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Technical Efficiency of Fertilizer Adoption and Smallholder Maize Productivity in Kenya. Stochastic Frontier Analysis

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Abstract

Empirical studies indicate that in Kenya, the adoption rates of inorganic fertilizers, irrigation systems, hybrid seeds, and agricultural extension services remain limited. This shortfall results in lower maize yields, decreased agricultural earnings, and ongoing food insecurity within the nation. This study aimed to assess the technical efficiency of chemical fertilizer usage and determine the scale elasticity and cost flexibility in maize production within Kenya. Technical efficiency scores were computed using stochastic frontier analysis. The analysis employed output-oriented technical efficiency with a truncated normal distribution. The results showed low output elasticities, indicating that maize producers experience diminishing returns to scale and diseconomies of scale. The results suggest that current maize production is characterized by escalating costs of chemical fertilizer use, potentially leading to reduced usage, improper application, or being adversely affected by abiotic factors like climate change, including flooding and prolonged droughts. The study revealed a mere 11 percent technical efficiency in Kenya's agricultural sector, underscoring the urgent need to re-emphasize the implementation of the Agricultural Sector Transformation and Growth Strategy 2019 to improve technical progress, with literature also advocating for commodity-free trade of enhancing producer and consumer welfare in a Pareto optimal fashion.

Key words: stochastic frontier analysis, technology adoption, maize productivity, fertilizer use in Kenya and technical efficiency.
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1. Introduction

The research by Wawire et al. (2021) highlights a significant decline in soil fertility across sub-Saharan Africa attributed to prolonged nutrient mining without replenishment. In Kenya, this issue is compounded by the low usage of fertilizers in maize production (Jena et al., 2021). The situation is further exacerbated by the inefficiency of government subsidy programs, which predominantly benefit large-scale farmers (Mather et al., 2018). The United States Agency for International Development (USAID, 2019) reported a progressive decline in Kenya's agricultural growth, contrasted with rising population rates. Despite approximately 20% of Kenyan land being arable, its agricultural output still needs to be optimal, suggesting a significant potential for improvement through disembodied technical progress.

USAID (2019) also reported that many smallholder farmers in Kenya need essential agricultural inputs, including modern farm equipment, credit, and access extension services. Furthermore, the World Bank (2015) highlighted a declining trend in smallholder farmers' access to agricultural extension services, which are skewed towards benefiting larger commercial farms. This problem is aggravated by reduced government investment in agricultural research and extension over the past decade, (Birch, 2018). The agricultural sector is dominated by smallholder farmers producing on farms between 0.2 hectares to 3 hectares, accounting for 78 % of the entire agricultural production and 70 % of commercial yields. Agricultural yield is low, especially in cereals (World Bank, 2015). The World Bank (2018) further emphasized this point, showing that maize yields per hectare in

2014 were lower than those in 1994, and the proportion of smallholder farmers receiving extension services is remarkably low compared to large-scale farmers. The World Bank (2019) suggested increasing fertilizer application rates per acre to boost productivity.

Table 1: Trends in cereal production, Kenya, Ethiopia, and Uganda

	1995			**2005**			**2016**		
	Kenya	**Ethiopia**	**Uganda**	**Kenya**	**Ethiopia**	**Uganda**	**Kenya**	**Ethiopia**	**Uganda**
Population(millions)	27.3	57.3	20.6	36.0	76.7	28.5	49.7	105.0	42.9
Rural population (millions	22.4	49.1	18.3	28.0	64.2	25.0	36.1	82.7	35.6
Total Government agricultural spending (% total outlays	-	-	-	3.9	15.9	3.1	1.5	17.5	4.0
% Agricultural employment	45.9	89.4	81.3	41.4	80.2	82.1	38.1	69.0	75.8
Cereal Yield(kg/hectare)	1,753	1,034	1,571	1,646	1,361	1,574	1,628	2,325	2,019

Source: http://www.fao.org/faostat

A comparative analysis between Ethiopia, Uganda, and Kenya presented in Table 1, reveals a stark contrast: while Kenya's cereal production declined from 1,753 kilograms in 1995 to 1,628 kilograms in 2016, Ethiopia and Uganda saw significant increases in their cereal production during the same period. These trends underscore the critical issue of low technology adoption in Kenya, which correlates with low maize productivity.

Table 2. Summary of Global Leading Maize Producers Fertilizer Consumption Per Kilogram

Country	**Average per hectare**	**Average per acre**
United States of America	126.923	50.7692
China	518.559	207.4236
Brazil	158.591	63.4364
India	164.338	65.7352
Argentina	37.231	14.8924
Ukraine	38.607	15.4428
Mexico	83.365	33.346
Indonesia	205.497	82.1988
France	160.637	64.2548
South Africa	59.095	23.638
Kenya	35.825	14.33

Source: Author's computations from World Bank Data 2020.

Dorfman (1996) noted that the adoption rates of improved maize varieties and inorganic fertilizers remain extremely low in Kenya, as a versed to the leading maize producers (Table 2). Despite the evidence of increased productivity from improved hybrid maize seeds and chemical fertilizer use in relation to other agronomic practices, uptake by smallholder farmers is very low in Kenya (Ogada & Nyangena, 2014).

Unraveling the persistent low levels of technology adoption (inorganic fertilizer) and its effects on smallholder maize productivity was the gist of this study. Available evidence shows that several studies, including field trials at agricultural stations in Kenya, have demonstrated the importance of improved hybrid seed varieties and optimal fertilizer application rates in increasing maize yields (Duflo et al. 2008). Table 2, and Figures 1 and 2 depict low fertilizer use by maize farmers in Kenya compared to the leading global corn producers and African region.

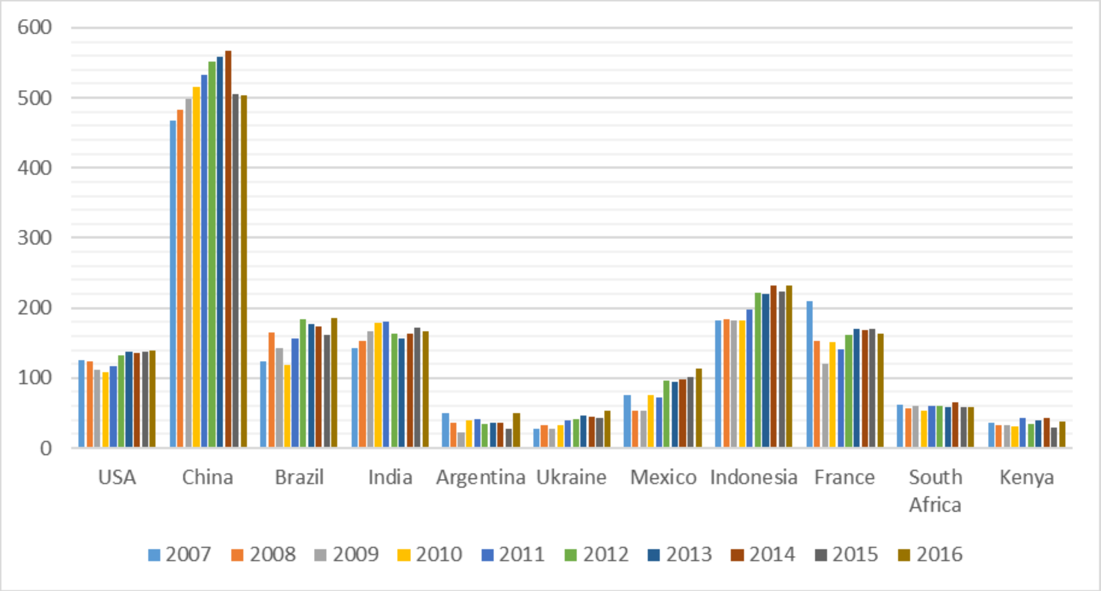


Figure 1. Country Fertilizer Consumption in Kgs/Ha of Arable Land

Source: Author's computation from World Bank data 2020

Figure 1 demonstrates the low level of fertilizer use in Kenya relative to the leading global corn producers.

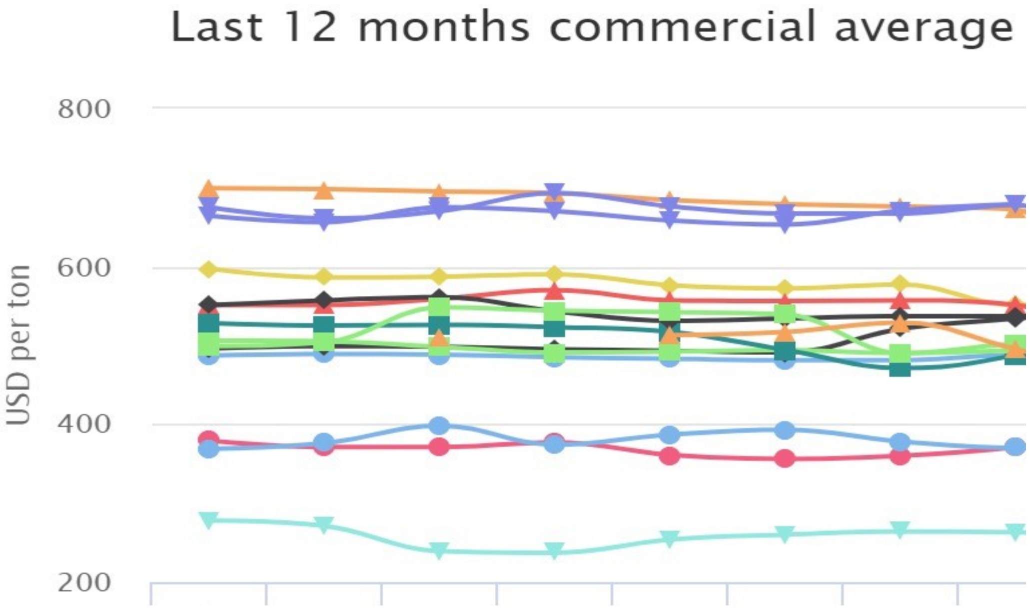


Figure 2. Fertilizer Average Prices in October 2019

Source: Africafertilizer.org

Figure 2 shows the prevailing high fertilizer retail prices in Kenya, compared to other African Countries. Indeed, African countries continue to offer high prices of fertilizer in relation to world prices. This could be one of the leading factors contributing to technical inefficiency in maize production.

