



Productivity, Technical Efficiency, and Sustainability of Mechanized Potato Production: A Case Study of Tillage Service Users in Kenya

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Abstract

Potato (*Solanum tuberosum*) has a considerable potential to contribute to income generation and food security for smallholder farmers in Africa, but sustainable farming practices are required to exploit this potential. Kenya is an interesting example, as it is a leading potato producer in sub-Saharan Africa, but productivity has been declining in recent years. While past studies on potential reasons have focused on the use of seed, fertilizer, and pesticide use, mechanized land preparation has received limited attention, even though mechanization plays an increasing role in potato farming. To address this knowledge gap, we analyzed data from 156 smallholder farmers in Nakuru County, Kenya, who use mechanized tillage services for potato production. To determine their technical efficiency, we applied a stochastic frontier trans-log production function. The technical efficiency scores ranged from widely 11% to 93%, with a mean value of 63, suggesting that there is ample potential to raise potato production without bringing new land into cultivation. The use of pesticides and use of labor had a significant positive effect on the potato output. Unexpectedly, a negative response of potato output to fertilizer was found. The reason is likely that only farmers who already experienced soil fertility problems started to use fertilizer and that they applied inadequate amounts. The study also revealed other problems that affect soil fertility and yields, especially a lack of practicing crop rotation. Farm-specific advice by private extension providers was found to be more effective in improving technical efficiency than generalized training.

Keywords Irish potato · Mechanized tillage · Stochastic frontier · Technical efficiency · Technical inefficiency

Introduction

Potato (*Solanum tuberosum*), typically referred to as “Irish potato” in African countries, is one of the most rapidly expanding food and cash crops in Africa (Muthoni and Shimelis 2023). It is an important food security crop for developing countries (Li et al. 2024). Potato has agronomic and nutritional advantages. The agronomic advantages are as follows: it has very high tuber productivity in terms of calories per hectare than cereal crops (Li et al. 2024); it is a short-cycle crop with a relatively short growing season (Haverkort and Struik 2015); and it adds to crop biodiversity (Ortiz and Mares 2017). The nutritional advantages include: it is an important source of energy, providing essential nutrients and minerals, high in several micronutrients, and having a modest protein content but of high biological value (Camire et al. 2009; Zaheer and Akhtar 2016). However, smallholder potato production in sub-Saharan Africa (SSA) has several challenges. For example, some of the major challenges are as follows: potato being a bulky crop – requiring more effort to transport seed material and harvest; prone to pests (e.g., cyst nematodes (PCNs), and diseases; low mechanization use – contributing to poor land preparation, planting, and harvesting (Muthoni and Shimelis 2023). Kenya is among the highest potato producers in Africa dominantly operated by smallholder farmers where land preparation is mechanized (Kaumbutho and Takeshima 2023; Muthoni and Shimelis 2023). Despite an increase in production, recent reports show that potato productivity is declining (Waaswa et al. 2022; FAO 2024). Studies show that mechanization plays an important role in enhancing total productivity (Avila and Evenson 2010; Olasehinde-Williams et al. 2020), but it demands technical and managerial skills of the smallholder farmers and concurrent implementation of sustainable agronomic practices. This is because, conventional mechanized tillage can potentially lead to land degradation (Tully et al. 2015; Tefera et al. 2024). This study considers and underscores the difference between technical efficiency analyses of cereal and root crops due to different agricultural field operations. Furthermore, mechanized potato production systems under smallholder conditions were less explored. Thus, limited studies are available on technical efficiency and to what extent sustainable farming practices are implemented by mechanized tillage users under smallholder conditions in SSA as stated in the literature review section.

Against this background, this paper presents an explorative case study of smallholder potato farmers in Nakuru County who use mechanization services. The paper has two major objectives: First, we aim to analyze the productivity and the technical efficiency of potato farmers and identify the factors that influence these performance parameters. Second, we aim to identify to what extent mechanized potato farmers apply farming practices, that are considered to be “good agricultural practices” and thus contribute to the sustainability of potato production. On this basis, we aim to derive implications for advisory services and policy-makers.

For this paper, we collected quantitative and qualitative primary data from 156 farmers who use mechanized tillage services in Nakuru County focusing on their

cropping practices, input use, and yields as well as factors that influence farming practices, such as access to years of experience in mechanized farming and access to training and advisory services. We analyze the productivity and the technical efficiency of our sample farmers by applying a Stochastic Frontier Analysis, which is a powerful econometric tool that makes it possible to assess how effectively farmers use agricultural inputs and to identify the factors that determine their technical efficiency (Ellis 1993; Kalirajan and Shand 1999). To our knowledge, this is the first study in sub-Saharan Africa (SSA) that analyzes the productivity and technical efficiency of potato producers who use mechanized tillage services.

The paper is structured as follows: The literature review section presents insights from the literature. The methodology is described in the materials and methods section, followed by a presentation of the results in the results section. The discussion section discusses the findings and the final section concludes.

Literature Review

Kenya is the fourth largest producer of potato in Africa and first in sub-Saharan Africa, excluding South Africa (FAO 2024). Kenya, Ethiopia, and Rwanda account for 71% of the continent's potato production (Muthoni and Shimelis 2023). Potato is the second most important major food security crop (Mburu et al. 2020; Kimathi et al. 2021) produced by approximately 500,000 farmers in Kenya (Kamau et al. 2019; Wang'ombe & van Dijk 2013). Thus, potato production has a major role in improving food security and contributing to poverty reduction (Muthoni et al. 2013) by generating income and employment opportunities for smallholder farmers (Marita et al. 2016). Figure 1 presents the potato yields recorded in Kenya according to FAO statistics. Between 2004 and 2010, there was a considerable increase in crop yields from 10 to more than 20 tons/ha, followed by a decline to previous levels. According to the literature, the primary constraints to production are the low adoption and utilization of farm inputs such as clean seeds, fertilizers, fungicides, and irrigation (Wang'ombe and van Dijk 2013). Climate variability is also one of the major contributors to the decline in potato productivity in Kenya (Adhikari et al. 2015; Bolt et al. 2019; Waaswa et al. 2022), with current yields at 9–10 tons/ha, compared to a potential yield of 20–40 tons/ha (Mburu et al. 2020). While these challenges require solutions, it is becoming increasingly evident that enhancing the efficiency of farmers is a necessity for improved potato productivity through farm input utilization and sustainable agronomic practices and management (Barasa et al. 2019; Kamau 2019; Panhwar et al. 2019; Shah and Wu 2019).

