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Are Chilimira Fishers of *Engraulicypris sardella* (*Günther*, 1868) in Lake Malawi Productive? The Case of Nkhotakota District

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Abstract: An ecological shift has populated *Engraulicypris sardella* as a livelihood and economic drive among fishers in Malawi. However, the paucity of biological information regarding *E. sardella* limits the effective monitoring and sustainable management of the fishery. This has created a heavily invested fishery in terms of the effort put into fishing, but it is poorly managed. Moreover, the current production capacity from the fishery has a negligible impact on lessening the shortfall of the national fish demand, indicating its underperformance. Therefore, the productive efficiency of Lake Malawi Chilimira fishers in exploiting *E. sardella* was analysed. A multi-stage sampling technique was used to sample 355 Chilimira fishers between July and October 2021. Results from the translog stochastic frontier model revealed that Chilimira fishers had an overall mean technical efficiency of 60% that ranged between 21% and 92%. This indicates that Chilimira fishers are 40% technically inefficient in exploiting *E. sardella*. The fishing inputs of bunt area, light emitting diode (LED) bulbs, and mesh size significantly contributed to technical efficiency, whereas boat size, fishing depth, number of hauls, and mosquito net lining significantly reduced the technical inefficiency. On average, the Chilimira fishery is operating with increasing returns to scale with bunt area, the quantity of fuel (litres), and the number of LED bulbs having positive input–output elasticity. This means that new developments in the fishery, including LED bulbs, increased bunt area, and boat size, are key factors that will improve fishing efficiency for sustainable fishery exploitation. In contrast, illegal fishing units of small bunt mesh size and mosquito net lining at the bunt threaten the sustainability of the fishery. It is, therefore, important that relevant stakeholders put policy measures in place that promote sustainable fishing effort approaches in exploiting the virgin offshore fishery to maximise catch.

Keywords: Chilimira net; *Engraulicypris sardella*; technical efficiency; Lake Malawi; Southeast Africa; fisheries management

Citation: Simfukwe, K.; Limuwa, M.M.; Njaya, F. Are Chilimira Fishers of *Engraulicypris sardella* (*Günther*, 1868) in Lake Malawi Productive? The Case of Nkhotakota District. *Sustainability* **2022**, *14*, 16018. https://doi.org/10.3390/su142316018

Academic Editors: Juan Rengifo-Gallego, Javier Pérez-González and Sebastián J. Hidalgo-de-Trucios

Received: 10 October 2022
Accepted: 8 November 2022
Published: 30 November 2022

1. Introduction

Recent trends in global capture fisheries indicate the increasing total catches of fish species [1]; however, individual fish weight and length have declined [2]. This corroborates the drastic decline of high-valued fish species and the rise of small-sized species [1,3]. The manifestation of small-sized species indicates a reduced trophic level of fish assemblage in the ecosystem caused by increased fishing pressure [2,4], among other factors. This picture describes Lake Malawi's fishing ecosystem in Southeast Africa, where small-sized *Engraulicypris sardella* (Usipa) species have replaced the high-valued *Oreochromis spp*. (Chambo) fishery [5–7]. For instance, species biomass has reduced by 35.5% while the annual catch rate has increased by 240% from 2007 to 2021 [8,9]. The annual catch landings from *E. sardella* have significantly contributed to no less than 58% of the total catch for the past decade [3,5,6].

The surge of *E. sardella* in Malawian waters has re-energized the role of artisanal fisheries in socio-economic bonding, nutritional improvement, and poverty reduction [3,6,10].

Moreover, it has also provided rural areas with a cheap animal protein source [3,10,11]. However, the 2.8% annual human population growth rate [12] has increased the demand for fish [6,13]. This has limited the capacity of the fisheries to meet the fish demand, resulting in reduced per capita fish consumption. For example, per capita fish consumption has decreased by 32% from 14 kg in the 1970s to around 9.6 kg/person/year in 2020 [6].

Although several factors exacerbate the poor performance of the artisanal fisheries in Malawi, the impacts associated with fishers' best allocation of inputs to maximise output are overlooked. In this case, efficiency studies are critical for performance improvement and expanding the resource base or developing new technologies. Productive efficiency involves identifying and using the best combination of inputs that maximise output sustainably from the current level of production [14–19]. Technical, allocative, and economic efficiency are the established approaches used to measure productive efficiency in fisheries science [14–26]. However, for this subject, a technical efficiency approach has been used to analyse fisheries' productive efficiency.

Technical efficiency involves using a fixed level of fishing effort (inputs) and technology to measure and improve productive performance [14,16,19,21,23,27,28]. A method is an important tool for providing a sustainable level of inclusion for the perceived effective fishing methods in the *E. sardella* fishery. It also analyses the inclusion of technological and managerial sustainable practices in fishing [15,25,28,29].

Nonetheless, *E. sardella* fishery growth has seen a marked increase in innovative fishing methods and a lack of management approaches, which limits its sustainability. For instance, ref. [30] reported that the catch level for *E. sardella* fishery was above the biological reference point (maximum sustainable yield (MSY)). Fishing factors, such as fishing experience, changes in fishing grounds, and the modification of Chilimira gear, were identified as major driving factors for improved catch rates [30]. However, the study did not specify the influence of each factor on fishing efficiency improvement. Furthermore, *E. sardella* is dominantly fished using Chilimira gear and uses light technology through night fishing to tap the resource [3,30–34]. It has been intensively modified over the last decade, especially its design, vessel size, and type of light source, in response to changes in fishing location and reduced catch rates [5,10,30,32,35]. However, little is known about how innovative fishing inputs affect *E. sardella* fishery, which has resulted in a debate on their use in fisheries.

This lack of knowledge is further exacerbated by open access to the Malawi fisheries, which makes it difficult for fisheries' managers to control the proliferation of fishing efforts in the fisheries [5,36–40]. Furthermore, the paucity of biological information about the fishery structure and its growth characteristics have limited the efforts made to manage the fisheries [30,31,34]. However, in many cases, the overcapacity of the fishing efforts in fisheries results in the collapse of the fishery, for example, the Chambo fishery in Lake Malawi [4,7,41,42] and Lake Malombe [4,7,41,43], the *Diplotaxodon* fishery in Lake Malawi [44], and the Nile Perch fishery in Lake Victoria [45]. Hence, fishery assessment and performance studies are important.

The dominance of *E. sardella* in the catch [3,5,6] attracts attention for species assessment, monitoring, and management for sustainable utilisation. Hence, this study was conducted to understand the sustainable performance of the fishery using econometric approaches, which are key for policy interventions and guidance. Econometric efficiency analysis provides an optimum level of resource exploitation based on the existing capacity of the available scarce resources. The provision of knowledge on input usage is key for the government and relevant stakeholders in fisheries choosing efficient fishing methods for policy interventions and sustainable resource utilisation. The study is also key in supporting governments' overarching efforts to improve fisheries productivity for improved socio-economic and nutritional factors [5]. In addition, the study also plays a key role in informing relevant stakeholders about available options to manage the fishery for sustainable exploitation.