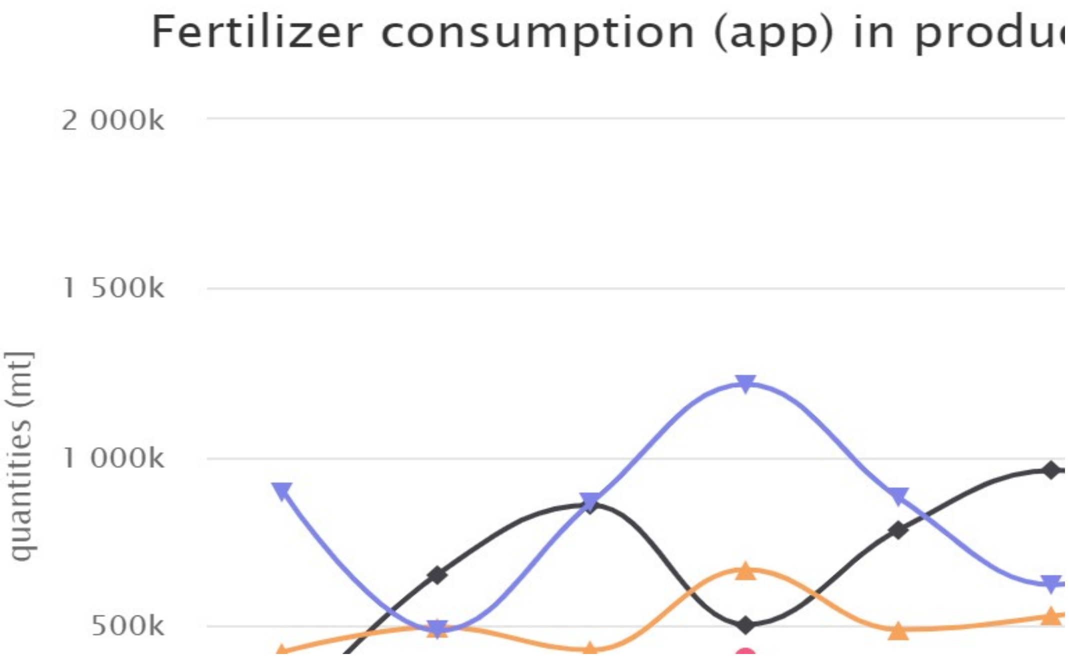


Figure 3. Fertilizer Consumption in Africa

Source: AfricaFertilizer.org

Still within the Africa region, as denoted in Figure 3, Kenya lags Nigeria and Ethiopia in fertilizer consumption, while Tanzania is already surpassing Kenya.

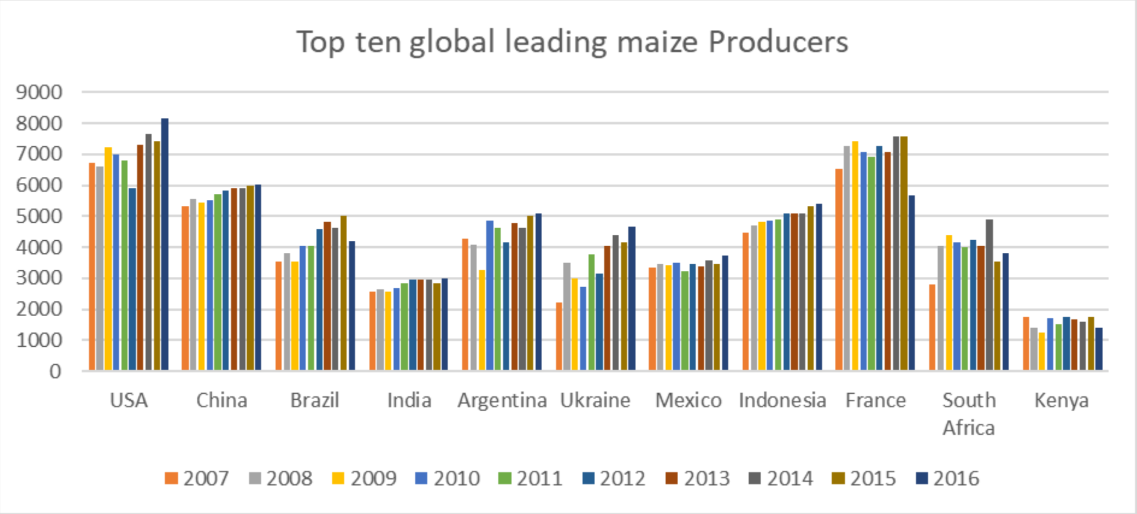


Figure 4. Maize productivity for the leading World producers and comparing with maize productivity in Kenya.

Source: Author's computation from World Bank Data 2020

Agricultural productivity measurement research is not new and can be traced back to the classical theory of economic growth. Solow (1957), Diewert (1980), Ball et al. (1997), and Ball & Norton (2002) recently made significant contributions to establishing a better understanding, measuring, and analyzing agricultural output. Productivity analysis has always assumed the absence of technical inefficiencies in the production process. Beginning with Nishimizu and Page (1982), and continuing with Fare et al. (1989), the research community has placed increased attention on the breakdown of improvements in productivity into a technological change component and an efficiency component. Grosskopf (1993) pointed out that overlooking inefficiencies in productivity analysis can lead to misleading conclusions about technical change, resulting in potentially erroneous policy decisions. This is especially relevant given the decreasing availability of crucial resources and production inputs, like land and water, in adequate quantity and quality. Understanding and evaluating agricultural efficiency becomes imperative in this context. The primary aim of this paper is to assess the current technical efficiency of chemical fertilizer usage in Kenya's maize production. Additionally, it seeks to ascertain cost levels and the viability of expanding production with existing technology by analyzing returns to scale and cost flexibility for maize producers.

2. Literature Review

This section reviews the literature relating to smallholder access to agricultural extension services that promote the adoption of relevant input technology, especially inorganic fertilizer, and improved maize seed application. It provides an overview of the global and Kenyan historical development of agricultural research and extension.

2.1 Historical Perspective of Agricultural Research and Extension Policy Development

2.1.1 The global perspective

Zivkovic et al. (2009) noted the establishment of the first farmer's association in Scotland in 1723, followed by similar organizations in France (1756), Denmark (1769), and later in England and the United States (1784). They highlighted the significant role of research and extension in the United States, starting with the Morrill Land Grant College Act of 1862. This Act provided states and U.S. territories with land to establish institutions focused on practical education in agriculture and the mechanical arts, leading to the creation of land-grant colleges and universities. In 1887, the Hatch Experiment Station Act furthered this initiative by establishing state agricultural experiment stations (SAES) under the supervision of land-grant institutions, and allowed the USDA, which was already conducting significant agricultural research, to direct federal funds to these stations.

Zivkovic et al. (2009) also emphasized the importance of the Smith Lever Act of 1914, which established the Cooperative Agricultural Extension Service as a collaboration among federal, state, and local governments. Collectively, the Morrill, Hatch, and Smith-Lever Acts aimed to disseminate the practical benefits of education and scientific research to U.S. residents, with a specific focus on improving the economic prospects and quality of life for farmers, farm families, and rural communities.

2.1.2 Kenyan perspective

Suda (1990) observed that during the colonial era, from 1895 to 1963, European settlers in Kenya cultivated large-scale farms and focused on export crops in high-potential agricultural zones. This export-oriented policy of the colonial government had lasting negative impacts on enhancing smallholder productivity in post-independence Kenya.

Since gaining independence, the Kenyan government has implemented significant agricultural sector reforms aimed at revolutionizing and revitalizing smallholder agriculture. This includes emphasizing the importance of agricultural extension services in boosting productivity. The first post-independence acknowledgment of extension services' importance was in Sessional Paper Number 10 of 1963. This policy advocated for education, training, and exposure to commercial and profitable farming practices, complemented by credit and extension services to enhance African agricultural productivity.

To further bolster agriculture, the Kenyan government initiated the Strategy to Revitalize Agriculture (SRA, 2004), underscoring the significance of agricultural extension services in enhancing productivity and reducing poverty in rural areas. The essential role of these services is also highlighted in subsequent policy initiatives, such as Kenya Vision 2030 (2007), the Agricultural Sector Development Strategy (ASDS) 2010-2020, and the National Agriculture Sector Extension Policy (NASEP, 2012).

NASEP (2012) delineates strategies for the effective management and organization of agricultural extension in a pluralistic framework, encouraging collaboration between private and public service providers. This policy underscores the Kenyan government's commitment to using agricultural extension as a key tool for promoting productivity.

> "Agricultural sector extension service plays an important role in sharing knowledge, technologies, and agricultural information and linking the farmers to other actors in the economy. Therefore, the extension service is one of the critical change agents required to transform subsistence farming to modern and commercial agriculture. This is critically important in promoting household food security, improving earnings, and reducing poverty" p 4.