Appropriate soil management plays an important role in achieving technical efficiency (Lal 1998; Nowak et al. 2015; Addo and Salhofer 2022). Sustainable production systems require an effective use of innovations and require avoiding the use of inputs that have an adverse effect on the environment (Pretty et al. 2011). On the one hand, the unpredictability of climate change may require the use of chemical inputs, and mechanization technologies (e.g., for timely land preparation and planting) to maintain or increase productivity at the farm level. On the other hand, however,

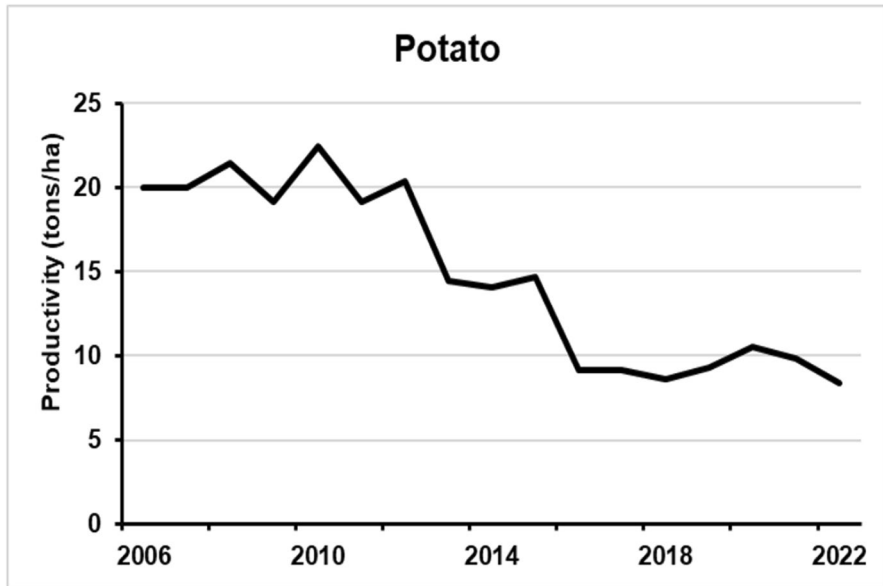


Fig. 1 Trends of potato productivity (2006–2022) in Kenya (*Source:* authors calculation from FAOSTAT data as of August 19, 2024)

the use of chemical fertilizers, pesticides, and conventional mechanized tillage can potentially lead to land degradation, reduced soil productivity, and yield reductions if sustainable practices are not duly considered (Lal 1991; Stonehouse 1991; Pahalvi et al. 2021). In arid regions susceptible to climate change that often have fragile soil, unsustainable land management practices, such as intensive tillage, can lead to erosion, runoff, loss of soil organic matter, and soil compaction (Scoones 1991; Tully et al. 2015; Tefera et al. 2024). Similarly, monocropping, the use of mineral fertilizers, and chemical pesticides alter soil properties (e.g., soil organic carbon, pH, and enzyme activities), resulting in changes in microflora functions, disturbing soil structural and functional properties, and ultimately negatively affecting soil health (Yang et al. 2011; Abd El-Azeim et al. 2020; Pahalvi et al. 2021). Thus, sustainable practices are essential to mitigate these negative impacts.

Potato cultivation is a labor-intensive activity, particularly when undertaken manually (Ünal and Kızıldeniz 2023). Except for tillage, the majority of other significant operations in SSA potato production are conducted manually. These activities include planting (which necessitates the transportation of substantial quantities of seeds), ridging, dehauling, and root harvesting. In Indonesia, these operations contribute to the overall labor intensity of potato cultivation, requiring 503 to 751 person-days per hectare from land preparation to product transportation when manual labor is employed (Widodo 2016), while in Kenya, it is about 331 person-days, excluding transport labor (Durr and Lorenzl 1980). The labor intensity comparisons for manual and mechanized operations can be found in Supplementary Material – Table S1. Farm transport, often done by human labor

or draft animals, is under-researched in SSA where poor rural road networks exist. For example, recent studies in Malawi and Ethiopia demonstrated that labor shortages for farm transport severely affect farmers, leading to a high demand for farm transportation services (Workneh et al. 2021; Tufa et al. 2024).

Against this backdrop, mechanization can play a key role in improving the productivity of potato production (Zheng et al. 2021). With regard to other crops, studies have shown that mechanization can improve productivity (Kirui 2019; Yi et al. 2019; Lu et al. 2022). Mechanization was found to lead to both cropland expansion and input intensification in SSA (e.g., Adu-Baffour et al. 2019; Kirui 2019). Since owning farm machinery is a challenge for smallholder farmers given the high capital outlay involved, service hiring systems tend to serve as alternative access points for mechanization services in the region (Sims and Kienzle 2016).

Potato production in Kenya is based on either family labor or hired labor for plowing, planting, weeding and harvesting (Gildemacher et al. 2009; Wainaina 2013). Men are primarily engaged in land preparation, furrow digging, spraying, bagging, and storage preparation, whereas women are primarily involved in planting, manure application and transportation, weeding, uprooting, and transportation of harvest (Wamuyu 2019). Mechanization of land preparation can be seen as important first step in mechanizing potato production in Kenya.

Tillage is already more mechanized than any other farm operation in Kenya (Kaumbutho and Takeshima 2023). Many scholars reported that the use of mechanization increased technical efficiency in SSA and elsewhere (Kibaara 2005; Hormozi et al. 2012; Abdulai et al. 2015; Shi et al. 2021; Baba et al. 2022; Huan et al. 2022) whereas few (e.g., Abdulai et al. 2018) reported negative impact of mechanization on technical efficiency. The majority of the technical efficiency studies on mechanization were conducted in Asia focusing on rice and maize (see review of technical efficiency studies in Supplementary Material – Table S2). Potato production typically requires more field operations than cereal crops, which makes direct comparisons between the technical efficiency of cereal crops and root crops such as potatoes challenging. Moreover, technical efficiency is influenced by environmental factors such as wet-dry periods (e.g., Ogada et al. 2014). Quantifying and understanding the sources of inefficiency is therefore particularly relevant in the context of SSA countries, where the majority of farmers use mechanization only for tillage, and where the willingness to pay for mechanization hiring services has recently increased (Houssou et al. 2016; Takele and Selassie 2018; Hodjo et al. 2021; Ngoma et al. 2023; Tufa et al. 2024).

While mechanization can contribute to sustainable production, transitioning from traditional to environmentally friendly practices requires adapting climate-smart agriculture (CSA) strategies (Batool et al. 2024). CSA practices for potato cultivation could be soil nutrient and water conservation practices (e.g., minimum tillage, soil residue management, and ridge planting), agronomic practices (e.g., crop rotation and intercropping) (Khatri-Chhetri et al. 2017; Waaswa et al. 2022; Ogisi and Begho 2023). Moreover, labor constraints would induce the adoption of labor-saving technologies such as using herbicides, but could negatively affect biodiversity (Daum et al. 2023). Thus, understanding the productivity and technical efficiency of mechanized farmers may contribute to the current paucity of literature from a sustainable production perspective.