Therefore, it can be said that assessing the technical efficiency of the Chilimira net fishing vessels could be interesting for both research and managerial purposes. Both the government and development partners, as well as the fishers, are concerned with the selection of efficient technology, as well as the allocation and levels of input that will produce the best sustainable output. The technical efficiency of Chilimira fishers in *E. sardella* exploitation was analysed based on the following research questions: (a) What is the technical efficiency level of the Chilimira net in *E. sardella* fishing? (b) What are the main factors affecting the technical efficiency change in the Chilimira net? (c) How has the Chilimira net technology change affected technical efficiency? (d) Would the Chilimira net be subject to increasing returns to scale?

2. Data and Methods

2.1. Study Area

The study was conducted in the central littoral zone of Lake Malawi in the Nkhotakota district (Figure 1), which is located between the Geographical Positioning System (GPS) of 12°26′40.8″ S 34°10′38.4″ E and 13°21′34.8″ S 34°17′54.3″ E. The district has a land area of 4338 square kilometres with a population of 393,077 people in which 51% are female [12]. Only 6% of the land is available for people to use in agriculture [46] and shelter makes fishing an important livelihood source among many residents of the district [33]. In 2021, fishing in Nkhotakota contributed to 18% of total landed fish catches and 20% of total *E. sardella* production [33].

The Nkhotakota fisheries are characterized by multiple fishing vessels, multiple fish species, and technology change, although the fisheries' activities are dominated by *E. sardella* fishery [33]. The district has 13%, 14%, 26%, 12%, 12%, and 12% of Chilimira gears, boats with engines, planked canoes, gear owners, crew members, and LED bulbs in Lake Malawi, respectively [6,33]. This provides a basis to analyse technical efficiency in the district.

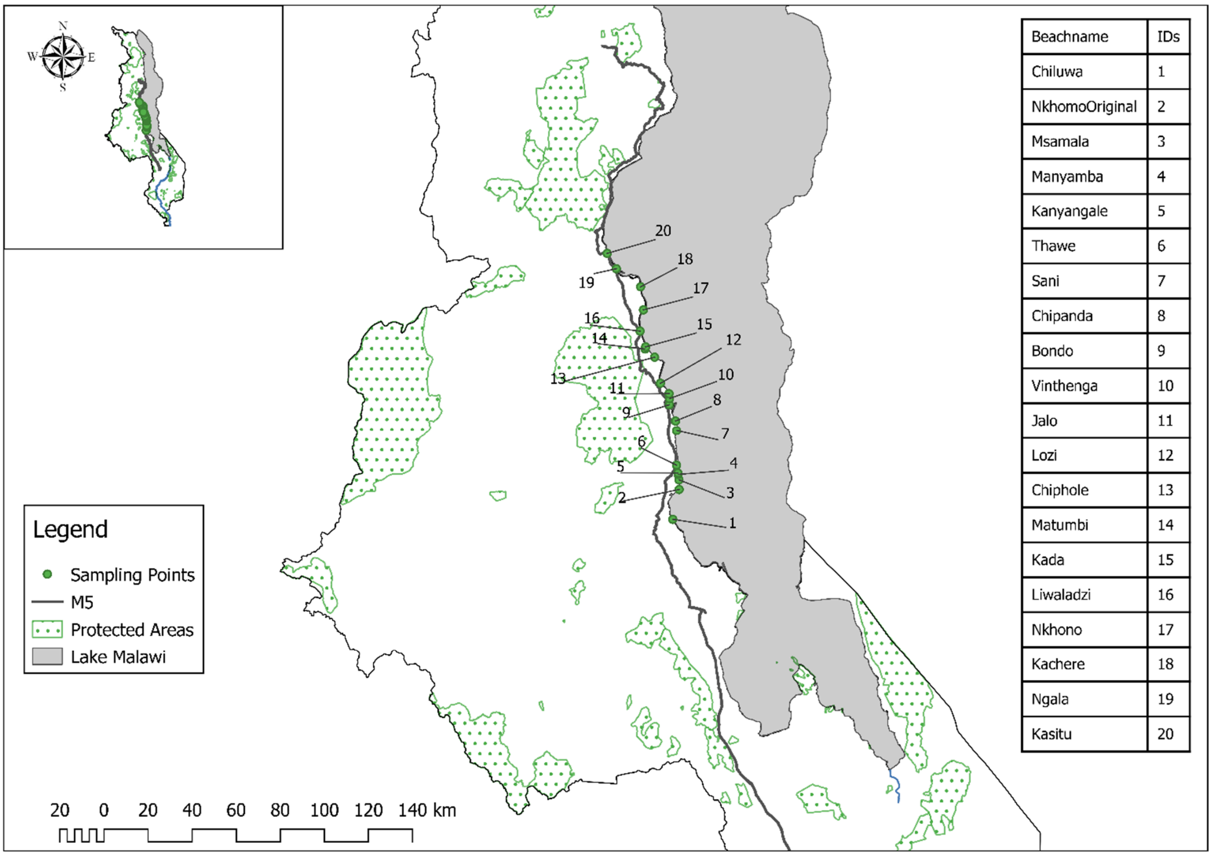

Figure 1. Map of Nkhotakota district showing study sites.

2.2. Sampling and Data Collection Procedure

The study employed a multi-stage sampling technique in the sampling of strata, beaches, and fishers between July and October 2021. Consultation and planning meetings with Nkhotakota District Fisheries Office and Beach Village Committees (BVC) played a key role in selecting four strata and twenty beaches active in *E. sardella* production. The following strata and beaches were sampled: stratum 5.1 (Chiluwa, Nkhomo Original, Msamala, Manyamba, Kanyangale, and Thawe), stratum 5.3 (Sani, Chipanda, Bondo, Vinthenga, Jalo, and Lozi), stratum 5.4 (Chiphole, Matumbi, Kada, Liwaladzi, Nkhono, and Kachere), and stratum 5.5 (Ngala and Kasitu) (Figure 1).

A total of 355 Chilimira fishers were randomly sampled from the 20 sampling beaches. The household semi-structured questionnaire was used to collect quantitative data, which included catch output; physical inputs of gear-specific details (gear area, bunt area, and mesh size); vessel-specific details (boat size, type of boat used, and vessel age), lighting technology (number of LED bulbs and battery used), number of signala (skippers) used, fishing depth, mosquito net lining area, fuel and oil usage, engine ownership and size, number of paddles, and labour for *E. sardella* production. Labour was calculated as the product of hours spent in fishing and crew member size [47], while output was calculated as catch weight for each trip made by the fishers. Furthermore, other factors that helped to describe individual characteristics, such as years spent in fishing, education level, age, household size, household income, role in the fishery, and gender were also captured.

