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Economic efficiency of cricket production reared under improvised cage system for improved food production

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In the recent past, cricket production has attracted a myriad of interests in the Global Food Sector. However, low production, limited input resources and rearing systems constrain the utilization of crickets. Scanty information exists on sundry input resources for upscaling of cricket production and how such inputs can be efficiently managed. This study sought to determine economic efficiency of improvised cricket rearing system using a generalized additive stochastic frontier approach (GAM-SFA) to assess the efficiency in cricket production under the new technology. Twenty-day old *Acheta domesticus* and *Gryllus bimaculatus* were separately reared in improvised cage system comprising bamboo hideouts, scrap blankets, cut bamboo stems and the plywood-based cages. GAM-SFA was used to estimate efficiency scores. Results revealed that the production was efficient. Feed, labor and water were positive and significant at 5% suggesting their importance and positive influence on cricket output. Similarly, the cost of feed, labor, water and scrap blanket were positive and significant suggesting that increase in these costs of inputs would increase the total cost. The mean TE, AE and EE were 85, 92 and 79%, respectively implying that there still exist potential to increase output using present technology and costs of production. Assessing key determinants of economic efficiency in cricket production under the system is necessary.

Key words: Economic efficiency, crickets, GAM-SFA, improvised system.

INTRODUCTION

Agricultural production in sub-Saharan Africa (SSA) is punctuated by increasing resource scarcity, depleting land fertility, limited technologies and low investment in sustainable agriculture (FAO, 2018). Climate variability and extremes continue to devastate yields and the lives of many rural households remain hanging in a balance (Holleman et al., 2020). Further, current Covid-19 pandemic has exacerbated the situation causing havoc in the food supply chain with many countries under lock-down. Ensuring a more sustainable climate-smart food

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resource is thus indispensable in the quest for increased nutrition-sensitive food diets that have low environmental impacts following increasing health challenges and exponential global population growth. According to Biodiversity International Report (2012), diversification of course and better novel strategies of production are requisite to sustainable agricultural production. Multifaceted efforts have been made by various food agencies to ensure regular access to enough high-quality food for healthy living. Edible insects have attracted a myriad of interests in this endeavour to enhance food security particularly in developing countries (Huis, 2013). About 2000 species of insects are edible globally and nearly 300 million people consume insects (Halloran et al., 2018b). In Africa, insects are part of diets for many households as a delicacy and approximately 500 species of edible insects are consumed (Kelemu et al., 2015). Many households in Kenya and most developing nations are embracing insects such as crickets as salient source of their livelihood (Ayieko et al., 2016; Halloran et al., 2017). Cricket rearing and consumption continues to gain ground especially among small scale farmers in Kenya and is poised to improve household food security due to its prominent, adaptive, environmental safety and nutritive benefits.

However, low production, labor intensive technologies such as use of cotton wool, limited input resources and rearing systems are apparently constraining the optimization, consumption and marketing of crickets and cricket-based products (Miech, 2018; Morales-Ramos et al., 2020; Orinda et al., 2018). There is need to explore sundry production resources and systems that are affordable and can be easily adopted by smallholder cricket farmers to sustain their production. Further, as claimed by Halloran et al. (2020), lack of market and limited equipment has led to low adoption of cricket farming amongst the small scale farmers in Kenya. Competing and limited input resources in cricket production could further exacerbate the adoption and sustainability of the enterprise (Halloran et al., 2018a). Some of the resources commonly used in cricket production such as cotton wools, plastic platters and egg trays are not only unaffordable for small scale farmers but also environmentally unsustainable (Flying Food, 2014; Highfield, 2019; Melissa, 2014; Orinda et al., 2018). In most cases, egg trays develop molds if the condition is damp (Melissa, 2014) and sometimes are chewed by crickets. They could also be costly at long-run since a producer has to replace them from time to time and due to competition with the poultry industry. It has also been alluded that carton egg trays especially those used in poultry production can cause high risk of contagion with *Salmonella* and *Campylobacter* when also used in rearing crickets (FAO, 2021).