Materials and Methods

Research Design and Sampling

In this study, we analyse the technical efficiency and production constraints of potato farmers who use tractor services for tillage operations and animal traction for transportation. For reasons of scope, the study did not aim at a comparison of mechanized and non-mechanized farms, but rather focused on the variation of technical efficiency within a group of mechanized potato farmers and on the reasons that explain this variation.

To identify the farmers included in this study, we collaborated with a major provider of mechanization services,¹ (hereafter referred to as Service Provider), located in Nakuru County. This county ranks second among the potato producing counties in Kenya (Soethoudt and Castelein 2021; Chepkoech et al. 2023). According to official data from 2016, 67% of households in the county utilize farm machinery and equipment, with 47% of them hiring rather than owning the machinery (MoALF 2016). Plowing (49%) and harrowing (24%) are the primary mechanized farm activities in the county (MoALF 2016).

By courtesy of the Service Provider, we obtained a list of all 200 clients located in the largest of its four service provision areas in Nakuru County. In addition to obtaining quantitative data on cropping practices, input use and output of potato production, the survey included qualitative questions on constraints to potato production. A digital survey questionnaire was prepared via ODK software. Three trained enumerators conducted face-to-face interviews with the respondents from September to October 2022, utilizing smartphones to enter data during the surveys. Forty-four cases were excluded due to missing or incomplete data, leaving a final sample of 156 potato-cultivating farmers. In addition to the farm survey, we interviewed a ward extension officer to obtain the insights on opportunities and constraints of potato production. Ethical approval was obtained from the University of Hohenheim before field data collection.

Analytical Methods

Next to providing descriptive statistics and qualitative interview information, our main analytical approach was to determine the technical efficiency of the potato farmers and to identify the factors associated with technical efficiency. Technical efficiency can be defined as “the capacity and willingness of an economic unit to produce the maximum possible output from a given bundle of inputs and a technology” (Kalirajan & Shand 1999; p149). Phrased differently, technical efficiency measures how far farmers operate below the production possibility frontier. To estimate technical efficiency, we applied a stochastic frontier analysis (SFA) approach since this approach accounts for the effects of “statistical noise” in the data (Thiam

¹ To ensure the anonymity of the respondents, the name of the service provider is not disclosed.

et al. 2001; Coelli et al. 2005; Qian et al. 2024). Coelli (1995a) established that farm-level data may be subjected to statistical noise that may affect the analysis if alternative approaches such as Data Envelopment Analysis (DEA) is used. Unlike the DEA, the SFA decomposes the error term into a two-sided random error, capturing random effects outside the firm's (farmer's) control, and a one-sided inefficiency component accounting for statistical noise (Thiam et al. 2001). The general stochastic frontier model is given as in Eq. 1:

$$Y_i = f(x_i; \beta) \exp(v_i - \mu_i) \quad (1)$$

where Y_i is the output of the i -th farmer. X_i is a vector of farm inputs. β is a vector of parameters to be estimated. v_i is a measure of the random variation in output (Y_i) outside the control of the farmer, and μ_i is the non-negative unobserved random error term.

The data for the inputs are derived from our famers' survey. They are shown in Table 2 and include land, labor, seeds, fertilizer and pesticides. We used the total amounts of these inputs without differentiating different types or quality (Beyene et al. 2020). This is obviously an approximation.

We followed the SFA estimation technique that was simultaneously developed by Aigner et al. (1977) and Meeusen and Van Den Broeck (1977) in estimating the technical efficiency of potato production. Following Battese and Broca (1997) and Battese and Coelli (1992), we used the more flexible trans-log functional form of the production function since it does not impose restrictions on the production technology (Huan et al. 2022), and it also nested the Cobb–Douglas production frontier (Eq. 2). The adopted trans-log production is specified as follows:

$$\ln(y_i) = \beta_0 + \sum_{j=1}^m \beta_j \ln(x_{ij}) + \frac{1}{2} \sum_{j=1}^m \sum_{k=1}^m \beta_{jk} \ln(x_{ij}) \ln(x_{ik}) + v_i - \mu_i \quad (2)$$

where y_i is potato output (in kg) for a household farmer i , j th inputs include; x_1 is land used for potato production in hectares; x_2 is fertilizer (organic and inorganic) used in kg; x_3 is pesticide (herbicides, pesticides, and fungicides) in liters; x_4 is labor in person-days and; x_5 is the quantity of potato seed in kg. v_i is (independently and identically) a normally distributed error term, denoting statistical noise (Eq. 3) and μ_i is a non-negative unobserved random error term with a one-sided or half-normal distribution (Eq. 4), and $\delta_1, \delta_2, \dots, \delta_9$ are the inefficiency parameters to be determined (Eq. 4). Thus, technical efficiency is the observed output over the stochastic frontier output (Coelli et al. 2005). The model can be described as in (Eq. 5 and Eq. 6). Thus, technical efficiency takes a value between 0 and 1. For the technical efficiency analysis, we first conducted a likelihood-ratio (LR) test (Vuong 1989) (Eq. 7) to determine whether a Cobb–Douglas or Trans-log production function best estimates our data.

$$v_i \sim N(0, \sigma_v^2) \quad (3)$$

$$\mu_i \sim N + \left(0, \sigma_u(z_i, \delta)^2 \right) \quad (4)$$

$$\sigma_u(z_i, \delta)^2 = \exp(z_i' \delta) \quad (5)$$

$$TE = \exp(-\mu_i) \quad (6)$$

$$LR = -2[\log(L_0) - \log(L_1)] \quad (7)$$

The factors associated with technical efficiency have been derived from the literature above. They are indicated in Table 1 and include variables referring to human capacity and skills (age, education, training, access to extension, years of experience in using mechanization) and financial capacity (access to credit, off-farm income and ownership of animals). Use of animal traction for transporting inputs and outputs has been added as it was found in previous research to influence technical efficiency of potato production in Ethiopia (Philphos and Tafesse 2025). Therefore, we hypothesize that farmers using animal traction for the transportation of farm inputs and output could improve their technical efficiency. Given the long-standing tradition of hiring mechanized tillage services among farmers in the study area (Pingali et al. 1987; Groote et al. 2020), we hypothesize that farmers who utilize mechanization services over a long period will exhibit higher technical efficiency.

The data obtained from the farmers' survey was cleaned using IBM SPSS statistics 26 packages (SPSS Inc, Armonk, NY 2019) and analyzed using Stata 18.0 MP-Parallel Edition software (StataCorp. 2023). As estimation method, we applied a single-step SFA approach using the "sfcross" command in STATA 18 to estimate Eq. 6. When $\mu_i = 0$, the farm's production follows an SFA function. When $\mu_i > 0$, the farm's output falls due to inefficiency. Qualitative information from the interviews of farmers and extension officers was analyzed using content analysis with the aim to identify major constraints in potato production.