3. Theory and Calculations

3.1. The Chilimira Gear of Lake Malawi

The present significance of artisanal fisheries from Lake Malawi rests heavily on the Chilimira fishing gear. The gear's popularity and significance have been exacerbated by the effects of trophic cascade and ecological shift that have resulted in the dominance of *E. sardella* catches. The gear design of conical appearance (Figure 2) and active pelagic gear [3,30,32,48] well suits the biology of *E. sardella* fish species. Further, the species' phototaxis biological behaviour has been assimilated by using the gear at night with the help of lighting technology [3,30,34,35]. Ref. [43] described Chilimira gear as important gear that is adaptative and responsive to catching the most profitable species at a given time, which drives people's livelihoods and fish business. For instance, the gear has been previously used to catch *Oreochromis* spp. (Chambo) and *Copadochromis* spp. (Utaka) [3,7,32,43]. Of late, fishing with Chilimira gear has been intensively modified to suit the *E. sardella* fishery and consists of 83% of open water seine nets [33]. For instance, the gear headline length has been adjusted to above 100 m from the below 70 m [35], the bunt area has been increased, the mesh size at the bunt has been reduced, the bunt has been lined with mosquito net, and there is an increase in light and vessel technology [10,32,33]. The cases of small mesh sizes at the bunt (6 mm and 8 mm) and the implantation of the mosquito nets are assumed to increase the efficiency of the gear by exploiting even small-sized *E. sardella* species (locally known as Bonya) [30], which threaten the fishery sustainability in the long run from the effects of growth overfishing. In addition, other investments in light, gear, and boat technology also improved fishing approaches to the *E. sardella* fishery with Chilimira net. This summarizes the modified multi-input Chilimira fishery that provides a basis for understanding the influence of gear modification on the productive efficiency of species exploitation for sustainable fishing.

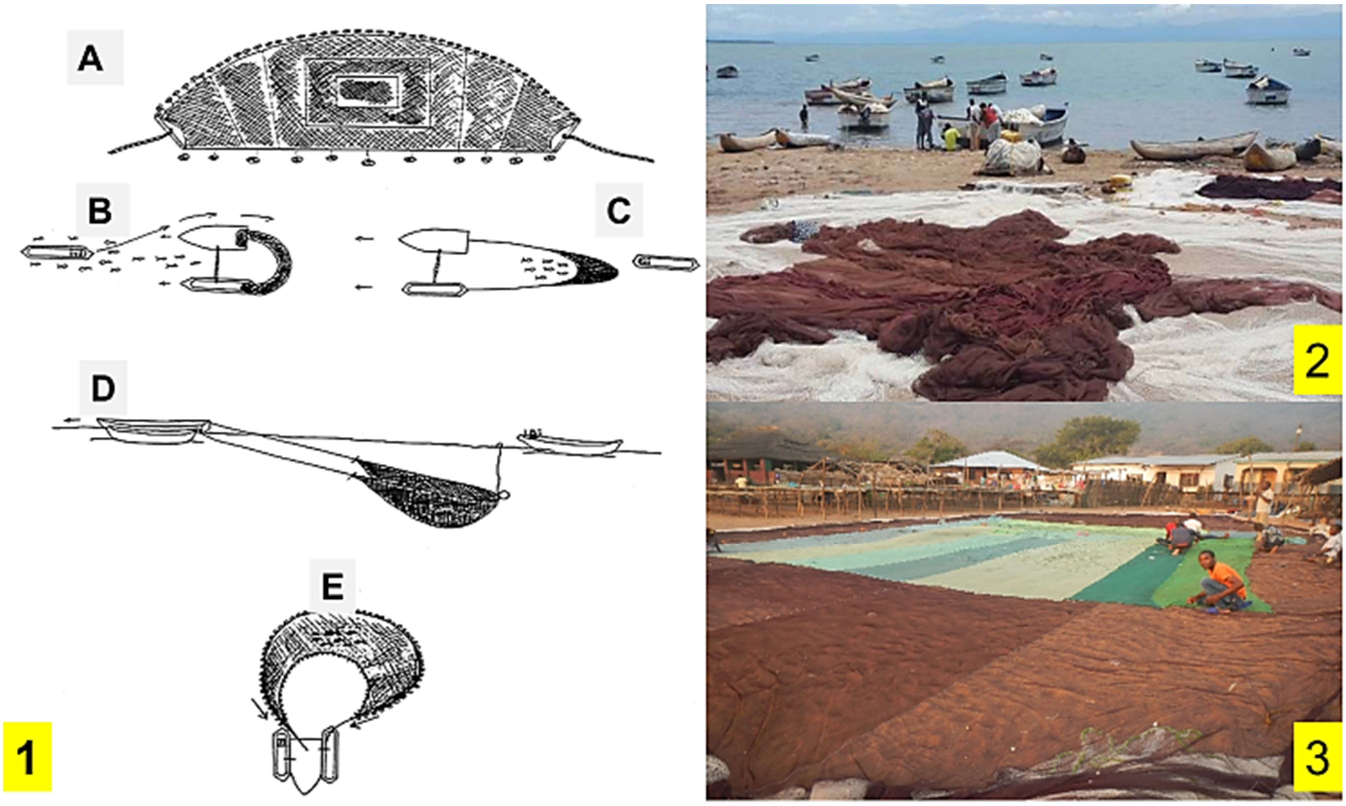

Figure 2. The Chilimira gear of Lake Malawi used for E. sardella fishing with (**1**) showing the 3D gear shape and how it works i.e., with (**A**) indicating 3D shape of Chilimira and (**B**–**E**) indicating the gear in operation (Source [48]), (**2**) showing the gear bunt, and (**3**) showing the mosquito net lining at the bunt.

3.2. Theoretical Framework

The fisher allocation of fishing effort and harvesting strategy aims to improve fishing efficiency in achieving the highest yield or operating at maximum fishing capacity [18,19,21,25]. The measurement of the maximum capacity of fishing is dependent on performance benchmarks, where the current effort in fishing can be compared [15,18]. Production frontier estimates compare the relationship between maximum potential outputs from the effort exerted, where the difference is counted as the inefficiency level of the fishery [14–16,18–20,25,29]. The observed effort use (input) and output attained are used in estimating a fishery's productive efficiency [14–16,20–22,47,49–51]. Therefore, productive efficiency provides a comparison between observed and frontier values of its input and output, which gives a picture of how to increase fishing input to attain frontier output [14,16–18,22,25].

The measurement of fisheries' productive performance can be modelled either using technical efficiency (TE), allocative efficiency (AE), or economic efficiency (EE) [14,18,20,22,23,25,29,47,49,50]. Both TE and AE aim to maximise output through the best combination of inputs (optimal level) that minimise input waste. However, they are different in that AE maximises output by combining the best inputs for their prices and technology use [16,23,52]. On the other hand, TE assembles the optimal level of raw inputs, which reduces input wastage, i.e., maximises output from the best input combination such that any increase in input is associated with wastage or does not contribute to the increase in output. It measures how firms (Chilimira fishers) can successfully maximize output from the given set of inputs used in the fishery [53]. When a fishery best combines inputs to maximise outputs, it is said to be operating at the production frontier, and hence is technically efficient and sustainable in the long run [16,18,19,27]. In contrast, technically inefficient fisheries fails to operate at the frontier line by not realizing maximum output from the available input combination [16,18,19,23,26,27]; thus, it uses more or fewer inputs for the fishery. The product of technical efficiency and allocative efficiency yields economic efficiency [18,23,54,55]. The concept of efficiency in the fishery is of great significance to fishers, which mainly aims to sustainably maximise catches from the fishing effort. Traditionally, fishers maximize catches through the behaviour of cost minimization and technological adoption.