Moreover, according to Ferronato and Torretta (2019), continued use and disposal of plastics (petri-dishes, platters, or saucers) could lead to environmental pollution thus unsustainable way of producing crickets. Little information exists on alternative cheap resources for producing crickets and how such resources in cricket production can be optimally allocated in a fashion that minimizes waste and inefficiency for optimization of production. Collectively, these factors could conspire and threaten economic sustainability and optimization of the cricket enterprise hence inhibiting the growth of cricket industry. Therefore, there was need to explore novel rearing system envisaged as efficient, sustainable, and affordable especially among small scale farmers. The study thus proposed an improvised plywood-based cage as an alternative rearing system and devised bamboo tree stem as platters for drinking and feeding while scrap woolen blankets were cleaned and used as substrates for drinking and laying. This was visualized to provide a cheaper alternative resource system for high production hence improve farmers' interest and incentive for adoption. Besides, due to existing dearth of information regarding the cricket input resource allocation and optimization of the improvised cage system, it was important to assess efficiency estimates of cricket production under the system.

In production economics, efficiency means the use of farm resources in an optimal fashion in order to maximize returns (Farrell, 1957). Estimation of efficiency is core to agricultural production since through efficient use of resources, scope of agricultural production can be expanded and sustained by farmers (Mussa, 2011). For this reason, the concept of efficiency has remained essential subject of empirical investigation particularly in developing countries where majority of farmers are resource-poor (Umoh, 2006). Technical efficiency (TE) is the ability to produce maximum output along the isoquants given the level of technology and production inputs (Battese and Coelli, 1995; Farrell, 1957). It can also be defined as the standard or measure of how available technology is used (Emmanuel et al., 2018). Technical efficiency of a farm is achieved when the farm produces maximum level of output that can be expected given the available resources (Cachia, 2018). An increase in technical efficiency increases productivity since more output can be produced from the same set of resources. Besides, allocative efficiency (AE) is the capability of a farm to use optimum amounts of inputs given their respective prices (Kahn and Cottle, 2014; Ahmad et al., 2017). It is an indication of the farmers' malleability as well as ability to alter production with the signals from the market (Dobrowsky et al., 2013). On the other hand, economic efficiency (EE) is the capacity of a firm to produce a given quantity of output at minimum cost for a given type of technology and specific proportion of input variables (Bravo-Ureta and Pinheiro, 1997; Farrell, 1957). It is estimated as the product of TE and AE.

Incessantly, Cobb-Douglas and Translog functions have been commonly used for parametric tests whereas

Data Envelopment Analysis (DEA) have been mostly applied in non-parametric analysis (Marie, 2014). However, Cobb-Douglas and Translog functions are overly restrictive, even inappropriate, and this may lead to a serious modeling bias and therefore misleading conclusions (Ferrara, 2020). Similarly, DEA results are sensitive to the selection of inputs and outputs and the number of efficient firms on the frontier increases with the number of inputs and output variables. To overcome these weaknesses, Ferrara and Vidoli (2017) and Vidoli and Ferrara (2015) proposed a Generalized Additive Model (GAM) framework for the estimation of stochastic production frontier estimates. As noted by Ferrara (2020), GAM is more flexible and determines best transformations simultaneously. It also relaxes on the modelling assumptions associated with Cobb-Douglas and Translog modelling frameworks

In light of these, the study sought to determine the efficiency of the improvised cricket cage rearing systems using a GAM stochastic frontier approach to assess the farm level efficiency in cricket production. The newly introduced system was anticipated to offer an alternative cheaper and affordable rearing system for resource-poor farmers. Besides, they were viewed as eco-friendly for environmental conservation and sustainable food production.

RESEARCH METHODOLOGY

Experimental design

The study was carried out at the INSEFOODS insect farm of Jaramogi Oginga Odinga University of Science and Technology (JOOUST). The coordinates of the area are 0°05'38.0"S and 34°15'31.0"E with a latitude and longitude of 0.093889 and 34.258611, respectively. House and field crickets, commonly known as *A. domesticus* and *G. bimaculatus,* respectively were each reared in plywood-based cages placed in a prefabricated housing. The plywood-based cages had a measurement of 139.5 cm by 46.5 cm by 46.5 cm each with three partitions of 46.5 cm by 46.5 cm by 46.5 cm per partition. Each partition was stocked with twenty day old 100 live crickets of either species. The inner side of the cages was lined with polyvinyl sheet to minimize frequent crawling and escape of the insects. The top-most part of the pens was covered with an improvised lid shutter made of both coffee wire tray and thin cotton net to prevent predators. The wooden cages were elevated off the ground by 15 cm with each leg dipped in water in small tins to prevent other insects from climbing into the cages.