Results

Descriptive Statistics and Qualitative Findings

Table 1 displays the descriptive statistics of the survey regarding the demographics and farm characteristics of the respondents. The findings indicate that the users of tractor services are younger and better educated than the average farmers reported in Kenya (e.g., Musafiri et al. 2022). Moreover, close to a quarter of the respondents were women, which is relatively close to the share of female-headed households in rural Kenya (KNBS 2022). Possibly, female-headed households tend to rely on tractor services due to labor shortages. What is also of interest is that more than 80% of the farmers do not own land, indicating that potato growers typically rent land for that purpose. More than half of the potato growers were engaged in off-farm economic activities. The data indicate that the training level

Table 1 Descriptive statistics of variables used for the inefficiency model ($N=156$)

Variables influencing technical efficiency		Description	Mean	SD	Min	Max
Age		Respondent's age (years)	39	9.4	19	78
Education level		Binary, 1 if respondent has formal education; 0 otherwise	.92	.27	0	1
Animal ownership		Binary, 1 if a farm household owns an animal; 0 otherwise	.73	.45	0	1
Animal traction use		Binary, 1 if a farm household uses animal traction for transportation of inputs and outputs; 0 otherwise	.54	.50	0	1
Mechanization hiring experience		Number of years that the farmer has used mechanized tillage services	7.3	4.4	0.5	20
Off farm business activity		Binary, 1 if farm household has a business; 0 otherwise	.64	.48	0	1
Training participation		Binary, 1 if the respondent has participated in training in the past season; 0 otherwise	.73	.44	0	1
Private extension access		Binary, 1 if the respondent has access to private extension services; 0 otherwise	.63	.48	0	1
Credit access		Binary, 1 if the respondent has access to credit; 0 otherwise	.80	.40	0	1

Source: own survey

of the farmers is also relatively high, as more than 60% used private extension services, and more than 70% had obtained training during the previous season from several training providers (See Supplementary Materials—Fig. S2 and S3). While access to credit is typically a major constraint in smallholder agriculture in Africa, more than 80% of the potato farmers in our sample had access to credit. Ownership of livestock and use of animal traction for farm input and products transportation was also relatively high in our sample of mechanized potato farmers, indicating that the use of animal traction may facilitate the step to using tractor services (Daum et al. 2023).

The years of experience in hiring mechanization services varied from 6 months to 20 years, with a mean of 7 years (Table 1), indicating that mechanization service provision is not a new technology in the research area. With regard to the type of mechanization used, it is worth noting that all farmers used tractor-plowing services in the 2021/2 farming season, but less than 10% have ever used tractor services for planting (Supplementary Materials—Fig. S1). 1.3% used tractor services for pesticide application (Supplementary Materials—Fig. S1). Despite high pesticide use (99%), the low mechanized spraying was expected since almost all farmers use a knapsack sprayer. 3.8% had reported using tractor potato harvesting services (Supplementary Materials—Fig. S1).

Table 2 presents the descriptive results about cropping practices and performance. On the average, the farmers achieved a potato yield of 9.4 tons per hectare (t/ha) which is comparable to the reported actual yield of 6–10 t/ha with a potential of 20–30 t/ha under rainfed conditions in Kenya (IFC 2019). In comparison, the yield obtained in South Africa was 35 t/ha, while Egypt achieved a yield of 25 t/ha (IFC 2019; Muthoni and Shimelis 2023). Expectedly, the yield showed considerable variation, ranging from 4 t/ha to 22.5 t/ha. Considering that the average arable crop land size per capita in Kenya is only 0.13 ha (FAO 2024), the plots on which mechanized farmers grow potatoes are relatively large, as the average of more than one hectare suggests.

All sampled farmers used conventional tillage practices using disc plow and disc harrow. Farmers do not use ridges to plant potatoes. Mulching is uncommon practice in the area. Dehauling is done manually using a machete.

Table 2 Descriptive statistics of variables used for the stochastic production frontier model ($N=156$)

Variables influencing productivity	Description	Mean	SD	Min	Max
Potato output	Total potato output (kg)	9982	10,764	800	72,000
Land	Land area cropped with potato (ha)	1.1	0.7	0.2	3.2
Fertilizer	Total amount of (organic and inorganic fertilizer) used (kg)	178	124	1	700
Pesticide	Total pesticides used (liters)	4.10	3.16	1	20
Labor	Total (hired and family labor) (days)	107	50	32	286
Seed	Seed used (kg)	1233	922	101	4188

Source: own survey

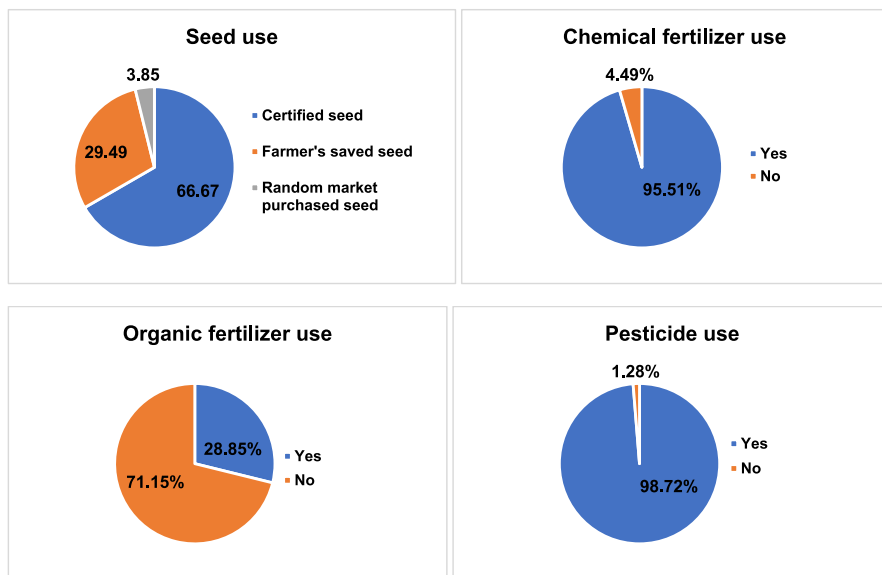


Fig. 2 Input use ($N=156$)

