

Sustainable Rice Cultivation Development Pathways in Liberia: Cost Reduction and Efficiency Enhancement

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Abstract

Rice is the primary staple food in Liberia and is considered the basis of national food security, rural livelihoods, and macroeconomic stability. Domestic production of rice is still insufficient despite the agroecological conditions being favorable, and as a result, the country has to depend heavily on imports, thus exposing itself to global price volatility. This paper thus explores different integrated production cost reduction and technical efficiency enhancement approaches for Liberia's rice sector through a mixed, methods design. Primary data was obtained through field surveys of 176 rice farmers in Bong, Grand Cape Mount, and Montserrado counties. Data Envelopment Analysis was implemented in the quantitative part to determine technical efficiency, while chi, square tests as well as frequentist and Bayesian ANOVA were used to check the relationships between farming methods, technology adoption, costs, and yield outcomes. The statistical analysis was also supplemented by the qualitative findings from the interviews with key informants. The study revealed that the sample of farmers had only reached 55% of the average technical efficiency level, indicating that there is a huge potential for productivity improvement by using the current resources. The use of modern production methods gave a yield that was about 31% higher than traditional systems. Labor costs were found to be the largest share of the production costs, while extension service was the factor most strongly associated with technology adoption. In light of the above, the research suggests a Cost-Efficiency Optimization Framework as a conceptual analytical tool that merges components of cost structures, efficiency, technology adoption, and institutional support. This research provides a set of policy, related factors for the development of rice self, sufficiency through the alignment of mechanization, irrigation, extension, and agricultural finance in Liberia.

Keywords

Rice Cultivation, Cost Reduction, Liberia

1. Introduction

Food security is still a major development problem in low, income and post, conflict economies. As a result, agricultural development is very tightly linked to poverty reduction, social cohesion, and overall economic stability. It has become an essential function of national food systems to provide sufficient, affordable, and accessible staple foods regularly for local populations. This issue has attracted much attention in the light of global market volatility, climate change, and geopolitical conflicts as reported by the [World Bank Group \(2023a\)](#). Countries lacking a strong production base have been identified as the most vulnerable to external shocks. These are mostly manifested through the increase of food prices and the higher level of household vulnerability, especially among the poor.

Rice has become a preferred staple choice in Sub-Saharan Africa resulting from a variety of factors among which rapid population growth, urbanization and dietary shifts rank top. Besides, rice consumption rate has surpassed that of the traditional staples such as cassava and maize. It is mainly promoted by its convenience and the increasing urban demand. However, local production of rice is far from meeting the ever, growing consumption demand, thus resulting in the region being transformed into one of the largest rice importers worldwide as confirmed by [AfricaRice \(2022\)](#) and [World Bank Group \(2023a\)](#). The widening gap between supply and demand is bound to have huge food security and foreign exchange implications. Economies without fiscal space or buffers are the most affected in such cases.

Liberia also represents an extreme case of the regional rice market paradox. In other words, though the country has good agroecological conditions, plenty of lowland ecosystems, and a long history of rice culture, it still needs to import most of the rice consumed. In fact, rice forms a major component of Liberia's social, economic, and cultural fabric. It is the staple food for both the rural as well as urban communities. The average rice consumption per person in Liberia is among the highest in Africa. [FAO \(2021b\)](#) reports that a great proportion of rural households in Liberia still depend on rice farming as their main source of livelihood.

However, local rice production accounts for less than 50% of the national consumption. Hence, the country imports rice several hundred thousand metric tons every year. This significantly drains foreign exchange reserves and exposes the Liberian economy to international price fluctuations as well as supply chain disruptions ([World Bank Group, 2023b](#)). Such a heavy dependence on imports increases the population's vulnerability to food price changes, thereby hindering the achievement of national food self, sufficiency goals.

The ongoing failure of the local rice sector performance in Liberia can be at-

tributed to a mixture of historical, structural and institutional factors. Civil war has completely devastated irrigation systems. Infrastructure such as storage, roads, agricultural extension services has also been damaged. Furthermore, the labor market and knowledge transmission in the countryside have been deeply disrupted because of the war (Wossen et al., 2015). However, it has been argued that even if some productive capacity has been restored through post, conflict recovery programs, rice production per hectare is still low compared to other regions or the world yield standards. The main reasons are low input use and weak soil fertility. Indeed, this hampers the use of agricultural machinery and leads to poor farm management.