Bamboo stems were improvised and used as hideouts for the two species of insects (Figure 1). Dry bamboo-based hideouts were stacked together with a binding wire and vertically arranged in each cage to streamline the cricket movements and reduce anxiety. Hideouts were elevated from the cage floor and holes drilled in each bamboo stem to enhance movement of the crickets and increase aeration within the hideouts. Similarly, water and chicken growers mash were issued *ad libitum* and the proportions consumed would be determined by subtracting the quantities remaining from the amount issued and computed on daily basis. Platters for drinking and feeding were improvised by cutting bamboo stems between two adjacent nodes. To avoid feed contamination, the platters were placed 20 cm away from each other. Cleaning of hideouts was done by simply shaking out frass accumulated within the hideouts at the end of production cycle. Bamboo feed platters were kept dry to avoid molds and would be thoroughly cleaned using water and dried in sun on weekly basis. Further, old clean woolen blanket was used both as drinking and laying substrate whereby crickets would sip water from the blankets. The blankets were folded to ensure thick layer for easy oviposition and moisture retention. Besides, cricket weights were equally measured per treatment on weekly basis over the production period. Temperature and relative humidity profiles were recorded at an interval of 1 h by HOBO data loggers (U12-012) placed in each cage over the production period. The average weekly temperature and relative humidity were then determined and recorded on weekly basis.

Sampling and data collection

Samples of 49 crickets were randomly selected from each cage (representing production farms) and weighed using electronic weighing machine per week. The response variables were the weight of crickets in grams and the minimum cost of production per week in each treatment whereas independent variables were measured in terms of quantities of feed, water, labor, old blanket and their consequent approximate market prices in Kenya shillings.

GAM-Stochastic Frontier model specification

Stochastic Frontier approach is the most popular parametric method that provides efficiency estimates or score of individual procedures (Cornwell and Schmidt, 2008). It requires a priori specification of the production function to estimate the level of efficiency. GAM-SFA was used in the estimation of efficiency scores since it is flexible and relaxes on the modelling assumptions associated with Cobb-Douglas and Translog modelling frameworks. GAM model fits a response variable *Y* using a sum of smooth functions of the explanatory variables, X_j for j = I... *p.* The general model is given as; $\mu = E(Y/X = x) = \alpha + \sum_{j=1}^{p} sj(X_j)$ where $S_j(.)$ is standardized smooth function with $E[S_j(X_j)] = 0$ (Hastie and Tibshirani, 1990).

As further simplified by Ferrara (2020), the model was expressed as follows:

$$y_i = \beta_0 + \psi(xi) + v_{i-}u_i \quad \text{(i)}$$

$$y_i = \beta_0 + f(x_i1) + f(x_i2) + \cdots + fp(x_ip) + v_{i-}u_i \quad \text{(ii)}$$

where Y_i is the observed output and Y_i^* is the frontier's output. TE takes value on the interval (0, 1) values. If Y_i is equal to Y_i^* then TE_i=1, reflects 100% efficiency. The difference between Y_i^* and Y_i is embedded in U_i. If U_i=0, this implies that production lies on the stochastic frontier, the farm obtains its maximum attainable output given its level of inputs. If $U_i < 0$, production lies below the frontier, an indication of inefficiency in the farm. Therefore, technical inefficiency = 1- TE_i , that is the margin with which the level of output for the farmer falls below the frontier output.

Further, the cost frontier functional form which is the basis of estimating the allocative efficiency (AE) of the farm was specified as follows:

$$C_i = g(Y_i, X_i; \alpha) + \varepsilon_{ii} = 1,2,...n \quad (3)$$

where C_i is the total production cost, X_i denotes the market input costs, α is the parameter of the function costs, and ε is the error