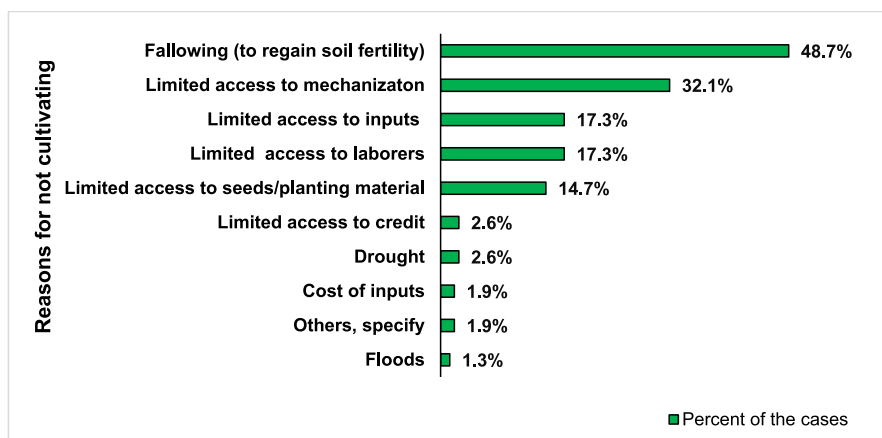


Fig. 3 Reasons for not cultivating all land; $N=156$ (Source: own survey). Note that multiple answers were possible

Figure 2 shows the input use among the sampled farmers. One third of the farmers use either saved or random market purchased seeds. Chemical fertilizer and pesticides are used by more than 95% of farmers. Less than one third of the farmers use organic fertilizer mainly manure. The combined use of organic and inorganic application is 178 kg/ha, which is quite low.

One important observation is that 74% of the farmers do not cultivate all the land that they own or rent. Almost half of the farmers use fallowing as a strategy

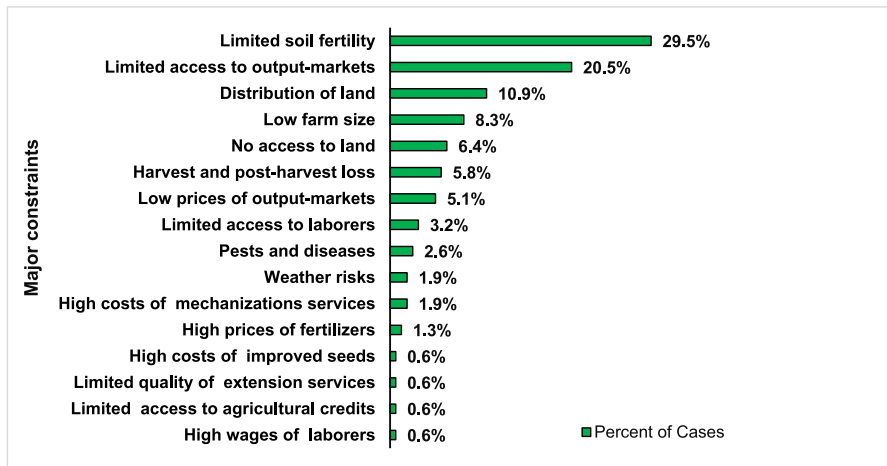


Fig. 4 Major constraints identified by the farmers for potato production; $N=156$ (Source: own survey). Note that multiple answers were possible

to restore soil fertility (Fig. 3), even though access to mechanization and inputs was also a reason for not cultivating all available land. Most of the farmers usually plant potato year after year, but few farmers keep the fallow up to two years. Notably, almost 90% of farmers practiced monoculture of potato farming on their plots.

The constraints displayed in Fig. 4 were also corroborated by the qualitative findings. Soil fertility and chemical fertilizer quality were raised as major concerns:

“Improvement on soil fertility is required.” [Female farmer]

“High quality fertilizer should be introduced.” [Male farmer]

“There is a high cost of inputs [...] lowering the cost of fertilizer would improve fertilizer use.” [Male farmer]

“One of our community challenges is declining soil fertility.” [Extension officer]

Pest and disease problems were also reported to be a major constraint. As one extension officer pointed out:

“The farmers of Mao region face a lot of challenges during the May to July season because of coldness in the area at which potato is affected by blight (²*Baridi*).” [Extension officer]

This concern was echoed by farmers, as the following quotes indicate:

“Our major challenge in this area is pests and diseases.” [Male farmer]

“Pest and disease were my challenge. Although I used this chemical [...] several times, it is not working effectively.” [Female farmer]

² Cold in Swahili.

Results of the Productivity and Technical Efficiency Analysis

For the analysis of technical efficiency, we first conducted a likelihood-ratio (LR) test (Vuong 1989) (Eq. 7) to determine whether a Cobb Douglas or Trans-log production function best estimates our data. The test statistic ($\chi^2(15)$) estimated is 59.11 (above the critical value observed ($\chi^2(15)$) at 1% = 30.58 and 5% = 24.99). Thus, the results obtained suggest that the H_0 where the Cobb Douglas function is the appropriate form should be rejected, and H_1 where the trans-log function is the appropriate model should be accepted (Table 3).

Furthermore, we used a restricted generalized linear model (glm) and conducted a likelihood ratio test to determine the presence of technical inefficiency (Lai and Huang 2010). The test statistic ($\chi^2(1)$) estimated is 14.77 (above the critical value observed ($\chi^2(1)$) at 1% = 5.41 and 5% = 2.71 (Kodde and Palm 1986). Thus, the null hypothesis (H_0) where there is no technical inefficiency in potato farms was rejected, and we accepted that there is inefficiency (Table 3). We conducted a maximum likelihood ratio test to determine whether the inefficiency terms of the frontier are stochastic or not (Coelli 1995b). The test statistic ($\chi^2(9)$) estimated is 57.26 (above the critical value observed ($\chi^2(9)$) at 1% = 21.67 and 5% = 16.92) suggesting to reject H_0 which specifies that the inefficiency terms are not stochastic, so that we accept H_1 (Table 3).

According to the analysis, 92.3% of the variance can be explained by $\gamma = \frac{\sigma^2_u}{(\sigma^2_u + \sigma^2_v)}$, technical inefficiency (distance from the efficient frontier), and 7.8% can be explained by random noise, such as measurement errors and random factors beyond the control of farmers (e.g., weather conditions).

Table 4 displays the elasticity coefficients for the variables included in the analysis. Significant elasticity estimates at the 1% level were obtained for land, fertilizer, pesticides and labor. The scale elasticity of potato production was found to be 1.24, demonstrating increasing returns to scale. Unexpectedly, the sign for fertilizer was negative, indicating that yields declined with increasing fertilizer use. Possible reasons will be discussed in the section Discussion.

Following Battese (1997), we included dummy variables for fertilizer and pesticide to correct for zero values of inputs.

The distribution of technical efficiency scores shows a wide range from 15 to 93% with a mean of 63% (Fig. 5). More than 37% of the farmers in our sample had a technical efficiency of less than 60% (Fig. 5). Table 5 displays the influence of different variables on technical inefficiency, indicating that variables with a negative sign tend to increase technical efficiency. The results indicate that age, the use of animal traction to transport inputs and services as well as training and use of private extension services were significantly associated with higher levels of technical efficiency (Table 5), whereas participation in training was, unexpectedly, significantly associated with lower technical efficiency.