Moreover, the cost structure of rice production is a critical factor that affects its competitiveness. Smallholder rice production systems in Liberia are predominantly labor, intensive, with very little use of machinery during different farming operations like land preparation, weeding, and harvesting. Therefore, the cost of labor tends to be the biggest component of overall production costs. As such, this situation is becoming less and less sustainable as wages increase and there is a shortage of seasonal labor (Sheahan & Barrett, 2017; FAO, 2021a). In addition to that, farmers are finding it difficult to get access to improved seed varieties, fertilizers, irrigation facilities, extension services, and formal credit. On the other hand, the quality of the harvested crop deteriorates through the different stages of marketing due to poor post, harvest handling and lack of adequate storage and processing facilities.

So far, the policy responses to these problems have been disjointed and have mainly consisted of small isolated initiatives such as seed distribution, fertilizer subsidies, or mechanization pilots only. Although these projects have led to some progress at the local level, they have failed to bring about a lasting transformation of the entire system. Consequently, a significant gap in the empirical literature has been identified as the lack of integration between the analysis of production costs and that of technical efficiency within a consistent analytical framework for smallholder rice farming systems in post, conflict regions, as stated by Mendola (2007).

Against this backdrop, the present research focuses on bridging the identified knowledge gap. Through the building up and testing of a Cost Efficiency Optimization Model (CEOM) for Liberia's rice sector, the study aims to bring the production costs and technical efficiency of rice farming together. The study also takes into account institutional factors like extension services, technology adoption, and access to finance. Using data gathered from rice farmers in the main rice, growing counties, the study measures the level of technical efficiency, production cost components, and the influence of institutional factors on these variables. The findings of the research will facilitate the formulation of policy measures for making local rice production more self, sufficient, raising the level of competitiveness of the rice sector, and decreasing reliance on imports in Liberia. This is accomplished by establishing a direct relationship between cost, saving and efficiency

improvement strategies.

2. Literature Review and Conceptual Framework

2.1. Rice Production and Food Security in Sub Saharan Africa

Rice consumption in Sub Africa has been growing at a fast pace during the past forty years. [FAO \(2021b\)](#) has indicated this expansion to be a result of population growth, urbanization, and changes in lifestyle. However, the growth of production has not matched the increase in consumption. Hence, the region is being converted into a net rice importer and the imports thus, increasing the exposure to international market price fluctuations ([World Bank Group, 2023b](#)). This reliance has significant macroeconomic consequences such as foreign exchange losses and reduced incentives for domestic agricultural investment. West African empirical studies on the matter have revealed that the main reason for rice import dependence is low productivity.

Therefore, yield gaps still exist even though the agro, ecological conditions are quite favorable. This can be attributed to inefficiency in input use, lack of institutional support, and low adoption of improved technologies ([AfricaRice, 2022](#)). Moreover, according to the [Ministry of Agriculture \(2023\)](#), in the case of post-conflict countries such as Liberia, the above challenges become even more severe due to the lack of infrastructure, insecure land tenure, and a weak extension system.

2.2. Cost Structures in Small Holder Rice Production

Production costs play a very important role in determining how competitive local rice is against imports. The production costs in small, scale farming systems are mainly made up of variable costs, with labor being consistently the largest cost component according to several studies ([Kassie et al., 2015](#)). As a matter of fact, most of the labor is utilized for manual land preparations such as transplanting, weeding, and harvesting.

Research conducted on rice systems in Africa reveals that labor makes up 40, 60% of total production costs. This figure has been reported to be on the increase due to rural people moving to the cities and wages going up ([AfricaRice, 2022](#)). Against this backdrop, rice economies in Asia have been able to make substantial cuts in their costs through mechanization, service provider models and collective action, hence, the crucial role of organizational and institutional innovations besides technological changes cannot be overemphasized ([FAO, 2021b](#)).

It has been recognized that input costs, especially for seed and fertilizer, are further limiting productivity. Therefore, the lack of a good seed system has made it necessary for farmers to depend on unofficial seed sources which have low genetic potential. In this case, while fertilizer use is still limited by high prices, inadequate supply, and farmers' risk aversion in rain, fed conditions as stated by [MoA \(2023\)](#). Consequently, many farmers are using inputs at levels which are below the

economically optimal ones, thus, low productivity and high per, unit costs are being perpetuated.

2.3. Technical Efficiency and Productivity Gaps

AfricaRice (2022) stipulated that technical efficiency is essentially a measure of how well farmers use the available resources to the maximum level of output. Various empirical research works that employ Data Envelopment Analysis and stochastic frontier models to African agriculture have strikingly shown a very high level of inefficiency with average efficiency scores that are mostly as low as 40% to 70%.

As a rule, efficiency gaps come as a result of incorrect agronomic practices, lack of extension support, and poor access to the source of information concerning the production of rice, thus, *Asante et al.* (2014) strongly agree with it. On the other hand, it is worth noting that efficiency analysis is capable of showing that a sizable output increase is possible even without the expansion of the cultivated land or the increase of input quantities. This revelation is especially valuable for a country like Liberia where land expansion is a cause for environmental and social concerns.