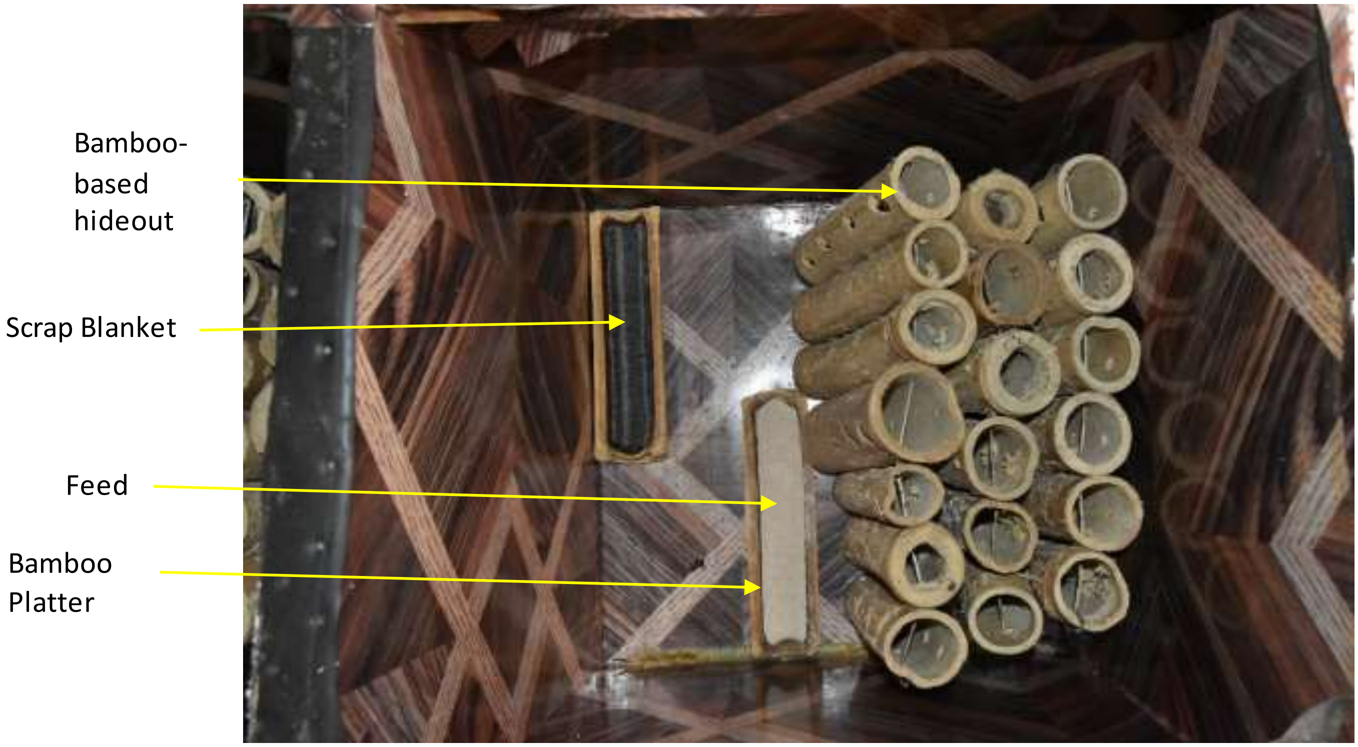

Figure 1. Improvised Cage System (Interior View).

Table 1. Summary statistics of production variables.

Variable	Mean	Std. dev.	Min.	Max.
Feed	165.45±7.71 g	42.21	104.65 g	233.40 g
Labor	5.99±0.30 h	1.64	4.06 g	8.56 h
Water	316.41±10.51 ml	57.57	229.30 ml	406.47 ml
Scrap Blanket	48.75±2.09 g	11.44	37.50 g	60.0 g
Output	110.71±3.67 g	20.13	79.58 g	142.24 g

term formulated as $\varepsilon_i = V_i + U_i$

Additionally, economic efficiency (EE) was taken as the product of AE and EE.

RESULTS AND DISCUSSION

Descriptive statistics of production variables

Summary statistics of response and predictor variables used in the stochastic production model are presented in Table 1 (n = 6 cages). Average feed, labor, water, and amount of scrap blanket used during the production cycle were 165.45±7.71 g, 5.99±0.30 h, 316.41±10.51 ml and 48.75±2.09 g, respectively. Maximum and minimum consumption levels of the feed, labor, water and amount of scrap blanket were 233.40 g, 8.56 h, 406.47 ml, 60.0 g, and 104.65 g, 4.06 g, 229.30 ml, and 60.0 g, respectively. Subsequently, the mean output was observed as 110.71±3.67 g while the minimum and maximum recorded were 79.58 and 142.24 g, respectively.