2.1.3 Agricultural research and extension services

Zivkovic et al. (2009) asserted that research and extension are not independent but interdependent parts of a more extensive system, emphasizing the critical role of technology innovations and transfer in accelerating public research and development investments, enhancing economic opportunities, and creating jobs, as highlighted by the USDA (2023). They argued that agricultural extension service providers need context-specific skills to effectively communicate with and motivate value chain actors to adopt innovations. This need is pronounced given the prevalence of small family farms with generally lower educational levels than other sectors.

The USDA (2023) noted that combining research-driven sustainable practices with effective extension services is essential for long-term environmental, economic, and social sustainability. The Food and Agricultural Organization (FAO, 2020) defined *agricultural extension* as providing technical advice on agronomic practices to farmers and facilitating access to new information and technology, such as improved crop varieties and water management techniques. Muyenga and Jayne (2006) highlighted that agricultural extension systems and input distribution are complementary, impacting agricultural output based on the functionality of the input distribution system.

Ayele (2016) discussed the Ethiopian agricultural extension delivery package, which uses model farmers to transfer technologies and information to smallholder farmers. Burton et al. (1997) and Ayele (2016) noted that agricultural extension conveys essential information to farmers. Christoplos et al. (2001) provided a comprehensive definition of extension, describing it as a practice that facilitates farmers' access to agricultural technologies and information, enhancing their technical, organizational, and management skills. Evans (2014) postulated that agricultural extension services are vital policy tools for improving agricultural productivity, emphasizing the importance of information and technology transfer.

The USDA (2019) observed that agricultural extension experts focus on research-based knowledge and technology transfer to support social, economic, and environmental development in rural areas. Birch (2018) noted that Kenya's government spending on agricultural research relative to GDP has decreased over the past decade, affecting its competitiveness. The USDA (2022) indicated that China and Brazil, significant players in global agriculture, have increased their agricultural R&D expenditure, with China becoming the leading funder of agricultural R&D. The United States, while potentially offsetting lower public R&D spending with private investment, faces challenges in maintaining its global leadership in agricultural sciences and trade competitiveness. Lastly, Fuglie (1996) emphasized that the foundation of agricultural development lies in research, involving the systematic investigation of problems faced by farmers and value chain actors and the creation of new technologies, crop varieties, and best practices to enhance the agricultural industry's productivity, yield, and sustainability.

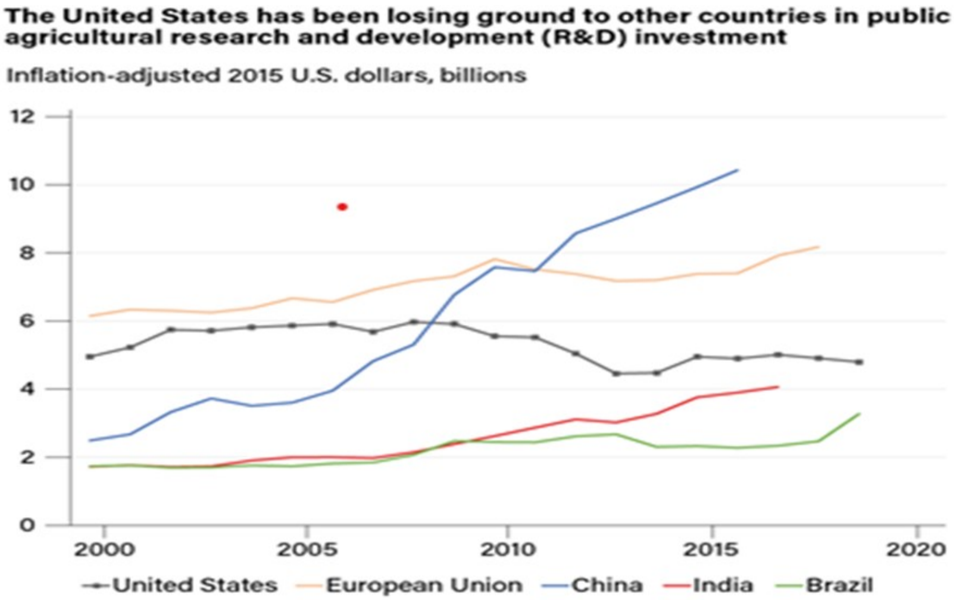


Figure 3. Global Research Funding and Agricultural Competitiveness

Source: USDA (2022)

2.1.4 Agricultural research and extension services

Expanding agricultural growth through uptake (adoption) and upscaling (diffusion) of contemporary agricultural technologies is vital for economic development and agricultural transformation in developing nations (Evenson, & Golin, 2003; Golin, 2010). This is especially ideal for Sub-Saharan Africa, where agriculture is the leading sector, albeit riddled with low productivity. Despite available evidence that many African Countries are now allocating more resources to the sector, overall technology adoption remains low (Minot & Benson, 2009; Byerlee et al., 2007; Rashid et al. 2013; Sheahan & Barrett, 2014). Literature is replete with low levels of technology adoption in Africa. The main limiting factors include lack of credit, high transaction costs, and market imperfections (Moser & Barrett, 2006; Gine & Klonner 2007; Duflo et al. 2011 & Minten et al. 2013).

Spielman et al. (2011) stated that in Ethiopia, extension services have conventionally been funded and delivered by the government, representing public sector gross investment exceeding 50 million U.S. dollars or 2 percent of the government's annual budgetary allocations. However, agricultural extension services and technology adoption have produced mixed results, with low extension services responsible for technology's non-adoption (Bonger et al., 2004). Spielman et al. (2011) concluded that public sector-led policies to promote improved seed and fertilizer adoption by smallholder farmers through government-owned input supply and extension service delivery is not effective because it leads to reduced quality of input services, is fiscally unattractive to the government, and creates significant risks to government and smallholders.

Abay et al. (2016) observed that agricultural development in Africa is characterized by a low degree of technology adoption. However, recent empirical evidence suggests the co-existence of enormous adoption heterogeneities among smallholders and the absence of optimal input combinations for farmers to exploit input complementarities, thus hindering the potential of using an appropriate optimal input combination. Besides, technology adoption demonstrates robust complementarity, approximately 70 percent between inorganic fertilizer and hybrid seeds, and relatively weaker complementarity, approximately 6 percent to 23 percent between the two inputs and extension services. Equally, Abay et al. (2016) noted that robust complementarities exist between particular extension services (for example, advice on seedbed preparation) and hybrid seeds and inorganic fertilizers instead of merely visits by extension officers. This implies that extra advantages can be obtained if the extension system is supported by "knowledge" inputs and not only "prodding" of farmers to apply the inputs.

Why is agricultural technology adoption rates low in Kenya despite empirical evidence of inorganic fertilizer efficacy and improved seed usage in increased maize productivity? Davis et al. (2010) noted that Ethiopia is one of the countries that has reported increased investment greater than 10 percent of its annual budgetary resources in agriculture for the past ten years and currently has achieved the leading frontline extension worker-to-farmer-ratio globally. Bachewe et al. (2015) found that, despite Ethiopia's' agricultural extension structure being directly linked to input distribution to smallholders (inorganic fertilizer and hybrid maize seeds), the mean adoption of these technologies is extremely low, with reported substantial heterogeneity in uptake and input combination among smallholder farmers.

2.1.5 Hybrid seed systems, markets, and optimal seed density

The importance of hybrid maize seed is captured by international organizations and researchers' efforts to develop for African smallholder farmers high yielding maize varieties through collaboration. The International Maize and Wheat Improvement Center (CIMMYT 2018) observes that Africa faces serious problems of low maize output, expensive inputs, escalating demand for food, and high climate variability. These factors contribute to the need to equip smallholder farmers with high-quality hybrid maize seeds for increased yields and incomes. In 2016, the Seed Production Technology for Africa (SPTA) was established to offer African smallholder farmers improved maize seed varieties. Indeed with funding from Bill and Melinda Gates Foundation to the tune of US$ 6.4 million, SPTA using technology developed by Corteva Agriscience and in collaboration with Agricultural Research Council of South Africa (ARC), CIMMYT, and the Kenya Agricultural and Livestock Research Organization (KALRO) is currently developing suitable high yielding maize seeds for smallholder farmers (CIMMYT 2018). Kenya Agricultural and Livestock Research Organization manage seed systems development and certification in Kenya. KALRO, which was established in 2013 through an Act of Parliament as a State Parastatal, with the mandate;

> "to establish a suitable legal and institutional framework for the coordination of agricultural research in Kenya with the following goals; Promote, streamline, coordinate and regulate research in crops, livestock, genetic resources, and biotechnology and expedite equitable access to research information, resources and technology and promote the application of research findings and technology in the field of agriculture" KALRO Act, 2013 p 394.

2.1.6 Hybrid maize seed development, marketing, and distribution in Kenya

The free trade in the maize market has enhanced the choices for smallholders. However, maize breeding and marketing firms are experiencing difficulties scaling out their new varieties to farmers. The government controls maize marketing through the National Cereals and Produce Board (NCPB) as the maize distribution system's fulcrum because of the importance of smallholder maize production in food security. Hybrid seed research and breeding has been in the hands of the defunct Kenya Agricultural Research Institute (KARI), and now the mandate is bestowed upon its successor KALRO. The Kenya Seed Company does hybrid maize seed production and distribution (KSC), established by farmers and taken over by the government (Jayne & Argwings-Kodhek 1997).