2.4. Technology Adoption and Institutional Determinants

The diffusion and innovation frameworks have been the major focus when talking about the adoption of improved rice technologies. Basically, Rogers' Diffusion of Innovation theory holds that adoption decisions depend on several perceptions such as perceived relative advantage, compatibility, complexity, trialability and observability (*Rogers, 2003*). Such perceptions are highly dependent on institutional factors. For example, in the case of smallholder rice systems, extension services constitute a major means of facilitation of adoption because through such services farmers are given knowledge and management capacity.

Empirical proofs are very consistent that farmers who have extension contact on a regular basis are the ones who adopt new technologies, and through the adoption, they reach higher levels of both productivity and efficiency (*FAO, 2021a*). Another factor that can explain adoption is the availability of finance, as most of the cost, saving and efficiency, raising technologies require the initial investment which is normally greater than the liquidity capacity of smallholders.

2.5. Integrating Cost Reduction and Efficiency Enhancement

There has been a surge in literature highlighting that the reduction of costs and the increase in efficiency are two objectives that call for each other, rather than being different policy goals. On the one hand, a mechanization reduces labor costs and, on the other, it can improve the timeliness of operations and therefore the yield outcomes. Besides that, the production of improved water management is said to always be more stable and more input, responsive (*AfricaRice, 2022*). Hence, collective action through farmer organizations also lowers transaction costs and

makes the access to services and markets easier (FAO, 2021b).

However, in spite of these complementarities, the majority of empirical studies still address costs and efficiency as two separate issues which, thus, limit their policy relevance. This work therefore raises a response to a proposal of a Cost, Efficiency Optimization Model (CEOM) which would be a model that production costs, technical efficiency, technology adoption, and institutional support are all maintained within a single, integrated analytical framework.

2.6. Conceptual Framework: Cost-Efficiency Optimization Model (CEOM)

The CEOM presents the rice production results as the combined effect of four mutually dependent dimensions: (1) input cost structures, (2) technical efficiency levels, (3) technology adoption, and (4) institutional support mechanisms. The framework assumes that to grow productivity in a sustainable way, there need to be coordinated interventions in these different dimensions instead of technological or policy changes done in isolation (World Bank Group, 2023b; MoA, 2023).

3. Methodology

3.1. Research Design

This study uses a mixed, methods research design which combines quantitative farm, level survey data with qualitative key informant interviews. A mixed, methods approach is a great fit for agricultural efficiency analysis. It is based on the fact that it allows one to conduct a hard statistical estimation of productive outcomes and also get hold of the institutional, managerial, and other aspects that influence the farmer's behavior (Creswell & Plano Clark, 2018).

The quantitative part is concerned with the measurement of production costs, yield outcomes, and technical efficiency of rice farmers. Whereas, the qualitative part gives a deeper understanding of the adoption of technology, the delivery of extension services, and the challenges of policy implementation in the rice sector of Liberia. Such an integrated design not only strengthens internal validity but also makes the findings more attractive to policymakers.

3.2. Study Area and Sampling

The research took place in Bong County, Grand Cape Mount County, and Montserrado County. Along with being the three main rice, producing regions, these counties were intentionally chosen to reflect differences in agro, ecological conditions, market accessibility, and production systems. This covered the upland, rain, fed lowland, and inland valley swamp rice ecologies in the area (MoA, 2023).

A multi, stage sampling process was also utilized. At the first stage, major rice, producing districts within each county were identified through consultations with the county agricultural offices. During the second stage, rice, producing communities were randomly chosen from the official farmer lists. At the third and final stage, individual rice, farming households were randomly selected within the cho-

sen communities.

Thus, 176 rice farmers were surveyed in total. The sample size was considered to be in line with efficiency studies in smallholder agriculture and adequate for Data Envelopment Analysis (DEA), which is based on cross, sectional comparisons of decision, making units (Coelli et al., 2005). The sampling includes:

- a) Registered farmer groups;
- b) Community agricultural cooperatives;
- c) Village-level rice producers.

3.2.1. Sampling Technique

A multi-stage sampling method was also used:

Stage 1: County Selection: Three counties selected based on rice production prominence.

Stage 2: Farmer Selection: Simple random sampling within counties to avoid selection bias.

3.2.2. Sample Size Determination

The original sample size requirement was determined from Cochran's formula for cross, sectional surveys, which suggested a minimum target of 384 respondents under the assumptions of a large population, 95% confidence level, maximum variability ($p = 0.5$), and 5% margin of error. This figure is the ideal sample size for estimating the population proportion at the population level and is not a strict requirement for econometric efficiency analysis.