Table 3 Hypothesis test for model specification

Null hypothesis (H_0)	Test statistics	Critical value	Decision
Cobb–Douglas nested within Trans-log ($\chi^2(15)$)	59.11	30.58***	Reject H_0 : Cobb Douglas is appropriate
No technical inefficiency ($\chi^2(1)$)	14.77	5.41***	Reject H_0 : no technical inefficiency
Frontier model is not appropriate ($\chi^2(9)$)	57.26	21.67***	Reject H_0 : Frontier is not appropriate

*** $p < 0.01$

Table 4 Estimation results for Trans-log production function (technical efficiency)

Explanatory variables	Parameters	Coefficient
Constant	β_0	-3.773 (2.555)
ln(land)	β_1	0.877**** (0.121)
ln(fertilizer)	β_2	-0.308**** (0.0852)
ln(pesticide)	β_3	0.228**** (0.0677)
ln(labor)	β_4	0.318*** (0.100)
ln(seed)	β_5	0.126 (0.0977)
$\frac{1}{2} \ln(\text{land})^2$	β_6	-0.306 (0.306)
$\frac{1}{2} \ln(\text{fertilizer})^2$	β_7	0.182 (0.201)
$\frac{1}{2} \ln(\text{pesticide})^2$	β_8	0.202 (0.154)
$\frac{1}{2} \ln(\text{labor})^2$	β_9	0.226 (0.315)
$\frac{1}{2} \ln(\text{seed})^2$	β_{10}	-0.0283 (0.239)
$\ln(\text{land}) * \ln(\text{fertilizer})$	β_{11}	-0.155 (0.0908)
$\ln(\text{land}) * \ln(\text{pesticide})$	β_{12}	-0.201 (0.136)
$\ln(\text{land}) * \ln(\text{labor})$	β_{13}	0.187 (0.201)
$\ln(\text{land}) * \ln(\text{seed})$	β_{14}	0.314 (0.229)
$\ln(\text{fertilizer}) * \ln(\text{pesticide})$	β_{15}	0.0480 (0.0684)
$\ln(\text{fertilizer}) * \ln(\text{labor})$	β_{16}	-0.0767 (0.130)
$\ln(\text{fertilizer}) * \ln(\text{seed})$	β_{17}	-0.00768 (0.0704)
$\ln(\text{pesticide}) * \ln(\text{labor})$	β_{18}	-0.321** (0.153)
$\ln(\text{pesticide}) * \ln(\text{seed})$	β_{19}	0.00855 (0.126)
$\ln(\text{labor}) * \ln(\text{seed})$	β_{20}	0.224 (0.174)
Fertilizer dummy	β_{21}	4.252 (2.625)
Pesticide dummy	β_{22}	-0.0944 (0.578)

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$

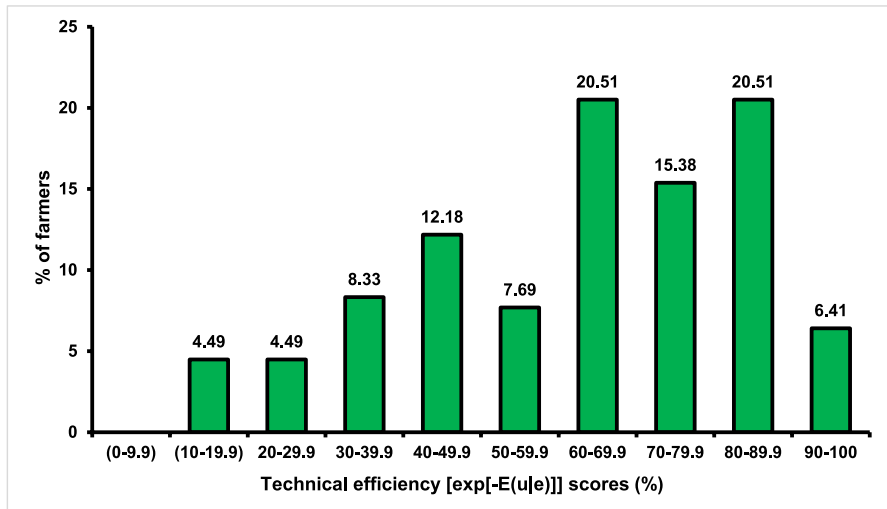


Fig. 5 Distribution of technical efficiency scores; $N=156$

Discussion

Productivity and Sustainability

The descriptive results indicate that mechanized potato farmers are the better educated and have better access to resources as well as advisory services than the average Kenyan smallholder farmers. Yet, on average, the sample farmers did not achieve potato yields that were above the national average of approx. 9 t/ha. There was a considerable variation among the yields of our sample farmers, but only 5% of the farmers in our sample achieved yields above 20 t/ha, which had been the average in the years between 2006 and 2012 (see Fig. 1). One major reason for this observation is likely the fact that a large share of the farmers did not adopt the sustainable farming practices that would be required to achieve high potato yields in the long term. As pointed out above, for potatoes, a crop rotation is recommended that includes at least three other crops (see, e.g., Mutegi et al. (2021: 19). Yet, almost 90% of the farmers interviewed for this study reported monocropping of potatoes. This problem has been observed in earlier studies, but typically not to the same extent. For example, Kwambai et al. (2023: 765) studied potato farming in three locations and found that the highest rate of farmers who did not practice crop rotation was 50%.

Not surprisingly, farmers perceived lack of soil fertility as the main constraint to potato production (Fig. 4). Personal observation of the first author during the survey indicates that intensive mechanized tillage may have aggravated the soil fertility problem, as many of the potato plots are prone to erosion as a consequence of intensive conventional mechanized tillage in hilly topography (see also supplementary data: Fig. S4 and Video). Our results also agree with Damiba et al. (2024) and Mugo et al. (2020) who reported an increasing prevalence of soil fertility loss, largely

Table 5 Estimation results for Trans-log production function (technical inefficiency)

Mu (inefficiency model)	Parameters	Coefficient
Constant	δ_0	− 3.773 (2.555)
Age	δ_1	0.0381** (0.0149)
Education level	δ_2	0.262 (0.370)
Animal ownership	δ_3	− 0.424 (0.256)
Mechanization hiring service years	δ_4	− 0.00878 (0.0304)
Animal traction use	δ_5	− 0.689** (0.308)
Off-farm business activity	δ_6	0.158 (0.247)
Training participation	δ_7	0.688** (0.314)
Private extension access	δ_8	− 0.512* (0.278)
Credit access	δ_9	0.0437 (0.261)
σ_u		
Constant		− 0.931** (0.420)
σ_v		
Constant		− 3.408**** (0.530)
λ		3.450695****
Log likelihood		− 76.9273
Wald $\chi^2(22)$		514.54
Prob > χ^2		0.0000
N		156

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$

attributed to poor unsustainable agricultural management practices in Narok County as a major obstacle to potato production.