The National Cereals and Produce Board (NCPB) is a state corporation established in 1985 through an Act of Parliament (cap 338 laws of Kenya), as the Maize and Produce Board. It was formed by the amalgamation of The Maize and Produce Board and The Wheat Board on July 1, 1979, to streamline the management, handling, and marketing of all grains in Kenya **(ncpb.co.ke, 2020).** Another organization at the center of maize seed development and distribution is the Kenya Seed Company (KSC). As aforementioned, Kenya Seed Company is a state corporation established in 1956 to undertake:

> ″Focused research, promote and facilitate the production of high yielding better quality certified seeds and to enhance food self-sufficiency and quality living standards for sustainable economic development

> in Kenya and the region. The company's range of products has expanded to include over 60 certified seed varieties of maize, pasture, horticulture, sorghum, sunflower, and vegetable seeds suitable for different agro-ecological zones in the region. The company controls over 80 percent of the seed maize market share in Kenya"(**kenyaseed.com, 2020).**

The Kenyan maize seed industry was liberalized in 1992, paving the way for new entrants such as Westen Seed Company, Monsanto, Pioneer, Pannar & Seed Co, (Swanckaert, 2012).

2.1.7 Optimal maize plant population and yield per acre

There is a growing global consensus that propagates for increased hybrid seed planting density for increased yields. For instance, the cost of certified hybrid maize seed continues to be the highest factor input for maize farmers in Indiana, United States of America (USA). In Indiana, farmers have been rapidly and steadily increasing plant population over the last ten years by approximately 315 plants per acre to stand at 30,400 plants per acre. The USA's average seeding population lies between 32,000 to 33,800 seeds per acre when a 90 % to 95% germination rate is considered. Genetic growth enhancement in total stress tolerance in the hybrid seeds calls for a steady increase in plant population (Nielsen, Jim Camberito, & Lee, 2019).

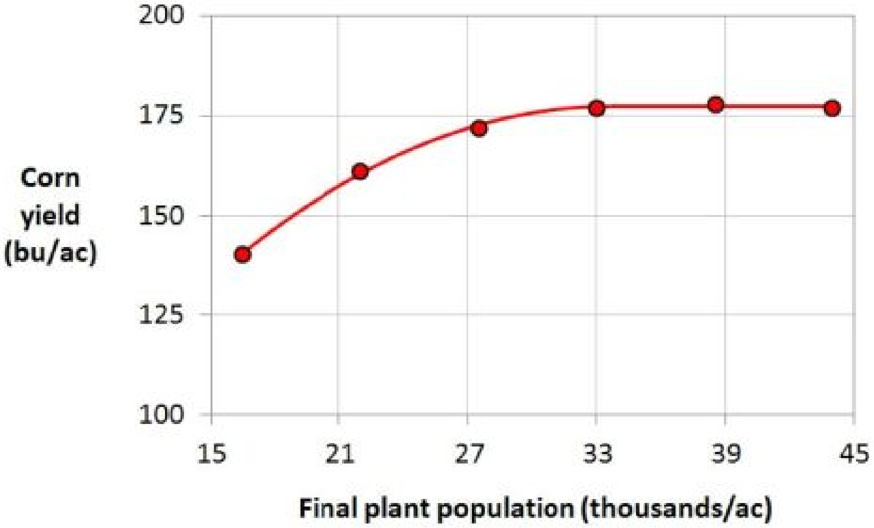


Figure 4. Optimal planting population of 34,000 to 36,000 plants per acre ideal for most farms in the United States

Source. University of Minnesota Extension 2018.

With rising maize production costs and highly variable grain market prices, smallholder farmers need to ensure that they obtain the required stand population because the cost of seeds accounts for approximately 15 % of the total production expenditure reported by Iowa State University (2018). Optimal returns require a final stand of between 32,000 to 34,000 plants per acre, and equilibrium production is achieved at 33,000 plants per acre. Most importantly, productivity did not decline as plant population increased to 44,000 per acre (Coulter, 2018). Coulter (2018) further recommends that the planting rate should exceed the equilibrium plant population to offset early season stand losses.

Maize for grain production in 2018 in the USA was 14.4 billion bushels, declining by 1 % from the 2017 yields, and averaging 176.4 bushels per acre (USDA (2019). This translates to approximately 4,481 kilograms per acre. In Kenya, the estimated maize yield of 1,463 kilograms per acre translates into approximately 58 bushels per acre, too far below USA productivity. It is worth noting that one bushel is equivalent to 0.0254 tons or 25.4 kilograms of maize grain (USA Grain Council, 2019). Table 3, Kenya Agricultural and Livestock Research

(KALRO, 2019), provides the following recommended spacing and plant population for Kenya's three different ecological regions.

Table 3. KALRO Recommended Maize Density in Kenya

Ecological region	**Spacing**	**Plant density per ha**	**Plant density per acre**
Highlands	75 cm by25 cm	53,333	21,333
Medium	75 cm by 30 cm	44,444	17,778
Drylands & Coastal Areas	90 cm by 30 cm	37,850	15,140

Source: KALRO, 2020 & author's computations

Kenya Agricultural and Livestock Research Organization, recommended plant population density is extremely low and not consistent with the global leading producers that requires on average a stand population of approximately 36,000 plants per acre. According to KALRO, the germination percentage for maize is estimated at over 85 %, implying that the stand plant population would yield 18,133, 15,111, and 12,870 plants within the ecological zones, respectively *Table 4*. This stand population could even be lower given many factors such as poverty levels forcing families to harvest and trade green maize and household subsistence. The average estimated seed rate using 85 % and 36,000 stands per acre would translate to 38,800, plant density per acre in the United States.

Table 4: Agro-Ecological Zones of Kenya

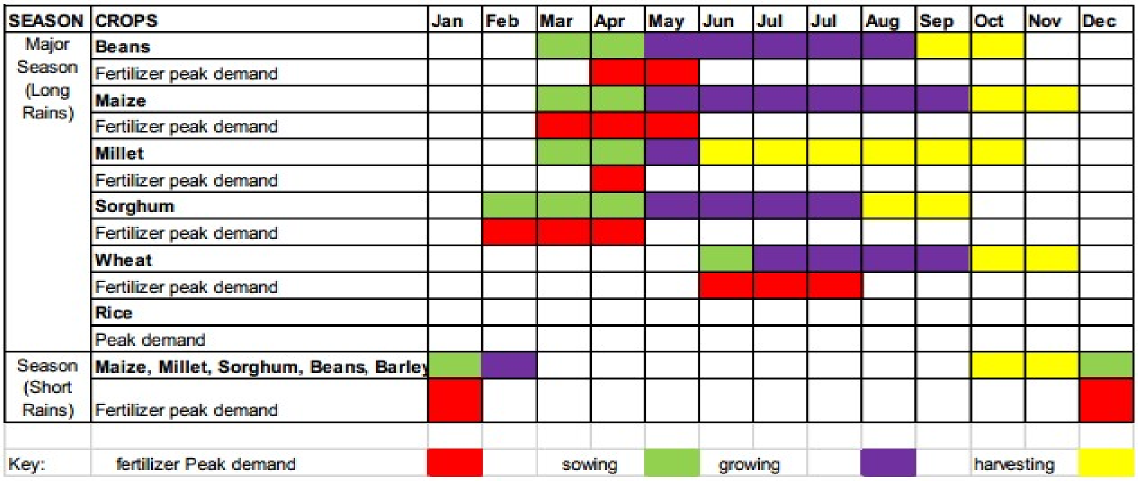
Zone	**Approximate Area in (square kilometers)**	**Percentage of total Area**
I: Agro-Alpine	800	0.137
II. High -Potential	53,000	9.096
III. Medium -Potential	53,000	9.096
IV. Semi-Arid Lands	48,200	8.273
V. Arid Lands	300,000	51.489
V. Avery Arid Lands	112,000	19.22
VI. Water bodies and others	15,646	2.685

Source; Maingi (2008). Kenya Soil Survey.

2.1.8 Sources of technical inefficiency in inorganic fertilizer Use in Kenya

Inorganic fertilizer, a more private good than seed, contains various characteristics that hinder early market development stages (Crawford, Kelly, Jayne, & Howard., 2003**;** Morris, Kelly, Kopioki, & Byerlee, 2007)**.** On the demand side, the cost of establishing a fertilizer market is high where consumers are broadly scattered physically or where their meager land sizes and scarce financial resources imply that they can only buy fewer quantities of fertilizer, which is expensive for retailers to sell (Jayne,et al., 2003; Harrigan, 2008).

Additionally, in rain-fed agriculture, fertilizer use is extremely seasonal, depending on rainfall patterns, leading to high yearly variability in fertilizer demand, with related risks to dealers of high closing inventory balances ***(Figure 5).*** Equally on the supply side, the economies of scale in the global supply chain means that fertilizer importers need to have high levels of cash and cash equivalents to purchase fertilizer (Spielman et al. (2011). Furthermore, Spielman et al. (2011) argue that the aforementioned traits indicate that, although fertilizer may be a tradable private commodity, growth of fertilizer markets requires public intervention in financing and market infrastructure development maturity of the fertilizer markets to be attained. According to Table 5, the fertilizer peak demand for maize crop is only three months out of 12 months.