GAM-Stochastic frontier production estimates for technical efficiency

The partial elasticities of feed, labor and water were positive as expected and significant at 5% suggesting their importance and positive influence on cricket output while scrap blanket was positive but non-significant (p>0.05) (Table 2). Labor had the highest output elasticity of 0.5151. That means that a 1% increase in labor *ceteris paribus*, leads to a corresponding increase in output

Table 2. GAM-SFA production estimates for technical efficiency.

Variable	Estimate	Std. Error	*t*-value	*Pr*(>|t|)
Constant	4.0333	0.1470	27.44	0.0000***
Feed	0.3600	0.0218	16.50	0.0000***
Water	0.1126	0.0098	1.29	0.0215*
Labor	0.5151	0.2421	29.74	0.0000***
Scrap Blanket	0.0025	0.0563	0.045	0.9640
Sigma(σ^2u+σ^2v)	0.2324	0.0495	0.7429	0.0038 **
Lambda λ ($\frac{\sigma^2 u}{\sigma^2 v}$)	2.2625	3.0456	4.6909	0.0968

*p<0.1, **p< 0.05, ***p<0.01.

(cricket weight) by 0.5151%. The higher elasticity of labor implied that its contribution to the total factor productivity was very vital compared to other inputs in this study. This is in consensus with the findings of Orinda et al. (2018) and Degefa et al. (2017) who also established that labour was the most limiting factor in cricket and tomato productions, respectively. Hired labor, which was considered in the study, has been associated with reduced efficiency (Okello et al., 2019). Use of hired labor requires close supervision or proper training to ensure quality and quantity work is done in the farm but supervision sometimes becomes difficult due to competition of different activities in the farm the farmer has to attend to hence this may reduce efficiency. Alternative type of labor such as off-farm labor or use of family labor should be encouraged in cricket production under similar technology. Shittu (2014) also noted that increasing off-farm labor supply increases efficiency of rural farm households. Automation of cricket production system or considering family labor may help enhance efficiency in cricket production.

Feed had the second highest coefficient of 0.36 implying that a 1% increase in feed, other factors held constant, would lead to 0.36% increase in cricket production. These findings are in line with those of Orinda et al. (2018) who also reported an inelastic, positive, significant estimate of 0.03% for feed in cricket production. Though a standard feed and optimal feeding regimes in cricket production are still lacking, feed remains essential factor in development and growth of insects since it generates energy essential for metabolic activities (Offor, 2010). However, this finding differed with the results of Ogunniyi et al. (2014) who observed a negative coefficients between feed input and production of poultry and pig.

Water experienced elasticity of 0.1126% which means that a 1% increase in water would lead to 0.1126% increase in cricket production. Normally, water helps in maintaining the physiological state conducive for the insect growth (McCluney and Date, 2008). This could explain its significance in improving cricket production. This is in consensus with the findings of Bravo-Ureta et al. (2015) who reported water as very essential in improving farm productivity.

While holding other inputs constant, a 1% increase in scrap blanket would result in 0.0025% increase in cricket production. Crickets in this study used scrap blanket as the main substrate source of water for drinking. This was the first study to the best of our knowledge to test on the effectiveness and efficiency of scrap blanket for water provision in rearing the crickets. Unlike cotton wool which has been commonly used, scrap blankets are more durable, cost-effective and can be recycled. It retains water for quite some time comparable to cotton wool and our preliminary farm observation showed it is a good media for cricket oviposition as well. There is need to compare laying capacity and hatching rates when blankets are used in cricket production in relation to other forms of substrates. There was a positive effect and significance of blanket media on improving cricket production. This was unlike the findings of Orinda et al. (2018) who reported negative influence of cotton wool on cricket production. This study findings thus postulates that scrap blanket would not just be an alternative cheaper resource for drinking and laying for crickets but an effective resource important in increasing the cricket productivity. Proper documentation on policy implementation strategies encouraging use of such waste materials in insect production is therefore necessary for sustainable utilization.

The sum of partial elasticities (function coefficients) was 0.9902 suggesting decreasing returns to scale. This means that an increase of one unit of production causes a less than proportional increase in weight of cricket production. The estimate however is close to one, which is the rational production stage.