3.3. Stochastic Frontier Analysis

Therefore, this study employed the stochastic frontier production function for cross-sectional data specified by [56]. The model is preferable due to its responsiveness to inherent stochasticity and individual luck during fishing. The stochastic function form is expressed as follows:

$$Y_i = f(x_i\beta)e^{\varepsilon}\ i = 1, 2, 3 \ldots ..n \quad (1)$$

where Y_i= quantity of *E. sardella* catch (kg) for *ith* fisher, x_i = vector of fishing inputs, β = vector of unknown parameters, and ε_i = error term.

The stochastic production frontier has composed the error term, which is specified as:

$$\varepsilon_i = v_i - u_i \ldots \ldots \quad (2)$$

where v_i is the statistical noise that accounts for stochastic effects that are beyond the Chilimira fisher's control, such as weather, unexpected waves, *Mwera*, etc. The variable takes either a positive or negative sign and it is assumed to be independent of u_i and x_i and it is identically distributed with $N\left(0, \sigma_V^2\right)$.

On the other hand, u_i is a positive variable that signifies specific factors that limit Chilimira fishers not reaching the deterministic frontier level, i.e., technical inefficiency factors. The random error was assumed to be distributed as a truncated normal distribution, with a mean (u_i) and variance $N\left(0, \sigma_u^2\right)$ [57]. The inefficiency error term was expressed as:

$$u_i = \alpha_i Z_i + \omega_i \quad (3)$$

where Z_i is the vector of explanatory variables, α_i is the unknown coefficient of vectors parameters to be estimated, ω_i is the random error term that is defined by the truncation of the normal distribution with zero mean and variance, σ_u^2, such that the point of truncation is $-Z_i^\delta$, i.e., $\omega_i \geq -Z_i^\delta$.

The parameters for the random variables in Equation (2), v_i, and u_i were simultaneously estimated using maximum likelihood estimation (MLE), as proposed by [58]. The random variables v_i and u_i are assumed to be independent of each other [16,18,23,58]. The ML provides estimates of β and the gamma. The deviation of the total output from the frontier output is explained by the γ variable, which is expressed as follows:

$$\sigma_s^2 = \sigma_v^2 + \sigma_u^2; \gamma = \frac{\sigma_u^2}{\sigma_s^2}\ and\ 0 \leq \gamma \leq 1 \quad (4)$$

The value of gamma (γ) lies between 0 and 1 to indicate the variation in output from the frontier line due to technical inefficiency. A value closer to 1 indicates that the inefficiency of the Chilimira fisher has a higher contribution to the fishery inefficiency level and less is contributed by random errors associated with fishing.

The technical efficiency for the *ith* fisher is calculated by taking ratios of the observed output to the corresponding frontier output, as expressed below:

$$TE = \frac{Y_t}{Y_{max}} = \frac{\exp(\beta x_i + v_i - u_i)}{\exp(\beta x_i + v_i)} = \exp(-u) \quad (5)$$

where TE is the level of technical efficiency, Y_t is the observed output at time t, Y_{max} is the frontier output to be estimated, and β is the model coefficient parameter.

3.4. Measurement of Output for Technical Efficiency Analysis

The technical efficiency analysis for the parametric econometric model uses an input–output model involving multiple inputs and single output only [15,16,19,22,24]. The multispecies nature of tropical fisheries and the higher diversity of Lake Malawi [9,59] meant that Chilimira net is prone to retaining catches of multi-species, despite the gear design and target being specified for *E. sardella* [3,32,43]. Hence, encountered catches of different species s (s = 1 . . . S) were aggregated into *E. sardella* weighted catch using the formulae by [60], as specified below:

$$Y_j^{weight} = \sum_{S=1}^{S} Y_{j,s}^{weight} \tag{6}$$

where $Y,\ j, s$ measure the catch weight of species s for vessel j in period t.

3.5. Empirical Specification Model

The Cobb–Douglas and the transcendental logarithmic (translog) production functions are used in modelling fisheries' technical efficiency. The squared and cross-product terms imposed on translog functional form are removed from Cobb–Douglas functional form [16,18,19,21–23,29,50,61]. Hypothesis testing is used to choose between the models based on model fitting. For this study, the translog function was used to indicate input cross-product effects having a significant impact on the model parameters. The R frontier package [62] was used to estimate the translog production form, as specified below:

$$lnY_j = \beta_0 + \sum_{i=1}^{5} \beta_i lnx_{ij} + \frac{1}{2}\sum_{i=1}^{5}\sum_{k=1}^{5} x_{ik} lnx_{ij} * lnx_{ij} + v_j - u_j \tag{7}$$

where i and ln are the *ith* fisher and logarithm to base e, respectively; $Y =$ output expressed weighted catch of fish in kilograms; x_1 = labour, which was estimated by the product of crew members and hours spent fishing per fishing trip; x_2 = quantity of fuel (petrol) in litres used in each fishing trip by fishers; x_3 = the number of light-emitting diode (LED) bulbs mostly used by the fisher in each fishing trip; x_4 = the area of the bunt for the fisher's individual Chilimira net reported in square metres; x_5 = mesh size of the Chilimira net at the bunt; v = the stochastic error term, the two-sided error term (technical inefficiency); u denotes non-negative random variable associated with the fisher specific factors, which contribute to the fishers not achieving maximum efficiency.

The empirical model for the inefficiency was expressed as follows:

$$u_i = \alpha_0 + \sum_{i=1}^{9} \alpha_i Z_i + \omega_i \tag{8}$$

where u_i denotes inefficiency; α_i denotes the vector of parameters; Z_i are fishers or Chilimira net characteristics covering socio-economic factors and fisher, fish-specific, and fisheries management factors; ω_i indicates the error term.

3.6. Output Elasticities

Output elasticities computed from Equation (9) were used to measure how *E. sardella* catch rates respond to changes in the input used. In contrast to Cobb–Douglas stochastic frontier production function where the model coefficients are output elasticities, the marginal effect principle was used to estimate output elasticities for the translog model using the micEcon package in R [63]. It is expressed using the following formula:

$$\varepsilon_k = \frac{\partial \text{lny}}{\partial \ln x_i} = \beta_i + 2\beta_{ii} lnx + \sum_j \beta_{ij} lnx_j \tag{9}$$

The x' and y are input variables and output means, respectively, while ε_k measures how output changes with a 1% increase or decrease of k^{th} fishing inputs are used. The summation of all output elasticities gives the return to scale (RTS) [16,23], which shows how output responds to the proportional change in all inputs used. Estimates that are less, equal to, or greater than 1 represent the fisher has decreasing, constant, or increasing returns to scale, respectively.