SEASON	CROPS	Jan	Feb	Mar	Apr	May	Jun	Jul	Jul	Aug	Sep	Oct	Nov	Dec
Major Season (Long Rains)	**Beans**			🟩	🟩	🟪	🟪	🟪	🟪	🟪	🟨	🟨		
	Fertilizer peak demand				🟥	🟥								
	Maize			🟩	🟩	🟪	🟪	🟪	🟪	🟪	🟪	🟨	🟨	
	Fertilizer peak demand			🟥	🟥	🟥								
	Millet			🟩	🟩	🟪	🟨	🟨	🟨	🟨	🟨	🟨		
	Fertilizer peak demand				🟥									
	Sorghum		🟩	🟩	🟩	🟪	🟪	🟪	🟪	🟨	🟨			
	Fertilizer peak demand		🟥	🟥	🟥									
	Wheat						🟩	🟪	🟪	🟪	🟪	🟨	🟨	
	Fertilizer peak demand						🟥	🟥	🟥					
	Rice													
	Peak demand													
Season (Short Rains)	**Maize, Millet, Sorghum, Beans, Barley**	🟩	🟪									🟨	🟨	🟩
	Fertilizer peak demand	🟥												🟥

Key: fertilizer Peak demand 🟥 sowing 🟩 growing 🟪 harvesting 🟨

Figure 5. Seasonal Fertilizer Demand in Kenya

Source: AfricaFertilizer.org

This low fertilizer use is the proximate cause of the decline in maize productivity and the main hindrance to adopting more productive and sustainable agricultural technologies (World Bank 2010). World Bank (2010) further stated that there are various reasons elucidating low fertilizer use in Africa, and mainly market failure. The market failure has led governments to assume control over fertilizer markets and provide targeted subsidies that influence the consumption of fertilizers, improved hybrid seeds, and other productivity-enhancing technologies. The importance of fertilizer in increasing agricultural productivity is amplified by the 2006 Abuja Declaration during the African Fertilizer Summit;

> 'The African Fertilizer Summit was one of the largest history meetings to focus on Africa's food issues. Head of states and governments called for eliminating all taxes and tariffs on fertilizer in the historic Abuja Declaration for African Green Revolution. Summit participants also agreed on 12 resolutions designed to increase fertilizer use five-fold in 10 years in the Abuja Declaration" ifdc.org/africa-fertilizer-summit/.

Due to low soil fertility, smallholder African farmers incur yield losses of approximately US$ 4 billion annually. This is mainly attributed to low fertilizer use at 12 kilograms per hectare per year, translating to a paltry 4.8 kilograms per acre. The high poverty level among African smallholders negatively prevents them from accessing financial resources and required inputs such as fertilizers. Extension officers, input retailers, and other stakeholders should be trained on fertilizer optimization and aim to transfer the same to the farmers (Kaizzi, Mohammed & Nouri 2017).

There is a massive intervention in the cereals market by the Kenyan government, especially in the distribution of inputs. However, in the 1990s, Kenya's fertilizer market was liberalized, allowing the private actors to import and distribute the bulk of fertilizers. Simultaneously, the government continues to import and distribute fertilizers to smallholders through the fertilizer subsidy programs. The fertilizer value chain is characterized by uncertainty over the timing of delivery, poor targeting of subsidies, delayed planting, and smallholder dependency (D'Allessandro et al.,2015).

The Input Subsidy Programme (ISP) partly crowd out commercial fertilizer demand and divert the advantages of subsidies, thereby decreasing their effectiveness. The size of these impacts is pronounced in Kenya because the private sector fertilizer markets are well established, and the majority of smallholders were already using fertilizer before the implementation of the subsidy program. For instance, an extra 100 kilogram of subsidized fertilizer is approximated to crowd out 50 kilograms of commercial fertilizer in Kenya when compared to 13 kilograms in Zambia (Jayne et al. 2018).

Additionally, Jayne et al. (2018) argued that smallholder crop output response to fertilizer is below average in Kenya, principally because inputs are used under unfavorable agro-ecological conditions (technical inefficiency). Thus complementary actions such as agricultural research and extension services, which at the moment may be crowded out by severe government expenditure on subsidies, are highly recommended to boost the agricultural profitability of ISPs.

According to the United Kingdom Department for International Development (DFID 2018), the National Accelerated Agricultural Inputs Access Programme (*Kilimo Plus*), Kenya's input subsidy program that ended in 2014, was more beneficial as it directly and positively impacted the targeted poor farmers, as opposed to the current program under the management of the National Cereals and Produce Board. (Mason et al. 2017), reports that *Kilimo Plus* subsidy program was able to increase agricultural crop output and had a positive impact on poverty reduction, and therefore there is a compelling need to adopt a complementary partnership between private and public sector investments in research, extension, irrigation, transport infrastructure, information and affordable innovations to increase smallholder productivity.

Rahnema, Giordano & Otieno (2017) stated that the Kenyan fertilizer market has faced numerous obstacles, ranging from poor governance and weak fertilizer policies. The supply chain is inefficient, and fertilizer is not effectively distributed to reach the smallholders during planting season. Furthermore, most farming households with low education levels are not aware of the advantages of using inorganic fertilizer to improve their productivity.

Ultimately, smallholder farmers' capacity to access credit and financial services greatly undermine their ability to adopt new technology. This is corroborated by (Nathan Associates, 2017) arguing that in Kenya financial sector considers smallholder agriculture a high-risk enterprise and therefore attempts to ameliorate risk exposure. This is depicted by low credit access to the sector at only 4.3 percent of total credit. World Bank (2018) supports the low credit access by smallholder farmers by indicating that credit requirements for the agricultural crop chains in 2015 were approximated to be Kenya shillings 130 billion, but the sector received only 40 billion of credit.

2.1.9 Agricultural productivity and technical efficiency

FAO (2017) postulates that productivity and efficiency in agriculture are focal points of numerous discussions, policies, and initiatives pertaining to the agricultural sector. Further the Sustainable Development Goals' emphasis on agricultural productivity highlights the numerous justifications for further research that can enhance productivity and efficiency. FAO (2017) noted that agricultural productivity data is associated with several indicators pertaining to the 2030, Sustainable Development Goals, specifically: 1) Indicator 2.3.1: Volume of production per labor unit by classes of farming/pastoral/forestry enterprise size; 2) Indicator 2.3.2: Average income of small-scale food producers, by sex and indigenous status; 3) Indicator 2.4.1: Proportion of agricultural area under productive and sustainable agriculture. Figure 6 is an illustration of how technical efficiency analysis can be used to formulate public policy that guides pareto optimal maize productivity.

2.1.10 Technical efficiency and international commodity trade

Figure 6 denotes a general equilibrium model with several input markets and
q_2 and q_1 $are\ maize\ and\ wheat\ outputs, while$ PP' is the production possibility frontier (PPF) curve representing the optimal production level using the current technology (fertilizer) at maximum level (technical efficiency). Assuming autarky condition (no trade) point f is the inefficient level of production of both wheat and maize. Point (a) is the pareto optimal level of production, implying that no movement away from that point can make consumers better off without making producers worse off. Without further resources or technological

advancement, it is impossible to move beyond the production possibility frontier curve, and no movement below the Scitovsky indifference curve C_1, will make all consumers at least as happy (Pareto optimal level).

Now supposing the country is in an open economy, thereby able to trade with other countries on the basis of the Ricardian principle, and the relative world prices or terms of trade are $P_1^2 P_2^2$, while $P_1^1 P_2^1$ is the domestic price ratios. The differential price ratios between countries is attributable to country heterogeneity in terms of resource endowments, technology and agro-climatic conditions. If the country wants to increase maize productivity from current level (a) to (c) more investments in new technology and improvement in current technology will shift the PPF curve tangential to the Scitosvky indifference curve C_2. With trade the government can satisfy its consumers by exporting quantities $(q_2^1 - q_2^2)$ of maize and importing $(q_2^1 - q_1^2)$ of maize. According to the government of Kenya Economic Survey (2023), the quantity of imported maize continued to increase for three years consecutively, reaching 793, 800 metric tons in 2022, while import volume of wheat diminished by 11.3 percent, from 1,889,900 to 1,676,600 in 2022. Maize production technology of chemical fertilizer also recorded a decrease in imported quantities by 25.9 percent.

Contemporary proponents of free trade such as Devadoss (2006) noted that in developing nations, where agriculture serves as the primary source of livelihood for numerous farmers and workers, it is economically challenging to provide subsidies for agricultural production at the elevated levels that developed countries can afford. Holtman et al. (2022). Observed that the shift towards policies that prioritize free-market principles is essential for the enhancement of global trade, especially as agricultural production, consumption, exports, and imports continue to grow. If policymakers adeptly address numerous domestic challenges during the negotiation of a comprehensive global free trade agreement, it is probable that their countries will experience positive outcomes. However, Holtman et al. (2022) reported that the defensive positions exhibited by both developed and developing nations in diminishing trade-distorting policies—such as domestic subsidies, export subsidies, and import tariffs—resulted in an impasse during the Doha Round negotiations. This deadlock has led numerous countries to persist in substantial subsidies for their agricultural production, and elevated import tariffs continue to endure in the global market. The Doha Round of WTO trade talks commenced formally during the Fourth Ministerial Conference held in Doha, Qatar, in November 2001. Its objective was to bring about substantial reform in the global trading system by implementing reduced trade barriers and updated trade regulations. However, Baldwin. (2016) stated that the deadlock in the Doha negotiations has not hindered tariff liberalization, quite the opposite. Baldwin averred that over the past 15 years, a majority of WTO members have significantly reduced barriers to trade, investment, and services through bilateral, regional, and unilateral measures—practically everywhere except within the framework of the World Trade Organization (WTO). In the realm of contemporary international commerce linked to offshoring, the critical trade rules focus less on tariffs and more on safeguarding investments and intellectual property. Additionally, legal and regulatory measures are crucial to ensure unimpeded two-way flows of goods, services, investment, and people.