According to Ferrara (2020), the lambda parameter is an indicator of relative variability of two sources of error. If $\lambda \to 0$, the model excludes the presence of technical inefficiency. The result estimates lambda of 2.2625 showed that $\lambda \neq 0$ thus presence of technical inefficiency in the cricket production under improvised cage system. Similarly, the value of sigma squared (σ^2) for the cricket production frontier was 0.2324 which was different from

Table 3. Description of cost variables.

Variable	Mean	Std. dev.	Min.	Max.
Feed cost	8.27±0.39	2.11	5.23	11.67
Labor cost	261.86±13.04	71.45	177.23	373.88
Water cost	0.08±0.00	0.01	0.06	0.10
Scrap Blanket cost	5.58±0.24	1.31	4.29	6.86
Output	55.35±1.84	10.06	39.79	71.12

Table 4. GAM-SFA cost estimates for allocative efficiency.

Variable	Estimate	Std Error	*t*-value	*Pr*(>|t|)
Intercept	1.9174	0.0776	24.686	0.0000***
Feed price	0.7687	0.1904	14.540	0.0000***
Water price	0.1092	0.0036	1.285	0.0220**
Labor price	0.2572	0.6611	30.140	0.0000***
Blanket cost	0.0112	0.2462	-0.045	0.964
Sigma(σ^2u+σ^2v)	0.1162	0.0203	5.7256	0.0053**
Lambda λ ($\frac{\sigma^2 u}{\sigma^2 v}$)	2.2625	0.7019	3.2233	0.0000***

*p<0.1, ** p<0.05, ***p<0.01.

zero and significant at 5%. The significant value of the Sigma (σ^2u+σ^2v) indicates the goodness of fit and correctness of the specified assumption of the composite error terms.

Description of cost variables

Summary statistics of response and explanatory variables for allocative efficiency is presented in Table 3. The mean cost of feed, labor, water, and amount of scrap blanket used were 8.27±0.39, 261.86±13.04, 0.08±0.00 and 5.58±0.24 shillings, respectively. Maximum and minimum input costs of the feed, labor, water, and amount of scrap blanket were 5.23, 177.23, 0.06, 4.29 and 11.67, 373.88, 0.10, 6.86, respectively. Subsequently, the mean for total variable cost of production was observed as 55.35±1.84 while the minimum and maximum total cost of production recorded were KES. 39.79 and KES. 71.12, respectively.

The estimation of GAM Stochastic Cost Frontier results presented in Table 4 revealed that all the coefficients of explanatory variables were positive hence conform to a priori expectation and were significant at 0.1 and 5% except for the blanket cost.

Feed had the highest price elasticity of 0.7687 hence a 1% increase in price of feed, *ceteris paribus*, would increase the total cost of production by 0.7687%. This means that feed price is the highest contributing factor to the cost of cricket production. The findings are in agreement with those of Okello et al. (2019) who in determining farm level allocative efficiency in dairy production observed that cost of feed was the main contributor to the overall cost of production. Chicken growers mash was used in feeding crickets since previous studies have showed its better performance in cricket production compared to other feeds (Bawa et al., 2020; Orinda et al., 2017; Sorjonen et al., 2019). It is important to consider alternative cheaper source of feed for crickets which can equally perform well in the production.

The price elasticity of labor was 0.2572, therefore a 1% increase in price of labor, *ceteris paribus*, would result in an increase in cost of production by 0.2572%. This is consistent with the findings of Gebretsadik (2017) and Okello et al. (2019) who also reported that increase in cost of labor increased the cost of production in sesame and rice production by 0.021 and 0.503%, respectively. Labor was computed in terms of man-hours per day (1 day=8 h) whereby the cost of hired labor was estimated based on the daily average wage rate of Ksh.349.50 applied for semi-skilled casual labourers in the study area. This could explain its highest contribution to the total production cost. However, the results are inconsistent with the findings of Maina et al. (2018) who observed that an increase in labor price would result in reduction in production cost. For small scale cricket farmers, it could therefore be more reasonable to use the family labour instead of hired labour to reduce the cost of production and maximize the returns.

Water had a price elasticity of 0.1092, hence an increase in price of water by 1% would increase the cost of production by 0.1092%, other factors held constant. Unlike major conventional livestock, insects generally consume little water thus low water footprint in cricket production (Huis, 2013). Further, quantities of water required for cricket production are meagre and therefore readily available and inexpensive.