3.7. Statement of Hypothesis

The model appropriateness for the study was based on three hypotheses, which include: the validation for the use of the translog model in frontier analysis, assessment of the presence of technical inefficiency, and assessment of the significance of inefficiency factors in explaining inefficiency among Chilimira fishers of Lake Malawi. The tested hypotheses are:

$$H_0 : \beta_{ij} = \beta_{ij} = 0 \quad (10)$$

The coefficients of the square values and the interaction terms in the translog model sum up to zero.

$$H_0 : \gamma = \delta_0 = \delta_1 \ldots .\delta_{12} = 0 \quad (11)$$

There are no inefficiency effects among Chilimira net fishers.

$$H_0 : \gamma = \delta_0 = \delta_1 \ldots .\delta_{12} = 0 \quad (12)$$

Fishing, socioeconomic, and other institutional factors included in the model are not responsible for the inefficiency term (u_i).

The above-mentioned hypothesis parameters were tested using the generalized likelihood-ratio statistics (λ), as specified below:

$$LR(\lambda) = -2[\{(lnL(H_0)\} - \{\ln L(H_1)\}] \quad (13)$$

where $L(H_0)$ denotes values of the likelihood function under the null hypothesis, and $L(H_1)$ denotes values of the likelihood function under the alternative hypothesis. The null hypothesis is accepted when the test statistic (λ) has a chi-square distribution with degrees of freedom equal to the difference between the estimated parameters under the H_1 and H_0 hypothesis, respectively.

4. Results and Discussion

4.1. Fishers' Demographic and Socio-Economic Characteristics

Fishers maximising their utility to efficiently exploit and manage the resource depends on the socio-economic characteristics summarised in Table 1. The average age of the fisher was 43.14 ± 11.26 years old. Fishing experience had a mean of 22.65 ± 11.62 years that ranged between 1 and 57 years. A minimum fishing experience of a year indicates that many people are still joining the fishery, which is still evolving as the main source of economic livelihood among lakeshore dwellers [3,6]. Fishing experience and age of the fisher had a correlation of 0.71, which was significant at alpha level 0.01 (p < 0.01). The fishery was dominated by males (95%) who are active in fish production as gear owners (94%), signala (100%), and crew members (100%), while there was passive involvement of women (6%) as gear owners. The harsh intensive night fishing activity [3,10], rough weather at the lake, and socio-cultural beliefs limit female participation in direct production activities in Chilimira fishing [64]. The average education level for Chilimira fishers was grade seven of primary educational level, and this was exacerbated by high school drop-out rates in lakeshore areas. On the other hand, Chilimira fishers had a mean household size of eight people. The gross household income was captured as a cumulative income from fishing and alternative economic activities. All the respondents had fishing as a primary economic activity; however, 48.3%, 25.2%, and 6.7% had farming, fish business (fish processing and trading), and petty business (groceries and other small business) as alternative economic activities. The gross average monthly household income level was MK 147,521.10 ± 80,021.50, (USD 174.58 ± 94.70), and a median income of MK 100,000

(USD 118.34). The fisher's gross income ranged between MK 5000 (USD 5.29) and MK 1,500,000 (USD 1775.15).

Table 1. Chilimira fisher's socioeconomic factors.

Socio-Economic Factors	Mean	Std. Dev	Median	Minimum	Maximum
Respondent age (Years)	43.14	11.26.	42.00	21.00	79.00
Fisher experience (Years)	22.65	11.62.	21.00	1.00	57.00
Education level (Years)	6.62	3.14	7.00	1.00	12.00
Household size	8.54	4.18	8.00	2.00	26.00
Household income (USD)	174.58	94.70	118.34	5.92	1775.15

4.2. Fisher and Fishing-Specific Factors

Table 2 shows summarised statistics for fisher and fishing variables used in the study. The mean catches per individual Chilimira gear per trip was 1074 ± 293.92 kg. The catch was attained by a Chilimira gear with an average head length and height of 101.62 ± 25.99 m and 52.73 ± 10.64 m, respectively. The average bunt area for the gear was 3696.04 ± 549.81 m^2. Mesh sizes used at the bunt were 6 mm (0.25 inch), 8 mm (0.32 inch), 10 mm (0.40 inch), and 12 mm (0.48 inch) in the proportions of 5.1%, 58.6%, 35.8%, and 0.6%, respectively. Refs. [35,65] also found a similar average head length of 107 m and 58% use nets with mesh sizes ranging from 0.25 to 1.75 inches from the study site. Futhermore, 25.6% of the fishers were implanting mosquito nets (MN) at the bunt. A proportion of 81.3%, 74.1%, and 100% of the fishers were using plank boats with engines (mean length 20.9 ft ± 2.24), planked canoes (mean length 14.3 ft ± 1.44), and dug-out canoes (mean length 8.5 ft ± 1.34) either as owned or rented, respectively. The multi-craft fisher used light emitting diode (LED) bulbs for night fishing that had a mean of five bulbs with a range of 2 to 12 LED per signala of a night trip fishing. On average, each Chilimira gear was using two signala and one acid lead N70 battery of 70 Ah capacity. The proportion of 81% of Chilimira fishers were using at least one petrol-operated engine having an average size of 15.2 ± 6.39 horsepower and consuming at least 24.1 ± 11.34 litres of petrol per trip. Furthermore, fishing with Chilimira gear was performed at fishing depths between 60 m and 300 m, which had a mean of 173.4 ± 53.56 m. On average, fishers were spending 13.0 h fishing, which is a slight increase from the 8 to 12 h reported by [65] and the 9 to 10 hours by [66]. Fishing with Chilimira gear involves nine crew members, which is a reflection of previous work [3,32,35,65,66]. The study also conducted interviews with gear owners (80%), signala (12%), and crew members (8%) that revealed that prominent experienced actors were triangulated to support the cross-sectional design approach and provide reliable information for the fishery in measuring technical efficiency.

Table 2. Summary of fisher and fishing characteristics for Chilimira fishery.

Fisher and Fishing Factors	Mean	Std. Dev	Minimum	Maximum
Fish output (kgs)	1074.03	293.92	120.00	4000.00
Chilimira Head length (m)	101.62	25.99	52.50	175.00
Chilimira Height (m)	49.86	10.60	22.00	96.00
Bunt area (m^2)	1352.99	549.81	256.00	3844.00
Mosquito Net (MN) area (m^2)	32.90	10.17	20.00	36.00
LED bulbs	4.52	1.78	2.00	12.00
Boat with engine size (ft)	20.91	2.24	17.00	26.00
Planked canoes size (ft)	14.29	1.44	12.00	21.00
Canoes size (ft)	8.44	1.32	5.00	12.00

Table 2. *Cont.*

Fisher and Fishing Factors	Mean	Std. Dev	Minimum	Maximum
Engine size (horsepower)	15.20	6.39	5.00	30.00
Fuel (litres)	24.09	11.34	10.00	50.00
Time spent fishing (Hours)	12.95	1.77.	7.50	16.00
Number of hauls per trip	6.92	2.51	2.00	15.00
Fishing depth (m)	173.59	53.56	60.00	300.00