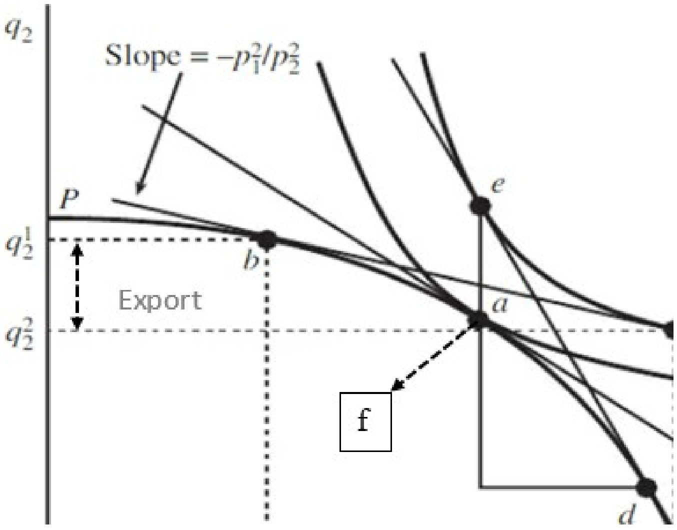


Figure 6. Technical Efficiency and Welfare Economics of Public Policy

Source: Adopted from Just, Hueth, & Schmitz. (2005)

Several empirical studies have employed the stochastic frontier model to assess technical inefficiency in agricultural productivity. Nisrane et al. (2011) conducted research using panel data from the Ethiopian Rural Household Survey, covering 1994 to 2009. Their study implemented a two-step stochastic frontier analysis, considering inputs such as cultivated land area, household labor, precipitation, fertilizer, plowing oxen, average land quality, hoes, and the number of plows. The results indicated that increased use of traditional inputs—like land size and quality, labor, and the number of oxen and hoes—played a significant role in boosting agricultural output, with precipitation also having a notable impact. Conversely, fertilizer usage had a minimal effect on output growth. The study also highlighted low input elasticities regarding fertilizer use.

Bibi et al. (2021) focused on South Asia's agricultural sector's technical and environmental efficiency levels, using a balanced panel dataset from 2002 to 2016. They adopted a trans-log stochastic frontier analysis to estimate output-oriented technical and input-oriented environmental efficiency. Their trans-log production model findings showed output elasticities for land, labor, capital, and fertilizer at 2.13, 1.26, 0.01, and 0.17, respectively. The log-likelihood test results indicated technical inefficiency in the agricultural sectors of South Asian countries.

Ali et al. (2017) studied Pakistan's sugarcane farmers using a two-process stochastic frontier analysis. This cross-sectional study assessed inputs like land, seed, urea, DAP, farmyard manure, tractor hours, irrigation, and pesticides, finding low output elasticities (0.121 to 0.020) for each. The second stage of the analysis modeled inefficiency against various factors, including grower age, experience, family size, off-farm income, education, distance between farm and house, and contact with extension agents. The results suggested farmers' age, experience, education, and access to extension services significantly reduced inefficiency.

2.1.11 Smallholder agricultural commercialization

Can smallholder maize commercialization contribute to African Green Revolution?. (Kirsten et al., 2013) conducted a systematic literature review on agricultural commercialization in Sub-Saharan Africa and confirmed that smallholder agricultural commercialization is not profitable and sustainable. Several factors hamper successful commercialization: The socio-economic variables of smallholder producers, for example, education, gender, asset ownership, and labor market access, show that market access alone is not sufficient for commercialization. Olwande et al. (2015) found that smallholder commercialization in maize, kale, and dairy was not successful in Kenya. Table 5 indicates the defintion of smallholder farms, as farms between 0.5 hactares to 5 hactares. Compared to global averages, Netherlands has approximately, 51,000 farms with an average farm size of 32 hectares or 80 acres (Wageningen Economic Research and Statistics Netherlands, 2021). In the United States, the average farm size is 445 acres in 2021. Small farms average 231 acres, large family farms are 1,421 acres while large farms average 2,086 acres, with small family farms constituting more than 88 percent of total farms in America. (USDA, 2022).

Table 5. Characteristics of Farms in Kenya

Category	**Small-Scale**	**Medium-Scale**	**Large-Scale**
Size of farm	0.5-5 ha	5-100ha	>100ha
Share of farms in Kenya	66 %	20%	14%
% of marketed agricultural produce	65%	5%	30%

Source: ASTGS, 2019.

According to Kirsten et al. (2013) other factors impacting smallholder commercialization negatively include insufficient access to agricultural support services (market information, credit, extension, and factor markets). High transport and transaction costs, storage, and poor infrastructure all contribute to hinder successful smallholder commercialization.

3.0 Methodology

3.1 Stochastic Frontier Model

Charlton and Taylor (2016) highlighted that production and marketing risks in agriculture, stemming from weather variability and the seasonal nature of the farm labor market, render the agricultural production process stochastic at every stage. Kumbhakar et al. (2015) referenced early literature on studying the link between production and exogenous determinants, which employed a two-step technique. This approach, used by various researchers including Pitt and Lee (1981), Reifschneider and Stevenson (1991), Kumbhakar, Ghosh, and McGuckin (1991), Huang and Liu (1994), Battese and Coelli (1995), Kalirajan and Shand (1999), and Rada and Buccola (2011), first estimates the production possibility frontier (PPF) value, followed by regressing the inefficiency index against independent factors. In this regression, a negative coefficient of explanatory variables implies greater efficiency or lower levels of inefficiency.

However, Battese and Coelli (1995) identified a bias in the two-step technique, attributing it to misspecification in the first phase's model. Consequently, Kumbhakar et al. (2015) pointed out that the unfavorable statistical features of the two-step process make the single-step procedure a more suitable approach for examining the impact of external factors on efficiency. The single-step technique parameterizes the inefficiency distribution function as a function of independent variables affecting inefficiency. This one-step approach in the truncated-normal model was initially employed by Kumbhakar, Ghosh, and McGuckin (1991), Reifschneider and Stevenson (1991), Huang and Liu (1994), and Battese and Coelli (1995). Wang and Schmidt (2002) added that the one-step procedure simultaneously specifies the stochastic frontier and how the inefficiency noise (u) depends on variables (z), estimating it using the maximum likelihood estimator. A truncated-normal stochastic frontier production function with the inefficiency distribution of a non-zero mode u_i as proposed by Stevenson (1980) is specified as

$$lny_i = lny_i^* \quad u_i, \tag{1}$$

$$lny_i^* = x_i\beta + v_{i,} \tag{2}$$

$$u_i \sim N^+(\mu\, , \sigma_u^2), \tag{3}$$

$$v_i \sim \mathrm{N}\ (0, \sigma_v^2), \tag{4}$$

The truncation of the normal distribution $N(\mu,\sigma_u^2)$ at zero from above is represented by the notation $N^+(\mu\,,\sigma_u^2)$. Equation (1) and (2) can be rewritten as:

$$lny_\iota - x_\iota\beta + \epsilon_\iota, \tag{5}$$

$$\epsilon_i = v_i - u_i. \tag{6}$$

The density function $Z_i\,, f(z_i)\; of\; the$ truncated normal distribution of random variable Z_i obtained by the normal distribution $N\,(\mu\,,\sigma^2)$ truncated at a point α from above, is derived as:

$$f(z) = \frac{g(z)}{1-\Phi\left(\frac{\alpha-\mu}{\sigma_2}\right)} = \frac{\frac{1}{\sigma_2}\text{Ø}(z-\mu)}{1-\Phi\left(\frac{\alpha-\mu}{\sigma_2}\right)}, \tag{7}$$

where, $z \geq \alpha$, Ø(·) and Φ(·) represents the probability density and probability distribution functions for the standard normal.

Suppose $\alpha = 0\; and\; z_i \geq 0$ the density function of the variable z_i is written as:

$$f(z_i) = \frac{\frac{1}{\sigma}\text{Ø}\,(z_i)}{1-\Phi\left(\frac{-\mu}{\sigma}\right)} = \frac{1}{\sqrt{2\pi\sigma\Phi\left(\frac{\mu}{\sigma}\right)}}exp\left\{\frac{(z_i-\mu)^2}{2\sigma^2}\right\} \tag{8}$$

Based on equation (1) – (4) the log-likelihood function for observation i^{th} is obtained as:

$$L_i = -\frac{1}{2}ln(\sigma_v^2+\sigma_u^2) + ln\,\text{Ø}\left(\frac{u+\epsilon_i}{\sqrt{\sigma_v^2+\sigma_u^2}}\right) + ln\Phi\left(\frac{u_{*i}}{\sigma_*}\right) - ln\Phi\left(\frac{\mu}{\sigma_u}\right), \tag{9}$$

where,

$$\mu_{*i} = \frac{\sigma_v^2\,\mu - \sigma_u^2\,\epsilon_i}{\sigma_v^2+\sigma_u^2} \tag{10}$$

$$\sigma_*^2 = \frac{\sigma_v^2\;\sigma_u^2}{\sigma_v^2+\sigma_u^2} \tag{11}$$

The mean of the inefficiency noise (u_i) of the truncated-normal model is stated as:

$$E(u_i) = f(\mu,\sigma_u) = \sigma_u\left[\frac{\mu}{\sigma_u} + \frac{\text{Ø}\left(\frac{\mu}{\sigma_u}\right)}{\Phi\left(\frac{\mu}{\sigma_u}\right)}\right], \tag{12}$$

Equally, the variance of the inefficiency term is:

$$V\,(u_i) = g(\mu,\sigma_u) = \sigma_u^2\left[1 - \frac{\mu}{\sigma_u}\left[\frac{\text{Ø}\left(\frac{\mu}{\sigma_u}\right)}{\Phi\left(\frac{\mu}{\sigma_u}\right)}\right] - \left[\frac{\text{Ø}\left(\frac{\mu}{\sigma_u}\right)}{\Phi\left(\frac{\mu}{\sigma_u}\right)}\right]^2\right] \tag{13}$$

where, Ø is the probability density and Φ represents cumulative distribution function of a random standard normal variable. The one-step stochastic frontier model assumes that the mean of distribution u_i is a linear function of the independent variables specified as:

$$\mu_i = z_i'\delta + w_i \tag{14}$$

where z_i represents vectors of the determinants of inefficiency of the ith observation while δ is a vector of corresponding coefficients and w_i is a random variable. The mean and variance of the inefficiency term u_i as well as the technical efficiency are determined by the random exogenous variable z_i'

Technical efficiency (TE) of the ith farmer is calculated as:

$$TE_i = \frac{y_i}{exp(f(x_\iota,\beta)+v_\iota)} = exp(-u_i) \tag{15}$$

Technical efficiency scores range from zero (technically inefficient) to one (technically efficient).

