopting covid-19 preventive measures? Evidence from small-scale rice farmers in Morogoro Tanzania. Econ Insights-Trends Chall. 2024;13(3):102. https://doi.org/10.51865/EITC.2024.03.06.
12. Mussa J, Msuya E, Longo J. Determinants of inorganic fertilizer use by smallholder rice farmers in Mbeya and Morogoro regions of Tanzania. Afr J Empir Res. 2024;5(3):408–16. https://doi.org/10.51867/ajernet.5.3.36.

13. Mwalyagile N, Jeckoniah JN, Salanga RJ. Gender differences in rice production participation among smallholder farmers in small-scale irrigation schemes in Mbarali district Tanzania. J Agricu Food Res. 2024. https://doi.org/10.1016/j.jafr.2024.101390.
14. Kulyakwave PD, Shiwei X, Wen Y. Climate and socio-economic factors affecting the adoption of irrigation practices for improved rice yield in Mbeya region Tanzania. J Environ Sci Manag. 2023. https://doi.org/10.47125/jesam/2023_1/01.
15. Sanga DL, Mwamahonje AS, Mahinda AJ. Soil salinization under irrigated farming: a threat to sustainable food security and environment in semi-arid tropics. J Agric Sci Pract. 2024. https://doi.org/10.31248/JASP2024.468.
16. Anna M, Damas P. Determinants of Profit Efficiency among Rice Farmers in Kilombero Valley, Morogoro, Tanzania. Asian J Agric Ext, Econ Sociol. 2024;42(6):62–74. https://doi.org/10.9734/ajaees/2024/v42i62463.
17. Utonga D, Kamwela LJ. Towards sustainable maize farming in Tanzania: understanding yield predictors among smallholder farmers. Contemp Res Bus, Manag, Econ. 2024. https://doi.org/10.9734/bpi/crbme/v4/3435G.
18. Onyango J, Huang J, Babu K, Njuguna S, Wanzala W, Yan X.. Evaluating the interaction of plant communities with microplastics found in water and soil sediments of lake Victoria. 2024. https://doi.org/10.21203/rs.3.rs-4513150/v1
19. John I, Peter B, Holt D, Nkonde C, Gandidzanwa C. Mapping suitable areas for indigenous crop production: exploring Tanzania's Agroecological zones based on environmental tolerances. Available at SSRN 5064747. 2024. https://doi.org/10.2139/ssrn.5064747.
20. Zella AY, Lunyelele SS. Adaptation strategies of paddy farmers to build resilience to climate change in Kahama district, Tanzania. World J Adv Sci Technol. 2024;5(2):052–67. https://doi.org/10.53346/wjast.2024.5.2.0022.
21. Saddique MAB, Ali Z, Sher MA, Hakeem S, Su D, Muneer MA. Biofortified rice for zero hunger: current status, challenges, and prospects. Biofortific Grain Vegetable Crops. 2024. https://doi.org/10.1016/B978-0-323-91735-3.00004-2.
22. Yonfa-Medranda M, Sabando-Vera D, Parrales-Guerrero K, Cueva-Tumbaco J, Ramírez-Prado M. University-community partnership contribution towards rural sustainability: participatory action research in the rice farming community of Paipayales. Ecuador Rural Sustain Res. 2024;51(346):66–80. https://doi.org/10.2478/plua-2024-0007.
23. Hosono A. Transforming Economies for Jobs and Inclusive Growth. Singapore: Springer Singapore; 2022.
24. Chang SHE, Benjamin EO, Sauer J. Factors influencing the adoption of sustainable agricultural practices for rice cultivation in Southeast Asia: a review. Agron Sustain Dev. 2024;44(3):27. https://doi.org/10.1007/s13593-024-00960-w.
25. Yadav, N. Towards sustainable agri-food systems: Assessment of climate risk and its impact on rice productivity for Indian states. *32nd International Conference of Aricutlrual Economics, 2–7 August 2024*. New Delhi India. 2024. https://doi.org/10.22004/ag.econ.344338
26. Fiawoo HD, Tham-Agyekum EK, Ankuyi F, Osei C, Bakang JA. Rice farmers' adoption of climate-smart agricultural technologies and its effects on yield and income: empirical insights from Ghana. SVU-Int J Agric Sci. 2024;6(1):120–37. https://doi.org/10.21608/svuijas.2024.268924.1342.