4.3. Estimation of Technical Efficiency

4.3.1. Hypothesis Testing and Model Validity

Table 3 provides the results of the diagnostic tests for the hypothesis. The first hypothesis tested the null hypothesis of the suitability of the Cobb–Douglas function form, a model without a second-order coefficient of inputs, to estimate technical efficiency, which was rejected at a 1% level of significance ($p = 0.004$). This indicates that the translog function form fits the Chilimira fishery data better and was capable of producing more accurate results. The second null hypothesis tested whether the one-sided error inefficiency parameter (μ_i) was absent in the model $(\gamma = 0)$ and had no sufficient evidence at a 1% level of significance ($p < 0.01$). The last null hypothesis, $H_0 : \gamma = \delta_{ij} \ldots = \delta_{13} = 0$, tested whether technical inefficiency μ_i was independent of the 13 explanatory variables, which was rejected at alpha level 0.01 ($p < 0.01$). This ascertains that the 13 explanatory variables can be used to explain the one-sided error term μ_i.

Table 3. Likelihood ratio tests of stochastic production frontier parameters.

Null Hypothesis	X^2 Test Statistics	Df	$P > X^2$ Statistics	Decision
$H_0 = \beta_{ij} = 0$	35.98	15	0.00	Reject H_0 Translog is appropriate
$H_0 : \gamma = 0$	35.51	1	0.00	Reject H_0 Inefficiency effects are present
$H_0 : \gamma = \delta_{ij} \ldots = \delta_9 = 0$	69.76	13	0.00	Reject H_0 Socioeconomic and fisher-specific variables determine the inefficiency (U_i)

4.3.2. Diagnostic Tests

The stochastic translog model diagnostic test is summarised in Table 4. The model returned a Wald chi-square statistic of 141.56, which was significant at alpha level 0.01 ($p < 0.01$), meaning the model variables used are worthy of inclusion in the model. The goodness of fit or sigma squared (σ^2) value was significant at alpha level 0.01 ($p < 0.01$), indicating goodness of fit between Chilimira fishery data and the translog model. Lastly, the gamma (γ) or variation ratio that floats between 0 and 1, which is calculated as $\gamma = \sigma_\mu^2 / \left(\sigma_v^2 + \sigma_\mu^2\right) = \sigma_\mu^2 / \sigma_s^2$, had a value of 0.56, which was significant at alpha level 0.01 ($p < 0.01$. This means that socioeconomic and fishing-related factors statistically influenced the variation in the production frontier, compared to normal errors or luck in the fishery. Random errors from weather, resources, and the environment greatly manifest in fisheries [51]. Similarly, *E. sardella* has a complicated biological characteristic and its quantity of catch is responsive to climatic and environmental changes [3,30,31]. These jointly account for 44% of the technical inefficiency in this study.

4.3.3. Estimation of Parameters of the Stochastic Chilimira Production

Table 4 provides a summary of parameter estimation from translog stochastic analysis. The square and cross products from the translog analysis vindicate the continuous effect of using the fishing inputs and complementarity or substitutability on fishing inputs in the Chilimira fishery [16,18,19,21,22].

Table 4. Translog estimates for technical efficiency.

Variable	Parameter	Estimate	Std. Error	Z	Pr(>|z|)
Intercept	α	−17.40	25.03	−0.70	0.49
Bunt	β_1	3.87	2.72	1.42	0.09 *
Mesh	β_2	−7.68	8.67	−0.89	0.03 **
Fuel	β_3	0.50	0.77	0.65	0.52
Labour	β_4	2.10	7.09	0.30	0.77
LED	β_5	3.37	3.09	1.09	0.08 *
Bunt squared	β_{11}	−0.03	0.29	−0.11	0.91
Mesh squared	β_{22}	3.01	2.29	1.31	0.19
Fuel squared	β_{33}	0.30	0.10	3.15	0.00 ***
Labour squared	β_{44}	0.74	1.32	0.56	0.57
LED squared	β_{55}	−0.38	0.37	−1.02	0.31
Bunt × Mesh	β_{12}	−1.09	0.54	−2.01	0.04 **
Bunt × Fuel	β_{13}	0.00	0.06	0.06	0.95
Bunt × Labour	β_{14}	−0.32	0.40	−0.79	0.43
Bunt × LED	β_{15}	0.23	0.21	1.10	0.27
Mesh × Fuel	β_{23}	0.20	0.21	0.91	0.36
Mesh × Labour	β_{24}	−1.85	1.23	−1.50	0.13
Mesh × LED	β_{25}	0.21	0.67	0.31	0.76
Fuel × Labour	β_{34}	−0.23	0.14	−1.68	0.09 *
Fuel × LED	β_{35}	−0.12	0.09	−1.33	0.18
Labour × LED	β_{45}	0.57	0.46	1.25	0.21
Diagnostic statistics					
Lambda	λ	1.09	0.14	8.07	0.00 ***
Sigma Squared	$\sigma^2 = \sigma_v^2 + \sigma_\mu^2$	0.36	0.05	7.03	0.00 ***
Gamma	$\gamma = \frac{\sigma_\mu^2}{(\sigma_v^2+\sigma_\mu^2)}$	0.56	0.17	3.10	0.00 ***
Log likelihood function		−285.77 ***			
Likelihood-ratio test	$\lambda = -2\log[\mathrm{L}(H_1) - L(H_0)]$	31.78 ***			
Wald chi-square [20]		148.38 ***			
Observations	N	355			

Notes: Single, double, and triple asterisks (*) indicate value significance at * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$ levels, respectively.

The coefficients for the bunt area and LED bulbs were positive and significantly increased by the technical efficiency indices ($p < 0.1$), while mesh size had negative coefficients that significantly reduced technical efficiency indices ($p < 0.05$). This suggests that fishers that use larger bunt surface area are more efficient as it provides a better fishing base for the offshore fishery that has untapped 30,000 tonnes$^{-\mathrm{yr}}$ of fish species [5,35,67,68]. Similarly, fishers using more than four LED bulbs increased fishing efficiency because it increases the illuminating strength to attract more fish species, and also LED bulbs provide a better platform for offshore fishing [33,35,69]. On the contrary, fishing efficiency decreases with larger mesh size as they are more selective [36,65,70]. The efficiency of small-size nets means there is increased use of unsustainable fishing gears [10,36,38,39,65,70,71], indicating an overfished unsustainable fishery resource that responds to the decline of the large-sized fish species [10,41,65,72]. On the other hand, the positive coefficients of the quantity of fuel and labour did not significantly influence fishers' efficiency. The insignificant fuel quantity can be attributed to an increase in small-sized *E. sardella (Bonya)* that were fished in relatively inshore waters [30,31,34,65]. This contrasts with findings by [15,19,21] who found that fuel quantity increased fish efficiency and catch rates. Similarly, the insignificant labour variable, which was captured as the product of crew size and time spent fishing [47], means the current quantity of the crew size and fishing time spent on Chilimira does not maximise catch rates, i.e., more than the required crew size, and time spent fishing is not relevant in Chilimira catch rates. This supports the claim that the *E. sardella* fishery is a reliable employment provider among people along the lakeshore for improving their socio-economic status.