Reduced tillage systems, which involve strip-till or no-till systems, are usually recommended to prevent soil erosion in mechanized farming systems (Myers and Waggener 1996; Lenka and Lal 2013; Komissarov and Klik 2020). However, these practices are less suitable for potatoes, which recover well-drained soil for tuber development. The Kenyan “Guide to Good Agronomic and Plant Nutrition Practices” for potato production (Mutegi et al. 2021) recommends two rounds of hilling.

Minimum soil disturbance could, however, be applied to the crops planted in a crop rotation between the potato crops.

Next to crop rotation and sustainable tillage practices, soil nutrient management plays an important role in maintaining soil fertility. In this regard, our analysis yielded an unexpected result, as the elasticity coefficient for fertilizer was significant and negative, indicating that higher fertilizer use was associated with reduced yields. This result could be due to different reasons. Fertilizer use is expected to produce decreasing marginal returns up to a level, from which onwards an absolute decline of crop yields can be observed due to crop damage caused by overuse of fertilizer (Ellis 1993). Therefore, one possibility for our result is that farmers use excessive fertilizer. The other possibility is that only farmers who are already experiencing a decline in soil fertility use fertilizer and that they do not use sufficient amounts to counteract the decline in soil fertility. In principle this effect could be captured by including data on soil fertility into the analysis, but it was not possible to collect this data in the course of this study.

As pointed out above, 96% of the farmers included in this study used fertilizer, and applied on average 178 kg per hectare (of inorganic and organic origin). Even though we do not have specific data on the type of fertilizers used, and on the specific fertilizer requirements of our sample farmers, it is likely that the applied fertilizer rate is below the requirements for potato (see e.g., Mutegi et al. (2021)). Hence, the more likely explanation for the negative yield response to fertilizer use is that farmers who observe declining soil fertility use fertilizer, but in insufficient amounts to effectively reduce this decline. Our negative elasticity finding is consistent with studies by Kamau (2019), Kamau et al. (2020), and Chemjor et al. (2024), on potato production and profitability efficiency in Nakuru County. The use of organic fertilizer could play particularly important role in improving soil fertility and enhance crop nutrition, as is well documented in the literature. For example, Ishfaq et al. (2023) show that combined use of organic and inorganic fertilizers augmented nutritional quality of crops.

Interestingly, nearly half of the farmers engage in fallowing (Fig. 3), and the majority of them indicate the goal to restore soil fertility as the main reason. Fallowing may have phytosanitary advantages for potato production, but it would only effectively regenerate soil fertility if it is done for 20 years or if it is combined with planting of nitrogen-fixing plants, e.g., sesbania [*Sesbania sesban* (L.) Merr.] (Kwesiga et al. 1999); which can still take two to three years. In both cases, it may be difficult for most farmers in SSA to plant legume trees and abandon all of their farms without cultivating for consecutive extended periods, especially for major staple and cash crops such as potatoes. Planting food legumes, such as beans or peas, might be a more promising option.

Another important factor that influences the productivity of potato production is pest and disease control. The proper amount of pesticide application at the right time will increase potato yield, but pest control with chemical plant protection products is knowledge-intensive, and the challenge is to ensure accurate application and avoid overuse (Crissman et al. 1994; Pertot et al. 2017). Pest and disease control is particularly challenging, if farmers do not apply good agricultural practices, such as crop rotation. Moreover, climate change may lead to increased pest pressure. Previous

studies reported that Nakuru county is subjected to climate variability, with rising temperatures and climate change favoring pest incidences (MoALF 2016; Waaswa et al. 2022). Hence, it is not surprising that in our survey, 95% of the farmers identified pests and diseases as significant causes of pre-harvest potato losses (Supplementary Materials – Fig. S5) and that our analysis indicated a positive yield response to pesticide application. Consistent with our findings, increased pesticide use improved potato production in the Molo sub-county (Kamau et al. 2020). Although the findings from this study show that increased use of pesticides could increase potato production, numerous studies well documented the negative impact of increased pesticide application on biodiversity (e.g., humans, soil, and pollinators) (Barzman et al. 2015; Lykogianni et al. 2021; Munyaneza and Bizimungu 2022). Therefore, from an agricultural sustainability perspective, considering non-chemical control options could be important.

Our study also identified labor as a significant factor in influencing yields, as 1% increase in labor indicated a 0.3% increase in potato output, *ceteris paribus*. Land preparation was the only mechanized activity in our study, and the remaining operations including planting, weeding, spraying, and harvesting, necessitate manual labor. This finding is consistent with previous studies (Nyagaka et al. 2010; Obare et al. 2010; Philippos and Tafesse 2025) where increased labor input increases potato production in Kenya and Ethiopia. Labor is often short in supply, and the labor savings due to mechanized land preparation might increase the labor availability for planting. At the same time, improved land preparation may reduce the need for weed control, but a comparative study of mechanized and non-mechanized farms would be required to test for such effects.

The elasticity obtained for land has the highest value signifying its importance for potato production. Chemjor et al. (2024) and Nyagaka et al. (2010) also found that potato yields and profitability in Nakuru and Laikipia counties were higher if farmers cultivated larger plots.

Technical Efficiency

One of the main findings of our study is the wide variation in the technical efficiency of potato farmers, ranging from 11% to 93%, and the relatively low mean value of 63%. These findings indicate that eliminating inefficiency could improve potato production by almost 60% $[(1-0.63)/0.63] * 100$. The average technical efficiency values are comparable to previous studies (Nyagaka et al. 2010; Ogada et al. 2014; Barasa et al. 2019). In addition, previous studies in Kenya have reported a wide range of variation for technical efficiency (21%–93%), (21%–96%), and (22%–88%) (Nyagaka et al. 2010; Barasa et al. 2019; Kamau et al. 2020). The wide variation in technical efficiency indicates that there is ample opportunity to learn from the more efficient farmers, e.g., by farmer-to-farmer extension approaches.

One factor that influences technical efficiency is age. The mean age of the farmers in our study was almost 40 years, and the findings indicate that technical efficiency decreased with age. Studies by Liu & Zhuang (2000) and Li and Sicular (2013)

conducted in China found that, on the one hand, farmers' experience increased with age, while on the other hand, they lost physical strength and creativity, which resulted in efficiency declines after the age of 45. In the SSA context, Asravor et al. (2024) found younger farmers in Ghana to be less inefficient than their elder peers, albeit farmers in both age cohorts tended to have equal levels of technological endowment. Consistent with our findings, Chemjor et al. (2024) reported that the profitability of potato production reduced with the increase in age in Kenya. Similarly, Jote et al. (2018) found a positive impact of age on technical inefficiency for sweet potato production in Ethiopia.