3.2 Data and Model

Data on harvested maize production measured on metric tons were obtained from Food and Agricultural Organization Statistics of the United Nations (FAOSTAT) for the period 1991 to 2018. This study uses only two factor inputs, namely agricultural land and share of agricultural employment as a percentage of total employment. Agricultural land (square kilometers) encompasses climatic, elevation, vegetation, soils, and other natural resources and is the foundation of agricultural food crop production. Choosing the suitable land uses for specific socioeconomic and biophysical circumstances is critical for reducing soil erosion, recovering eroded land, guaranteeing the optimal and effective use of farmland, and optimizing resilience, particularly in the face of global warming and unpredictability. Employment in agriculture variables is defined as the percentage of agricultural employment over total employment as per the international labor organization (ILO) estimates. Fertilizer, the sole determinant of inefficiency in this study refers to the amount in kilograms of chemical fertilizer applied per acre for cereal production.

3.3 Empirical Specification

This study aimed to quantify the measures of output-oriented country-level technical efficiency scores of smallholders' maize production in Kenya using fixed-effect stochastic frontier analysis. The study used equation (17) which is consistent with the empirical application employed by Battese and Coelli (1995), Buccola (2011) and Murova and Chidmi (2013).

The one-step stochastic frontier model is specified as:

$$lny_i = \alpha + lnX_i\beta_1 + lnX_2\beta_2 + ln\delta_i + v_i - u_i \, , \qquad (16)$$

Where, lny_i is the natural logarithm of maize output in year 1, lnX_i natural logarithm of agricultural land under maize cultivation, lnX_2 is share of agricultural employment as a proportion of total employment, $ln\delta$ is the natural logarithm of the fertilizer as a determinant of inefficiency, v_i is the random shock, and $-u_i$ is the inefficiency noise. Equation (16) is thus estimated as follows.

$$lnProduction = \beta_0 + \beta_1 \ln Agricultural\ Land + \beta_2 \ln \text{Agricultural Employment} + \ln\delta\text{Fertilizer} + v_i - u_i \ (17)$$

3.3.1 Stochastic frontier suitability test

The three common tests for the suitability of stochastic frontier analysis are the likelihood ratio test, gamma parameter test of inefficiency, and the skewness tests. Skewness test statistic is less sophisticated than the two maximum likelihood estimations (Schmidt & Lin 1984). This study computes the gamma parameter test statistic to evaluate the suitability or validity of the stochastic frontier specification.

3.3.2 The gamma parameter test

Kumbhakar et al. (2015) provide the gamma test, which yields a ratio between zero and one. The gamma parameter value close to zero implies no inefficiency, and the best model is the restricted Cobb-Douglas production function. However, if a gamma parameter value is close to one, it justifies the use of the stochastic frontier model.

2.3.3 Hypothesis testing

The null hypothesis for the gamma parameter statistic is specified as,

$$The\ gamma\ (\gamma) = \delta_0 = \delta_1 = \cdots\ \delta_m = 0 \rightarrow no\ inefficiency \qquad (18)$$

$$The\ gamma\ (\gamma) = \delta_0 = \delta_1 = \cdots\ \delta_m = 1 \rightarrow technical\ efficiency \qquad (19)$$

$$The\ gamma\ (\gamma) = \frac{\sigma_u^2}{\sigma_u^2+\sigma_v^2} \quad (20)$$

4.0 Results and Discussion

4.1 Diagnostic Test

To justify the use of stochastic frontier model, the following variance relevance test was conducted as per equation (20) the gamma parameter test is obtained as

$$Total\ Variance = (0.7774098)^2 + (0.0686788)^2 = 0.604365997 + 0.004716778 = 0.609082775$$

$$Gamma\ Parameter\ (\gamma) = \frac{0.604365997}{0.609082775} = 0.9922559$$

Based on the results of the gamma test statistic, the null hypothesis is rejected, and we conclude that the model contains one-sided errors or there is technical efficiency, and thus there is sufficient justification for the use of the stochastic frontier model in this analysis. This is consistent with (Battese & Corra 1977;Kumbhakar et al., 2015). Kumbhakar et al. (2015) noted that, it is only after estimating the model parameters, that we may move to estimating the model's observation-specific efficiency, which is often the primary objective of a stochastic frontier model. Alternatively, Kumbhakar et al. proclaim that the predicted efficiency levels may be used to classify producers, determine those who are lagging, and those who are near or at the production possibility frontier, and concludes that this information is used to assist in the development of public policy or fertilizer subsidy programs aimed at increasing the overall efficiency of the producers. *Table 1* is the summary of the results of the transformed variables in logarithms and calculated technical efficiency in percentages.

Table 6. Summary Descriptive Statistics

Variable	***N***	**Mean**	**Std. Dev.**	**Min**	**Max**
lnproduction	28	14.853	.196	14.552	15.205
lnagland	28	156.527	.36	155.891	157.072
lnemptotal	28	15.792	1.032	14.389	16.918
Technical efficiency	28	14.853	.169	14.546	15.106

The most interesting observation from Table 6, is the technical efficiency in maize production in Kenya. The results showed that on average maize productivity efficiency is approximately 14.9 percent holding constant the two factor inputs, agricultural land and agricultural labor. The minimum productive efficiency is at 14.5 percent and maximum at 15 percent from the years 1991 to 2018.

Table 7 shows the results of the one-step stochastic frontier production analysis obtained using Stata software command:

```
sfpanel lnProduction lnAgricultural land LnAgriEmployment year, model (tfe) dist(tn) emean (lnFertilizer Ort
                                                                                        (o)              (21)
```

The Stata command clearly shows that the model has only two factors of production (agricultural land and agricultural labor), and the distribution is truncated normal with true fixed effects. Fertilizer is the variable or determinant of inefficiency in this output oriented–Ort (o) stochastic frontier model. The stochastic frontier results revealed that the coefficients of agricultural land and agricultural employment are consistent with the theory of production, which requires positive amounts of inputs and outputs and output elasticities of between zero to one (Cobb & Douglas, 1928). However, the low (inelastic) elasticities of outputs (0.338 and 0.008 for agricultural land and agricultural employment respectively) corroborate the findings by Nisrane et al. (2011) and have an interesting economic interpretation. The low elasticity of agricultural land signifies depleted soil fertility while for agricultural labor it is an indication of overabundance. The combination of the low elasticities is a confirmation of declining marginal value product of the two factors regarding maize productivity. The coefficient of agricultural land is statistically significant at 99 percent level of significance, while agricultural employment was not statistically significant. The insignificance of agricultural employment could be attributed to the overabundance and the inelastic supply of agricultural labor in the country. Indeed, World Bank (2023) indicates that in 2019, employment in agriculture was 54 percent of total employment in Kenya. To explore the nature of returns to scale within the sampled farmers, we examined whether the production function adheres to the null hypothesis of constant returns to scale or if it diverges in favor of the alternative hypothesis suggesting non-constant returns to scale. The null hypothesis tested was, $H_0: \beta_1 + \beta_2 = 1$

Scale elasticity is the sum of the output elasticities (0.338 plus 0.008) equals to 0.346. Because the scale elasticity is less than one, the null hypothesis is rejected in conclusion that the maize production process by small holder farmers in Kenya exhibits a decreasing return to scale. When there are decreasing returns to scale in fertilizer use in maize production, it implies that as the amount of fertilizer applied increases, the additional output or yield gained per unit of fertilizer decreases. In other words, the initial application of fertilizer might lead to a substantial increase in maize production, but as the quantity of fertilizer continues to rise, the incremental gain in output becomes less significant. The cost flexibility which is derived as the inverse of the scale elasticity (0.346) is obtained as 2.8902, and greater than one signifies diseconomies of scale in the maize production process in Kenya. In the long-run all factor inputs are variable, therefore the diseconomies of scale is a testimony that the cost of maize production is increasing at a faster rate compared to maize output. This makes commercialization of maize production less profitable and the leading cause of food insecurity in the country.

Holding agricultural land and agricultural employment constant, maize productivity due to fertilizer use is at 11 percent. The coefficient of fertilizer is negative meaning that one percent increase in fertilizer use on maize production reduces on average the level of technical inefficiency by 11 percent. This implies that the inefficiency of 89 percent in maize production is due to low fertilizer application by smallholder farmers. The lack of importance of fertilizer in maize productivity is corroborated by the insignificant coefficient of this factor in the results. This corroborates, with the findings of (Dorman 1996; World Bank 2010; Ogada & Nyangena 2014; Abay et al., 2016; World Bank 2019; USAID 2019; Boulanger et al., 2020).