4.3.4. Technical Efficiency for Chilimira Fishery

The mean technical efficiency score was 0.60 ± 0.19 and ranged between 0.20 and 0.92. This means that Chilimira fishers have the potential to improve production by 0.4 from the efficient use of available fishing inputs. Improving production up to 100% will ensure maximum performance of the fishery that is exploited sustainably, as productive efficiency analysis in fisheries is based on the current stock size and health. The majority of the respondents (64.2%) were operating above the average technical efficiency score (above 0.51). Fishers operating above an 80% level of technical efficiency returned a higher proportion (22.8%), compared to 5.4% of the fishers that had a technical efficient score of 20% and 30% (Figure 3). The mean technical efficiency from the study corroborates other studies of stochastic frontiers in fisheries in the least developed countries [19,21,29,50,61]. Reduced efficiency in fisheries of developing countries is being attributed to the limitation of fishing technologies when exploiting the offshore waters, resulting from the depleted inshore resources [10,36,65,73].

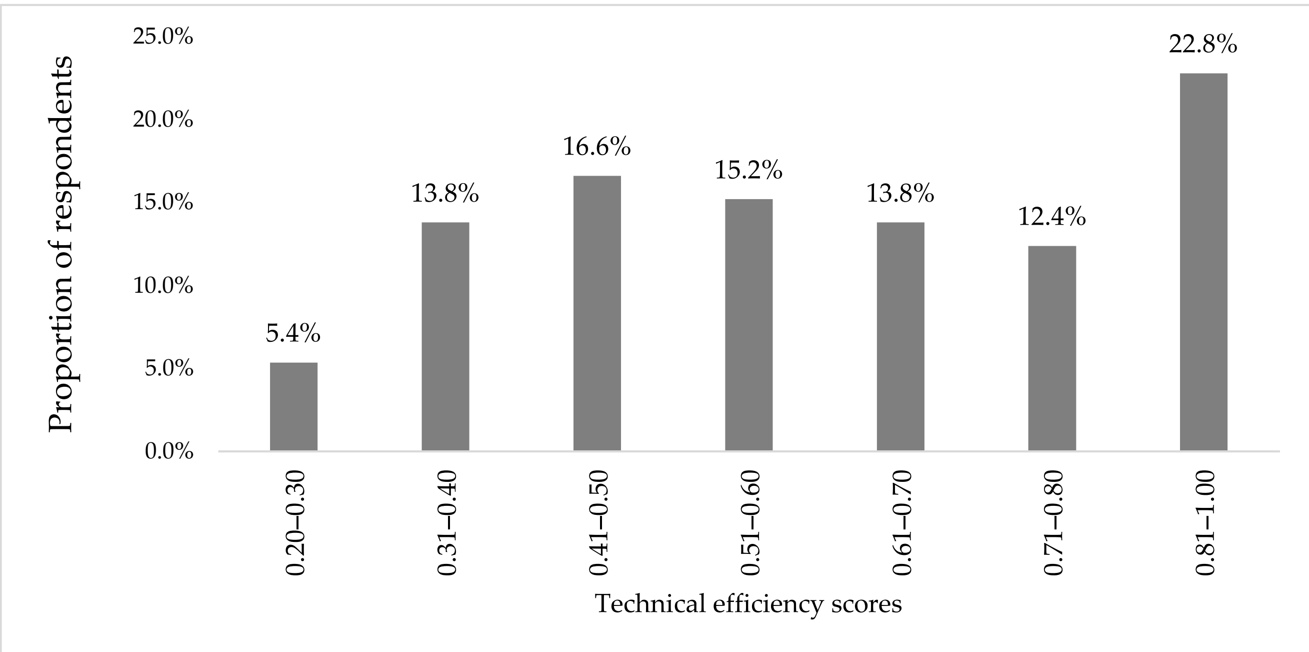

Figure 3. Technical efficiency distribution for Chilimira fishery.

4.3.5. Determinants of Technical Inefficiency

Table 5 provides estimates for technical inefficiency determinants, which are explained better by coefficients, algebraic sign, and statistical significance. In essence, a negative coefficient indicates that the determinant has a positive impact on improving fishing productivity and the positive sign is interpreted inversely. The translog analysis returned five variables (education, experience, boat size, role in the fishery, and mosquito net lining) that decreased inefficiency in the Chilimira fishery while the number of hauls, boat, fishing depth, and mosquito net lining were significant at alpha level 0.1 ($p > 0.1$).

Table 5. Determinants of technical inefficiency for Chilimira fishery.

Variable	Parameter	Coefficients	Std Error	Z	*p*-Value
Intercept	δ_0	0.62	0.47	1.31	0.19
ChAge	δ_1	0.01	0.01	1.12	0.26
Education	δ_2	−0.01	−0.02	−0.61	0.54
HHsize	δ_3	0.00	0.01	0.16	0.87
Experience	δ_4	−0.01	0.01	−0.93	0.35
Hauls	δ_5	0.05	0.02	2.50	0.01 ***
Head-length	δ_6	0.00	0.00	0.85	0.40
Horsepower	δ_7	0.01	0.01	0.83	0.41
Boat	δ_8	−0.05	0.03	−2.03	0.04 **
Depth	δ_9	−0.00	0.00	−2.12	0.03 **
Age	δ_{11}	0.00	0.01	0.19	0.85
BVC	δ_{12}	0.07	0.16	0.47	0.64
Role	δ_{13}	−0.08	0.08	−1.04	0.30
Mosquito net [MN]	δ_{14}	−0.04	0.02	−2.12	0.03 **

Notes: Double, and triple asterisks (*) indicate value significance at ** $p < 0.05$, and *** $p < 0.01$ levels, respectively.

Chilimira fishers using the larger boat with the engine were significantly reducing technical inefficiency at alpha level 0.05 ($p < 0.05$). Boats with engines are capable of sailing offshore and utilising the remote virgin stock. The results are consistent with findings from [19,21,47] that linked the size of the boat and distance travelled to a negative impact on technical inefficiency.

The use of mosquito net lining at the bunt significantly decreased technical inefficiency at alpha level 0.05 ($p < 0.05$). According to [74], mosquito nets are adapted in the Chilimira fishery as bunt or line seine nets and are a type of non-selective fishing gear. The gear is more efficient in the overfished inshore fishery that has small-sized fish species [65,72,74].

A fisher that increased the number of hauls was technically inefficient at a 1% level of significance ($p = 0.01$). Discussions with fishers revealed that fishers increase the number of hauls in response to fish scarcity during fishing operations. The number of hauls is inversely related to human power, which decreases fishing efficiency among crew members. Reduced productive performance with an increasing number of hauls or fishing trips has been reported by [25].