Our study did not find an effect of the years of experience in mechanization on technical efficiency, even though we would have expected that efficiency might increase with experience. We did not analyze whether mechanized farmers are more efficient than non-mechanized ones. Earlier studies reported a negative impact of mechanization access on technical inefficiency for northern Ghanaian maize farmers (Abdulai et al. 2015) and Nicaraguan maize and bean farmers (Abdulai and Eberlin 2001). In view of these results, the relationship between mechanization and efficiency appears to be a topic that deserves future research attention.

Expectedly, our findings indicate that the use of animal traction for transport of farm inputs (seed, fertilizer, and water for pesticide applications) and for harvested goods (bags of potatoes) increases technical efficiency. Consistent finding on the positive impact of animal traction use on technical efficiency has been reported in Burkina Faso for intercropping technology (Sawadogo et al. 2022). Moreover, a study in Indonesia found that distance to potato farmers' houses was associated with lower technical efficiency, and they therefore recommended improving access to farm transportation (Maulidiyah et al. 2024). Training and extension are important factors that can be expected to improve technical efficiency. Our analysis showed rather unexpected results, as participation in training had a negative impact, whereas access to private extension had a positive impact. Our survey results indicate that 73% of the farmers in our sample received training on various topics such as seed rate, seed bed preparation, row planting, and chemical fertilizer application (Supplementary Materials – Fig. S2). Most training was provided by farmer cooperatives, government extension services, and agro-vets, with minimal involvement from private extension service providers (Supplementary Materials – Fig. S3). One potential problem with training is that it was likely to be generic and did not address any specific challenges that farmers faced. This would, however, explain a non-significant and not a negative impact. The negative impact may stem from the fact that the more inefficient farmers were more likely to have participated in the training and that the training was not effective in improving their efficiency, e.g., because the farmers did not have access to the input such as improved seeds that the training may have recommended. Another possibility is that some of the messages provided in the training could, in fact, reduce technical efficiency. For example, fertilizer recommendations that are not based on specific soil fertility requirements could reduce technical efficiency. Consistent with our findings, Maulidiyah et al.

(2024) found that training in potato cultivation reduced technical efficiency in Indonesia. Likewise, Abate et al. (2019) reported that an ineffective and biased public extension system negatively affected the efficiency of red pepper production in Ethiopia. Bozoğlu and Ceyhan (2007) found that the effectiveness of training in vegetable production depended on quality delivery by research and extension institutions. There is also evidence that training approaches that are more specific, such as plant health clinics, can improve the efficiency of small-holder farmers for potato production when targeted and relevant training services are provided regularly (Chepkoech et al. 2023; Sultana et al. 2023).

Our finding that access to private extension increases technical efficiency is also interesting, since private sector extension is typically criticized for serving the interests of the manufacturers and traders of agricultural inputs rather than the farmers. Private companies may recommend an overuse of input, which would result in reduced technical efficiency. Our findings indicate that, however, that this was not the case for the farmers included in our study, since access to private extension services was associated with increased technical efficiency. This finding is not consistent with a study by Chemjor et al. (2024), who found that public extension access to information in agronomic management practices increased potato farmers' profitability in Nakuru. Consistent with our findings, a study in South Africa depicts that private extension access significantly improved farmers productivity than public extension access through market accessibility and adopting climate-smart agricultural practices (Mudzielwana et al. 2025).

Limitations

Our study is subject to several limitations. First, the study is based on a case study, utilizing a sample of mechanization users in a limited geographical area. Hence, the study is not statistically representative for Kenya. Second, since we included only farmers who use mechanization services, we did not assess the effects of mechanization on productivity, technical efficiency, and sustainability. We believe that this is an important field for future research, which should take into account different mechanized tillage practices and associated problems, such as soil erosion. Third, we used total amounts of fertilizer and pesticides as proxies for the use of such inputs and did not explore the details of the products used and their appropriateness in terms of crop nutrition and crop protection. More detailed specific studies would be required to cover these aspects. Fourth, our study did not include details on family and hired labor and the tasks performed by women and men, which would also be an important aspect for future studies, since mechanization is likely to have gender-differentiated effects, as pointed out above. In spite of these limitations, we believe that our results, especially regarding the large unexploited potential to improve technical efficiency, points to opportunities that are of wider relevance for potato production beyond our study area.

Conclusions

As mechanization of smallholder farming, based on machinery service providers, is on the rise in African countries, there is a need to better understand productivity, efficiency, and sustainability of increasingly mechanized farming systems. Our findings, which are based on a case study of potato farmers who use mechanization services for land preparation in Nakuru county, indicate that there is a remarkably wide variation in the performance of these farmers. Potato yields varied from 4 to 22.5 tons per ha. Similarly, the technical efficiency of the potato farmers, which measures how far away from the production possibility frontier farmers operate, varied from less than 20% to more than 90%. The farms that display high performance in terms of productivity and efficiency demonstrate the great potential for improving potato farming that can be achieved with already existing technologies. The study provides important clues on the factors that may help to unlock this potential. Access to farm-specific advice emerged as a key factor for improved technical efficiency, whereas providing generalized training appeared not at all effective in achieving this goal. Providing farm-specific advice is obviously more costly than providing generalized training, but our study suggests that more efforts to provide farm-specific advice are warranted. In spite of the widely held concern that private advisory services may not serve farmers' interests, our study suggests that access to private extension services was effective in improving farmers' technical efficiency.

The findings of our study indicate that farm-specific advice needs to focus particularly on the sustainability of potato farming systems. One of the most important good agricultural practices in potato farming is including potatoes in a crop rotation that includes at least three other crops. Yet, an astounding share of almost 90% of the farmers in our sample practiced monocropping. This percentage is higher than any share we found in the literature. The fact that more than 60% of our sample farmers have an off-farm business and that approximately 80% rent land for potato production suggests that mechanized potato production may often be carried out by entrepreneurs who rent the same plots of land to continuously crop potatoes, a practice that is not sustainable. The practice of fallowing fields to increase soil fertility may not be the most effective method as compared to alternatives, such as diverse crop rotations that include legumes. Field observations conducted during this study also point to problems of soil erosion on mechanized farms, which suggests that more empirical research would be beneficial to identify sustainable pathways towards mechanized potato production, a crop where reduced tillage is less feasible than in cereal crops. The fact that less than 30% of the farmers identified soil fertility as a major constraint indicates the need to raise more awareness about this important topic. Our study also suggests that improving crop nutrition, as one important aspect of soil fertility, requires further attention since the fertilizer strategies applied by the farmers included in our sample tended to decrease rather than increase potato yields. Last, but not least—the wide variation in performance observed among the farmers included in our sample suggests that the solution to the constraints identified here can be found among the

Kenyan smallholder farmers themselves. Learning from best farmers, for example by farmer-to-farmer extension, could be among the most promising strategies to harness the potential of potato production for sustainable food security in Africa.

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Data Availability Data will be available on request.

Declarations

Competing interests The authors declare no competing interests.

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