27. Magang DS, Ojara MA, Yunsheng L, Kinguza PH. Future climate projection across Tanzania under CMIP6 with high-resolution regional climate model. Sci Rep. 2024;14(1):12741. https://doi.org/10.1038/s41598-024-63495-w.
28. Mwasha S I. Livelihoods, vulnerability, and adaptation to climate change of small-holder farmers in Kilimanjaro, Tanzania. (Thesis). Keele University. 2021.
29. Mugabe P, Kipkulei H, Sieber S, Mhache E, Löhr K. Examining climate trends and patterns and their implications for agricultural productivity in Bagamoyo District Tanzania. Front Climate. 2024;6:1346677. https://doi.org/10.3389/fclim.2024.1346677.
30. Kyojo EA, Mirau S, Osima SE, Masanja VG. Modeling non-stationarity in extreme rainfall data and implications for climate adaptation: a case study from southern highlands region of Tanzania. Sci Afr. 2024;25: e02321. https://doi.org/10.1016/j.sciaf.2024.e02321.
31. Msongaleli B. The contribution of climate-smart agriculture to reducing climate-related risks to rain-fed maize production: insights from Tanzania's Semi-Arid and Sub-Humid Regions Ghana. J Geography. 2024;16(1):28–58. https://doi.org/10.4314/gjg.v16i1.2.
32. Mugi E. Diversification and intensification of smallholder farming through intercropping with grain legumes in northern Tanzania. Wageningen Univ Res ProQuest Dissert Theses. 2022;2022:30775122.
33. Anagha KS, Kuttippurath J, Sharma M, Cuesta J. A comprehensive assessment of yield loss in rice due to surface ozone pollution in India during 2005–2020: a great concern for food security. Agric Syst. 2024;215: 103849. https://doi.org/10.1016/j.agsy.2023.103849.
34. Ashraf H, Ghouri F, Baloch FS, Nadeem MA, Fu X, Shahid MQ. Hybrid rice production: a worldwide review of floral traits and breeding technology, with special emphasis on China. Plants. 2024;13(5):578. https://doi.org/10.3390/plants13050578.
35. Panneerselvam P, Senapati A, Mitra D, Priyadarshini A, Shadangi S, Behera S, Nayak AK. Enhancing soil quality and yield through microbial assisted in-situ residue management in rice-rice cropping system in Odisha Eastern India. J Environ Manag. 2024. https://doi.org/10.1016/j.jenvman.2024.120916.
36. Islam T, Mazumder T, Roni MNS, Nur MS. A comparative study of machine learning models for predicting Aman rice yields in Bangladesh. Heliyon. 2024. https://doi.org/10.1016/j.heliyon.2024.e40764.
37. Wang Q, Sun L, Yang X. Identifying spatial determinants of rice yields in main producing areas of China using geospatial machine learning. ISPRS Int J Geo Inf. 2024;13(3):76. https://doi.org/10.3390/ijgi13030076.
38. Takada A, Yoshida T, Ishigooka Y, Maruyama A, Kudo R. Potential barriers to adaptive actions in water–rice coupled systems in Japan a framework for predicting soft adaptation limits. Water Resources Res. 2024;60(4): e2022. https://doi.org/10.1029/2022WR034219.
39. Saberali SF, Darzi-Naftchali A. Yield gap analysis and the relative importance of factors explaining yield variability in paddy fields. Eur J Agron. 2024;156: 127172. https://doi.org/10.1016/j.eja.2024.127172.
40. Maung TW, Charoenratana S. Adaptation to climate impacts on rice production: an analysis of dry zone farmers in central Myanmar. Climate Res. 2024;92:151–70. https://doi.org/10.3354/cr01738.