The price elasticity for scrap blanket was 0.0112, implying that an increase in price of scrap blanket by 1% would increase the production cost by 0.0112%, *ceteris paribus*. Scrap blankets are readily available in many households and instead of being disposed can be utilized in cricket production due to their softness, durability and water retention capacity thereby reducing production cost of crickets in comparison to cotton wool. Further, blankets are reusable and can just be cleaned once a week, though this may depend with the stocking capacity. Blanket substrate is also not as susceptible to moulds as is with moist cotton wool. The scrap blanket cost used in the study was determined through estimation of their depreciation costs over the years that they were purchased.

The value of lambda estimates of 2.2625 was different from zero thus presence of allocative inefficiency in the cricket production under this system. According to Lema et al. (2016), lambda estimate greater than one shows that the one sided error term (*u)* dominates the random error (*v*) This therefore means that most of the variations in cricket output are as a result of farmers' practices and not random variability. Similarly, the value of sigma squared (σ^2) for the cost frontier was 0.1162 which was different from zero and significant at 5%. The significant value of the Sigma (σ^2u+σ^2v) indicates the goodness of fit and correctness of the specified assumption of the composite error terms.

Distribution of efficiency scores

The technical efficiency (TE) obtained from GAM production function model using Stochastic Frontier Approach revealed that the level of TE of cages (individual farmers) ranges from 0.65 to 0.96 and exhibited an average of 0.85. This indicates that the least producing cage (individual farmer) operates at 65% while the best practicing farmer operates at 96% and that an average farmer experienced 85% of cricket production under existing technology. The mean TE suggests that, if individual farmers operated at full efficiency level, they would increase their output by 15% using the existing resources and same level of technology. Individual household farms can decrease their inputs by 15% to get the output they are currently getting. Further, if an average farmer was to achieve a technical efficient level of its most efficient counterpart, then the average farmer could realize 23.5% of output derived from {1-(0.65/0.85) × 100%} by improving technical efficiency under the existing technology. These results are consistent with the findings of Degefa et al. (2017) and Maina et al. (2018) who recorded a mean technical efficiency of 82.93 and 83.7% in maize and milk production, respectively. However, the mean TE in this study is higher compared to a mean of 73, 78.8, 62.3 and 59% realized in previous studies estimating technical efficiencies in both crop and animal productions as reported by Abate et al. (2019), Debebe et al. (2015), Kamau (2019), and Masuku et al. (2014), correspondingly.

The allocative efficiency (AE) obtained from GAM production function model showed that the level of AE of individual farmers (cages) ranges from 0.79 to 0.98 with an average of 0.92, suggesting that an average farmer incurs 92% of AE in cricket production under the present technology. This high AE is in line with the general view that resource-poor farmers are highly efficient in allocating the limited financial resources at their disposal (Mutoko, 2015). The mean AE shows that on average, the household farms could increase the cricket output by 8%, if they used the right inputs and produced the right quantity relative to input costs and output price. Average farm would save a cost of 6.12% if it were to operate at the same level with the most allocatively efficient farm [1-(92/98) × 100%], whereas the most allocatively inefficient farm would save a cost of 19.4% derived from {1-(0.79/0.98) × 100%} by operating at the level of the most efficient farm. Therefore, in short run, it is possible to reduce the production cost in cricket production in the study area by embracing the current technology. These observations are in line with the findings of Maina et al. (2018) and Gebretsadik (2017) who reported a mean AE of 91.32 and 89.88% in dairy and sesame production, respectively. These results are inconsistent with the previous findings of 57.1, 67.17 and 72% reported by Debebe et al. (2015); Degefa et al. (2017) and Kamau (2019), respectively.

In order to obtain the economic efficiency, the production and cost functions were first run and farm-specific production and cost efficiencies were generated. Economic efficiency was then generated as the product of production and cost efficiency scores (Table 5). The economic efficiency scores range from 0.50 to 0.94 with a mean economic efficiency of 0.79. This means that the cricket farm under this technology is less efficient, thus there is a 21% potential for the farm to increase its economic efficiency. It would be essential to assess the farm specific factors influencing the efficiency and improve management practices. It can be inferred that if an average cricket farm is to attain the level of economic efficiency observed by the most efficient farm, then they would realize a saving of 37 % [(1-(0.5/0.79) × 100] in terms of total production costs while maximizing their cricket productivity. This implied that economic efficiency could be improved significantly than both technical and allocative efficiency. The findings also reveal that there is a narrow gap between the least economically efficient and the most economically efficient cricket farm. These

Table 5. Summary of efficiency distribution.