Fishing in the offshore and deeper waters was also found to reduce technical inefficiency at a 5% level of significance ($p < 0.5$). This implies that increasing the fishing depth maximises catch rates from the Chilimira fishery as fishers exploit virgin and potentially productive offshore fishing grounds [5,35,68]. These results are consistent with [19,21,47] who reported that catch rates increase with fishing depth.

4.3.6. Estimated Actual and Potential Level of Output from Chilimira Fishery

The average fish catches (output) between actual and potential catches per trip were 1074.03 ± 42.14 kg and 1698.49 ± 53.29 kg, which were significant at a 1% level of significance ($p < 0.01$) (Table 6). This indicates that fishers have the potential to improve production by 624.46 kg per fishing trip with the existing level of input use.

Table 6. Paired t-test statistics between the actual and potential output from the Chilimira fishery.

Output	Mean	Std. Dev	Minimum	Maximum
Actual Output	1074.03 ± 42.14 [a]	793.92	120.00	4000.00
Potential Output	1698.49 ± 53.29 [b]	1003.99	315.76	6628.79

Note: The superscripts a and b indicate statistical difference; the difference in superscripts letter means statistically significantly different at alpha level 0.01.

Table 7 provides a summary of an analysis of variance (ANOVA) results from five means of actual and potential output among five classes of technical efficiencies. The less inefficient fishers (those operating between 0.20 to 0.50) had an actual output mean of 510.55 ± 323.22 kg per fishing trip, which was significant at alpha level 0.05 ($p < 0.05$), implying the ability to increase production by 250%. Notably, fishers that were 60% technically efficient had an actual and potential output that were not statistically significant at a 5% level of significance ($p > 0.05$), with those that were 92% technically efficient. This means fishers with technical efficiency above 60% have a similar combination of input usage.

Table 7. Comparison of estimated actual yield and potential catch from Chilimira net.

Output	Technical Efficiency Score	Mean	Std. Dev	Minimum	Maximum
Actual	0.20–0.50	510.55 [a]	323.22	120.00	2000.00
Potential		1282.92 [a]	682.20	315.76	4520.86
Actual	0.51–0.60	1134.81 [b]	652.58	320.00	4000.00
Potential		2017.92 [b]	1087.66	618.23	6628.79
Actual	0.61–0.70	1265.31 [bc]	602.81	400.00	2800.00
Potential		1945.14 [b]	913.80	571.77	4089.55
Actual	0.71–0.80	1579.53 [c]	1180.62	400.00	4000.00
Potential		2115.87 [b]	1590.86	503.75	5384.84
Actual	0.80–1.00	1527.32 [c]	713.72	480.00	4000.00
Potential		1765.49 [b]	792.20	589.48	4701.92

Note: The superscripts a, b, and c indicate the presence of statistical difference where means with the same superscripts letter are not significantly different at alpha level 0.05.

4.3.7. Chilimira Fisher Input Elasticity

The estimation of elasticity provides the responsiveness of the fish catch to the percentage change in the given inputs [18,19,21,23,29,50,61,75]. Fishing inputs variables of bunt area, mesh size, labour, fuel, and LED bulbs had an elasticity scale of 3.25, −1.03, −0.08, 0.15, and 2.01, respectively (Table 8). Bunt and LED were elastic input variables while fuel was an inelastic variable. This indicates that the bunt area, fuel, and LED were important fishing inputs that increased the catch for the Chilimira fishers once increased.

Table 8. Estimated production elasticities.

Input Variable (ln)	Description	Scale Elasticity	Std. Error
Bunt	Area of the bunt in metre square	3.25	2.68
Mesh	Mesh size of the bunt	−1.03	0.87
Labour	Crew member × fishing time	−0.08	4.60
FUEL	Quantity of petrol used per trip	0.15	0.27
LED	Number of LED bulbs per trip	2.01	2.57
Return to scale		**4.30**	

The return to scale was 4.30, indicating that the fishery is operating at an increasing return to scale. Refs. [15,19–21,29,47] also reported an increasing returns to scale in fisheries. This echoes the presence of high technology creep in fishing and increased fishing pressure in *E. sardella* fishing [10,30,42,65].

5. Conclusions and Policy Implications

The study analysed the technical efficiency of the Chilimira net in the *E. sardella* fishery. The average technical efficiency score of 0.6 means that the current fishing inputs have a production gap of 0.4 to reach the frontier line output. This means the presence of technical inefficiency among Chilimira fishers in *E. sardella* fishing, citing the need to improve efficiency by addressing important policy variables that both drive technical efficiency and inefficiency. The fishing input variables of bunt area, mesh size, and LED bulbs significantly influenced technical efficiency, while boat size, number of hauls, fishing depth, and non-selective illegal lining of mosquito net reduced technical inefficiency. Therefore, the productivity performance of *E. sardella* can be sustainably improved to meet the shortage in demand for fish in the country by maximizing the usage of increased bunt area, boat size, and the number of LED bulbs. Similarly, the use of small mesh sizes (8 mm and 6 mm) and mosquito net lining at the bunt should be abandoned as they are unsustainable fishing efficiency input variables in *E. sardella* fishery. This calls for the government, relevant stakeholders, and policymakers to institute policies, i.e., affordable to the fishers, which will enable fishers to access sustainable *E. sardella* fishing inputs, which will enable them to improve the utilisation of virgin offshore fisheries. Furthermore, in sustainable fish production, the government should consider adopting economic policy measures of subsidies for larger bunt mesh size (10 mm) for Chilimira net. The government and relevant stakeholders should also put in place measures to prohibit the usage of small bunt mesh size and mosquito net lining at the bunt through enforcement options along the lake, in shops, and borders. Finally, the species' responsiveness to climatic changes calls for the need for future research studies to analyse technical efficiency using panel data of species' productive efficiency based on climatic seasons. This can be assisted by digitalizing the fisheries database through the development of software in near-real-time observations of changes in the fishery through tracking fishing inputs and outputs. This will help with intensive monitoring of the fisheries for the real-time implementation of additional management measures to protect the fisheries and overcapitalization in the fishery.

Author Contributions: K.S. conceptualized the paper, designed the research, carried out data collection, analysed and interpreted the results, and prepared the manuscript. M.M.L. and F.N. contributed to the research design and framing study tools and methodology and reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Africa Center of Excellence in Aquaculture and Fisheries (AquaFish ACE) at the Lilongwe University of Agriculture and Natural Resources (LUANAR) through a World Bank grant [number Pl51847 Credit No. 5802-MW] to Malawi.

Institutional Review Board Statement: Ethical review and approval were waived for this study because it had minimal interaction with participants and the information obtained was anonymous.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: The authors render special recognition to the Africa Center of Excellence in Aquaculture and Fisheries (AquaFish ACE) of the Lilongwe University of Agriculture and Natural Resources (LUANAR), Nkhotakota Fisheries Office, Nkhotakota Beach Village Committee members, and Nkhotakota Chilimira fishers for their hand in the research study, coordination of field activities, and data collection. Furthermore, we would like to acknowledge the Sustainable food systems Programme in Malawi (FoodMa)'s support toward publication costs.

Conflicts of Interest: The authors declare no conflict of interest.

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