41. Rouf Sarkar MA, Habib MA, Sarker MR, Rahman MM, Alam S, Islam Manik MN, Nayak S, Bhandari H. Rice farmers' preferences for seed quality, packaging, and source: a study from northern Bangladesh. PLoS ONE. 2024;19(6): e0306059. https://doi.org/10.1371/journal.pone.0306059.
42. Li S, Wu F, Zhou Q, Zhang Y. Adopting agronomic strategies to enhance the adaptation of global rice production to future climate change: a meta-analysis. Agron Sustain Dev. 2024;44(3):23. https://doi.org/10.1007/s13593-024-00963-7.
43. Wen Y, Ma Y, Wu Z, Yang Y, Yuan X, Chen K, Sun Y. Enhancing rice ecological production: synergistic effects of wheat-straw decomposition and microbial agents on soil health and yield. Front Plant Scince. 2024;15:1368184. https://doi.org/10.3389/fpls.2024.1368184.

44. Nguyen LLH, Khuu DT, Halibas A, Nguyen TQ. Factors that influence the intention of smallholder rice farmers to adopt cleaner production practices: an empirical study of precision agriculture adoption. Eval Rev. 2024;48(4):692–735. https://doi.org/10.1177/0193841X231200775.
45. Sivakumar MV. Climate extremes and impacts on agriculture. Agroclimatology: Link Agric Climate. 2020;60:621–47. https://doi.org/10.2134/agronmonogr60.2016.0003.
46. Taer, A. Shrinking rice bowls: Tracing the decline of Philippine rice lands. https://doi.org/10.21203/rs.3.rs-3927443/v1. 2024.
47. Amnuaylojaroen T, Chanvichit P. Historical analysis of the effects of drought on rice and maize yields in Southeast Asia. Resources. 2024;13(3):44. https://doi.org/10.3390/resources13030044.
48. The United Republic of Tanzania (URT) (2012). National Sample Census of Agriculture - 2007/2008: Small Holder Agriculture. Volume II: Crop Sector—National Report. Pages 512. Available online: https://www.kilimo.go.tz/uploads/statistics/Crops_National_Report_11_June_2012.pdf
49. The United Republic of Tanzania (URT) (2024). Annual Agricultural Sample Survey 2022/23: National Report, September, 2024. https://www.nbs.go.tz/uploads/statistics/documents/en-1727940459-AASS%202022-23%20NATIONAL%20REPORT.pdf
50. Mpala TA, Simatele MD. Climate-smart agricultural practices among rural farmers in Masvingo district of Zimbabwe: Perspectives on the mitigation strategies to drought and water scarcity for improved crop production. Front Sustain Food Syst. 2024;7:1298908. https://doi.org/10.3389/fsufs.2023.1298908.
51. Mariano MJ, Villano R, Fleming E. Factors influencing farmers' adoption of modern rice technologies and good management practices in the Philippines. Agric Syst. 2012;110:41–53. https://doi.org/10.1016/j.agsy.2012.03.010.
52. Sriartha IP, Giyarsih SR, Purnamawati IGA. Comparing the adaptive capacity of traditional irrigated rice fields farmers in urban and rural areas to climate change in Bali Indonesia. Cogent Soc Sci. 2023;9(2):2275936. https://doi.org/10.1080/23311886.2023.2275936.
53. Mauki C, Jeckoniah J, Massawe G. Smallholder rice farmers profitability in Agricultural Marketing Co-operative Societies in Tanzania: a case of Mvomero and Mbarali districts. Heliyon. 2023;9(6): e17039. https://doi.org/10.1016/j.heliyon.2023.e17039.
54. Madzorera I, Isanaka S, Wang M, Msamanga GI, Urassa W, Hertzmark E, Duggan C, Fawzi WW. Maternal dietary diversity and dietary quality scores in relation to adverse birth outcomes in Tanzanian women. Am J Clin Nutr. 2020;112(3):695–706. https://doi.org/10.1093/ajcn/nqaa172.
55. Heri R, Malqvist M, Yahya-Malima KI, Mselle LT. Dietary diversity and associated factors among women attending antenatal clinics in the coast region of Tanzania. BMC Nutrition. 2024. https://doi.org/10.1186/s40795-024-00825-1.