Table 7. Stochastic Frontier Regression Results

ln production	**Coef.**	**Std.Err.**	**z**	**P>z**	**[95%Conf. Interval]**	
Frontier						
lnAgricultural land	0.338	0.083	4.050	0.000	0.174	0.501
LnAgriEmployment	0.008	0.037	0.210	0.831	-0.065	0.081
year	0.007	0.005	1.480	0.138	-0.002	0.016
lnFertilizer	-0.111	4.931	-0.020	0.982	-9.776	9.554
sigma_u	0.777	2.366	0.330	0.742	0.002	302.987
sigma_v	0.069	0.025	2.760	0.006	0.034	0.140
lambda	**11.320**	2.364	4.790	**0.000**	**6.687**	**15.952**

Lambda (λ) is the coefficient of the signal to noise parameter which is obtained as the quotient of

$$\frac{sigma\_u}{sigma\_v} = \frac{0.777}{0.069} = 11.2609 \qquad (22)$$

Table 7 shows the lambda parameter coefficient 11.320, the difference is due to rounding off. Lambda measures the degree of inefficiency and the uncertainty of the technical inefficiency in the mode. The higher the numerical value of lambda the more inefficient is the stochastic frontier production function. Sigma_u is the standard deviation of the noise parameter or error term, while sigma_v is the standard deviation of the time-invariant individual specific term.

Table 8. Technical Efficiency (%)

year	production	Agland	fertilizer	Emptotal	lnproduction	lnagriland	lnemptotal	lnagland	lnfertilizer	TE
1991	2.40E+06	268770	22.11	44.48	14.69	3.85	14.40	156.29	9.59	14.71
1992	2.40E+06	270720	19.26	44.51	14.70	3.86	14.41	156.47	8.75	14.79
1993	2.10E+06	268400	19.76	44.53	14.55	3.85	14.41	156.26	8.90	14.70
1994	3.10E+06	272320	23.81	44.46	14.93	3.87	14.40	156.62	10.05	14.85
1995	2.70E+06	272180	14.42	44.40	14.81	3.87	14.39	156.61	7.12	14.84
1996	2.20E+06	264510	34.43	44.45	14.59	3.84	14.40	155.89	12.52	14.55
1997	2.20E+06	265940	27.92	44.80	14.61	3.84	14.46	156.03	11.08	14.60
1998	2.50E+06	264580	27.17	45.07	14.72	3.84	14.50	155.90	10.90	14.55
1999	2.30E+06	268760	29.06	45.66	14.66	3.85	14.60	156.29	11.35	14.72
2000	2.20E+06	266710	29.79	48.73	14.59	3.85	15.10	156.10	11.52	14.65
2001	2.80E+06	268390	29.25	51.50	14.84	3.85	15.54	156.25	11.40	14.73
2002	2.40E+06	268180	27.31	54.28	14.69	3.85	15.95	156.24	10.94	14.74
2003	2.70E+06	268740	33.10	56.76	14.81	3.85	16.31	156.29	12.25	14.77
2004	2.60E+06	269920	27.68	58.93	14.77	3.86	16.62	156.40	11.03	14.82
2005	2.90E+06	270020	34.33	61.06	14.88	3.86	16.91	156.41	12.50	14.84
2006	3.20E+06	270540	33.15	61.14	14.99	3.86	16.92	156.45	12.26	14.86
2007	2.90E+06	270700	36.40	60.97	14.89	3.86	16.90	156.47	12.92	14.86
2008	2.40E+06	270850	33.29	61.11	14.68	3.86	16.91	156.48	12.29	14.87
2009	2.40E+06	272850	31.86	60.94	14.71	3.87	16.89	156.67	11.98	14.94
2010	3.50E+06	273200	30.35	60.32	15.06	3.87	16.81	156.70	11.65	14.96
2011	3.40E+06	276300	43.58	59.74	15.03	3.88	16.73	156.98	14.25	15.07
2012	3.70E+06	277300	34.39	59.22	15.14	3.89	16.66	157.07	12.52	15.11
2013	3.60E+06	276300	38.77	58.59	15.09	3.88	16.57	156.98	13.38	15.07
2014	3.50E+06	276300	42.85	57.94	15.07	3.88	16.48	156.98	14.12	15.06
2015	3.80E+06	276300	28.55	57.26	15.16	3.88	16.38	156.98	11.23	15.06
2016	3.30E+06	276300	29.03	56.53	15.02	3.88	16.28	156.98	11.35	15.06
2017	3.20E+06	276300	22.63	55.86	14.97	3.88	16.18	156.98	9.73	15.05
2018	4.00E+06	276300	15.69	55.08	15.21	3.88	16.07	156.98	7.58	15.05

Note. The source of Table 8 is Authors Econometric results. TE is Technical Efficiency. ln is natural logarithm.

Table 8 presents the technical efficiency (TE) scores expressed in percentages. While a technically efficient farmer would achieve a 100% TE score, this study found that the TE scores for fertilizer use among smallholder farmers in Kenya varied between 14.71% and 15.05%. These findings suggest a low level of technology adoption with regard to inorganic fertilizer use.

5.0 Conclusion

This study aimed to assess the technical efficiency of chemical fertilizer use in maize production and to evaluate the scale of returns and operations among smallholder maize farmers in Kenya. An output-oriented stochastic frontier production function with a truncated-normal distribution was utilized to estimate the optimal production level and technical efficiency scores. The results revealed low output elasticities, indicating that the marginal value product of agricultural land and employment is declining. This suggests a sluggish rate of technology adoption, specifically for inorganic fertilizer among smallholder farmers, contributing to reduced maize productivity, a staple food crop in this case, and persistent food insecurity in the country.

The low output elasticities also point to soil infertility caused by prolonged land degradation and inadequate nutrient replenishment while agricultural labor remains abundantly available. The findings on scale elasticity and cost flexibility indicate decreasing returns to scale and diseconomies of scale in maize production, respectively. The technical efficiency of inorganic fertilizer adoption was alarmingly low at just 11 percent. However, the existing 89 percent inefficiency presents an opportunity to enhance maize productivity through increased chemical fertilizer usage, assuming other factors remain constant.

The concept of decreasing returns to scale in fertilizer use for maize production suggests that as fertilizer application increases, the corresponding rise in maize output becomes proportionally smaller. Initially, fertilizer use can significantly boost maize yield, but the marginal impact on production decreases with continued fertilizer application. This pattern has critical implications for both farmers and policymakers. It highlights the need for an optimal level of fertilizer application, where the benefits start to diminish beyond a certain point. Farmers should focus on the cost-effectiveness of fertilizer use to balance input costs against the yield gains. On the other hand, policymakers and extension service providers should offer guidance and support to farmers for optimal fertilizer use, which is crucial for maximizing productivity and economic returns and promoting sustainable agricultural practices. Overuse of fertilizer can lead to environmental issues.

Therefore, under the current conditions of input supply and diseconomies of scale, smallholder maize commercialization in Kenya is not feasible. Diseconomies of scale imply that smallholder maize production is characterized by increasing high costs of production, undermining profitability.

6.0 Recommendation

The Kenyan government should develop pro-poor agricultural policies, including enhanced subsidies on farm inputs. The Agricultural Sector Transformation and Growth Strategy (ASTGS 2019) presents essential proposals to boost the efficiency of maize producers, thereby increasing productivity and reducing food insecurity. These recommendations include increasing budgetary allocations for agriculture by national and county governments and improving rural infrastructure such as roads, electricity, security, and storage facilities. The government in collaboration with extension service providers should expedite the implementation of ASTGS 2019, which proposes commercialization of the maize sector through agri-food value chain optimization, public-private partnerships, rural infrastructure investment, and agro-processing.

A review of the current definition of small farms in Kenya is necessary to align with global agricultural standards. For comparison, the average farm size in the Netherlands is 80 acres, and in the United States, it is 445 acres, whereas in Kenya, it ranges from 1.25 to 12.5 acres.

The strategy also advocates for accelerated technology adoption through land reforms, enabling individuals to lease agricultural land for commercial purposes and zoning highly productive areas to prevent further land subdivisions. This should be coupled with increased investments in irrigation and targeted input subsidies. Since smallholder maize commercialization is currently unfeasible, redefining small-scale farms to allow for mechanization and reasonable acreage is vital.

ASTGS (2019) outlines several vital initiatives: Anchor 1 aims to increase small-scale farmers' incomes by supporting rural development and optimizing agricultural food value chains, targeting 3 million farmers for input subsidy, equipment, processing, and post-harvest aggregation. Anchor 2 proposes establishing six large-scale agro and food processing zones through public-private partnerships and developing 50 new large-scale private farms, each exceeding 2500 acres with government-supported sustainable irrigation, power, roads, and protected land ownership. Anchor 3 focuses on promoting household food resilience by transforming the management of the strategic food reserve, supporting 4 million vulnerable Kenyans with minimum price controls, cash transfers, and private sector warehousing for storage.

Advocacy for free, fair, and equitable trade agreements should be prioritized at bilateral, regional, and global levels. Ensuring that these agreements address the needs of both exporters and importers can lead to a more balanced global agricultural system. Kenya should reassess its comparative advantage based on current resources and strategically pursue a maize production system that shifts the production possibility frontier curve, balancing the needs of large-scale producers and consumer utility.

This study utilized aggregated data from the World Bank for smallholder maize production. A detailed household survey in maize-producing regions is recommended to analyze various socio-environmental and economic factors affecting technical efficiency for both small and large-scale farmers. Additionally, exploring different distributions (normal, half-normal, exponential, and truncated-normal) in stochastic frontier analysis could determine the most suitable distribution for the region. Future studies should investigate the impact of imports, exports, and trade barriers on the technical efficiency of maize production to understand the role of trade in enhancing agricultural productivity.

Declaration of competing interest

The authors have no conflict of interest to disclose.

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