Variable	Technical Efficiency		Allocative Efficiency		Economic Efficiency	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
≤0.75	0	0	0	0	2	33.3
0.76-0.80	0	0	0	0	2	33.3
0.81-0.85	4	66.7	0	0	2	33.3
0.86-0.90	2	33.3	1	16.7	0	0
0.91- 0.95	0	0	5	83.3	0	0
≥ 0.96	0	0	0	0	0	0
Max.	0.8899		0.9346		0.8398	
Min.	0.8131		0.8993		0.7389	
Mean	0.8486		0.9146		0.7847	

findings are in agreement with those of Masuku et al. (2014) who also reported an average of 79.8% when determining EE of smallholder dairy farmers in Swaziland. However, the results differ significantly with those reported by Debebe et al. (2015), Gebretsadik (2017) and Maina et al. (2018). Debebe et al. (2015) reported average EE of 39% with efficiency scores of 0.041 to 0.837 among maize farmers which significantly differ from that recorded in this study. Maina et al. (2018) and Gebretsadik (2017) also reported a mean EE of 62.62 and 64.58% in milk and sesame productions, with efficiency scores of 31.19-94.89 and 22.37-92.76, respectively. These variances could be as a result of different enterprises and corresponding technologies under consideration.

The model output insinuated that the cricket farm using current technology is not fully efficient. These results of efficiency estimates corroborate previous findings that show that farmers do not attain maximum efficiency (Okello et al., 2019). This is majorly attributed to farmers' practices. Further studies should focus on farm management practices and determinants of efficiency that would further help improve economic efficiency of cricket farming. However, it is important to note that cricket farming under this technology is highly efficient (over 70%) and hence ideal for resource-poor farmers who should get encouraged to adopt this technology and undertake the cricket production in order to improve their food security status in the study region.

CONCLUSION AND RECOMMENDATIONS

The main purpose for this study was to assess the farm level economic efficiency of cricket production reared under improvised cage system. There are a number of studies that have done TE, AE and EE in developing countries especially in crop and animal production. However, to the best of authors' knowledge, no study has been carried out on TE, AE, and EE estimation of cricket production raised on such technology using GAM Stochastic Frontier Model. Therefore, this was an exploratory study to diversify scope of resources used in cricket production for increased adoption and utilization of crickets for food security and healthy living.

It was established that the farm-level cricket production was not fully efficient and there is still room to increase production and productivity and reduce cost of production. The maximum likelihood estimate of GAM Stochastic frontier model showed that feed, labor and water were positive and significant at 1, 5, and 10% level suggesting their importance and positive influence on cricket output while scrap blanket was positive but non-significant. Similarly, the cost of feed, labor, water and scrap blanket were positive and significant implying that increase in these cost of inputs would increase the total production cost.

The mean TE, AE and EE were 85, 92 and 79%, respectively showing that there is still potential to increase cricket production under similar technology in the region. Improvised cage system has great potential in increasing the cricket production. Comparative analysis of efficiency estimates with the conventional systems is necessary for exhaustive conclusion.

Assessing key determinants of economic efficiency in cricket production under similar technology is recommended to evaluate the factors influencing efficiency in cricket production.

Policies promoting use of natural resources such as bamboo available for most farmers including those in climate harsh areas should be established. Similarly, government and non-governmental organizations focusing on promoting food security should sensitize farmers to adopt climate smart and nutrition-sensitive food products such as crickets to cushion themselves against the effects of food-shortages and malnutrition especially in the wake of Covid-19 Pandemic.

SUGGESTIONS FOR FURTHER STUDIES

The study was conducted at one farm on an experimental basis and adopted time series data that could be prone to fluctuations of weather pattern within the production period in the study area. GAM-SFA model used for this study decomposes the random error and inefficiency error terms hence the fluctuations were to be corrected by the model. Further, the study was limited to the two species of crickets, *A. domesticus* and *G. bimaculatus* hence could not be used to generalize efficiency levels among all cricket species. Further research should focus on cross-sectional survey of cricket farmers' economic efficiency to validate the findings of this study.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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