56. Mtembeji AL, Singh DR. Dynamics of rice production among the food crops of Tanzania. South Afr J Sci. 2021;117(9–10):1–6.
57. Senthilkumar K, Sillo FS, Rodenburg J, Dimkpa C, Saito K, Dieng I, Bindraban PS. Rice yield and economic response to micronutrient application in Tanzania. Field Crop Res. 2021;270: 108201. https://doi.org/10.1016/j.fcr.2021.108201.
58. Nyamekye AB, Dewulf A, Van Slobbe E, Termeer K, Pinto C. Governance arrangements and adaptive decision-making in rice farming systems in Northern Ghana. NJAS - Wageningen J Life Sci. 2018;86–87:39–50. https://doi.org/10.1016/j.njas.2018.07.004.
59. Kabote SJ, Mbwambo EP, Kazuzuru BB. Determinants of farmers' choice of adaptation strategies against climate variability and change: lessons from central Tanzania in Manyoni district. Climate Services. 2024;34: 100470. https://doi.org/10.1016/j.cliser.2024.100470.
60. Fujimoto T, Suzuki A. Do fertilizer and seed subsidies strengthen farmers' market participation? Evidence from Tanzania's subsidy program. Rev Dev Econ. 2024;28(1):339–59. https://doi.org/10.1111/rode.13061.
61. Kansiime MK, Bundi M, Nicodemus J, Ochieng J, Marandu D, Njau SS, Romney D. Assessing sustainability factors of farmer seed production: a case of the Good Seed Initiative project in Tanzania. Agric Food Secur. 2021;10(1):15. https://doi.org/10.1186/s40066-021-00289-7.
62. Wolinsky H. The mystery of an unprecedented plant disease in Africa: The appearance of an Asian strain of bacterial blight in Tanzania threatens rice production in Africa. EMBO Rep. 2023;24(8): e57596. https://doi.org/10.15252/embr.202357596.
63. Benjamin J, Idowu O, Babalola OK, Oziegbe EV, Oyedokun DO, Akinyemi AM, Adebayo A. Cereal production in Africa: the threat of certain pests and weeds in a changing climate—a review. Agric Food Sec. 2024;13(1):18. https://doi.org/10.1186/s40066-024-00470-8.
64. Hashim N, Ali MM, Mahadi MR, Abdullah AF, Wayayok A, Kassim MSM, Jamaluddin A. Smart farming for sustainable rice production: an insight into application, challenge, and future prospect. Rice Sci. 2024;31(1):47–61. https://doi.org/10.1016/j.rsci.2023.08.004.
65. Weraikat D, Šorič K, Žagar M, Sokač M. Data analytics in agriculture: enhancing decision-making for crop yield optimization and sustainable practices. Sustainability. 2024;16(17):7331. https://doi.org/10.3390/su16177331.
66. Alam MJ, Sarma PK, Begum IA, Connor J, Crase L, Sayem SM, McKenzie AM. Agricultural extension service, technology adoption, and production risk nexus: evidence from Bangladesh. Heliyon. 2024. https://doi.org/10.1016/j.heliyon.2024.e34226.
67. Prasad R, Anil K, Prahlad P, Manohar KN, Rajesh CM, Jadhav A, Bhanu PB. A review on Eva[10]ation of the effectiveness of agricultural extension services in adapting to climate among subsistence farmers. Int J Environ Climate. 2024;14(7):454–65. https://doi.org/10.9734/ijecc/2024/v14i74286.
68. Chandel N, Kumar A, Kumar R. Towards sustainable agriculture: Integrating agronomic practices, environmental physiology and plant nutrition. Int J Plant Soil Sci. 2024;36(6):492–503. https://doi.org/10.9734/ijpss/2024/v36i64651.
69. Khan AA, Iqbal B, Jalal A, Khan KA, Al-Andal A, Khan I, Elboughdiri N. (2024). Advanced Molecular Approaches for Improving Crop Yield and Quality: A Review. *Journal of Plant Growth Regulation*. https://doi.org/10.1007/s00344-024-11253-7