Due to logistical constraints, accessibility of farming communities, and resource limitations typical of post, conflict rural settings, the data collection exercise yielded a final sample of 176 rice farmers only. Although the size of the sample is less than the Cochran, based target, it is still methodologically appropriate for the types of analyses carried out.

Data Envelopment Analysis (DEA) is one such technique that does not rely on probabilistic sampling assumptions and has been extensively used in smallholder agricultural studies with sample sizes of the same order or even smaller. Furthermore, the ratio of observations to inputs in the DEA model complies with the generally accepted rules of thumb for efficiency analysis. Likewise, the use of ANOVA and regression models with categorical predictors is statistically sound given the sample organization and the strength of the effects that were detected.

The trade, off, however, is the need for interpretation of the results with a degree of caution and due consideration when it comes to their generalization beyond the study areas. The limitations are made very clear and the results are seen as indicative of dominant structural patterns rather than representative of the precise population figures.

3.3. Data Collection Instruments and Procedure

Primary data was gathered through a structured questionnaire that was administered in face, to, face interviews. The questionnaire collected data on household

demographics, farm characteristics, input use, production costs, and yields. It also concentrated on post, harvest practices, access to extension services, and technology adoption. Prior to the pilot survey, the instrument was pre, tested to clarify, make consistent, and relate it to local farming conditions.

Besides farmer surveys, key informant interviews were held with agricultural extension officers. This was facilitated by cooperative leaders, input suppliers, and policymakers. Such meetings offered qualitative details on institutional constraints, service delivery gaps, and the effectiveness of the current rice development interventions.

Fieldwork was carried out during the 2024-2025 production season. The study adhered to ethical standards such as obtaining informed consent, ensuring voluntary participation, and keeping respondent information confidential throughout the research process.

3.4. Analytical Framework and Methods

3.4.1. Descriptive and Inferential Analysis

Descriptive statistics provided a summary of the socio, demographic characteristics, farm details, technology adoption levels, cost structures, and yield patterns. Frequencies, percentages, means, and visual representations were obtained with the help of SPSS software.

Relationships between core variables were tested through inferential statistics. Chi, square tests served to find associations between categorical variables such as workplace method, technology options, and extension services. For analyzing yield differences by farming methods and technology usage categories, one, way analysis of variance (ANOVA) was used along with Bayesian ANOVA. If necessary, post, hoc analyses were done to delineate group differences more clearly.

3.4.2. Technical Efficiency Analysis

Technical efficiency was gauged through Data Envelopment Analysis (DEA), a non, parametric frontier technique that has been extensively used in agricultural efficiency research. DEA determines the relative efficiency of decision, making units by locating their input, output combinations onto a production frontier of the best practice. Efficiency values are between zero and one, where values close to one denote high efficiency. The DEA model was set up as input, oriented, which is in line with the study's aim to minimize production costs without changing output levels.

The major inputs for the model were land, labor, seed, fertilizer, and mechanization, and the output was rice yield. This methodology corresponds to the Cost Efficiency Optimization Model (CEOM), which prioritizes cost reduction and the efficient use of resources. Thus, the Frontier, based efficiency measurement extends the work of [Aigner et al. \(1977\)](#) and [Battese and Coelli \(1995\)](#).

3.4.3. Regression and Cost Pathway Analysis

Determinants of technology adoption and cost reduction were identified through

multivariate regression models. Since technology choices (no technology, single technology, combined technology bundles) are categorical, a multinomial logistic regression framework was initially used.

Preliminary tests revealed quasi, complete separation, which was related to low, frequency categories and to perfect prediction of some technology outcomes by certain explanatory variables. Such situations are typical of small, sample agricultural adoption studies and may result in inflated standard errors and unstable coefficient estimates.

In order to resolve the issue and to make the parameters stable, two different correction methods were used. Firstly, low, frequency technology categories were merged into groups with analytical meaning, which decreased the sparsity of the dependent variable. Secondly, model estimates were validated through a penalized likelihood method consistent with Firth, type bias reduction, which is a standard approach for solving separation problems in logistic regression models.

Therefore, after such modifications, an interpretation of the model is directed towards the overall fit of the model, the effect directions, and the significance of the main predictors rather than on the magnitude of individual coefficients. Such a method safeguards the robustness of the inference with the preservation of the explanatory value of the regression analysis.

Labor cost share was regarded as one of the outcome economic indicators calculated from reported production expenditures, and not as a proxy for technology use, thus labor cost share was permitted to vary independently from technology adoption patterns.

3.5. Conceptual Alignment with the CEOM Framework

The analytical method was clearly designed in accordance with the Cost Efficiency Optimization Model (CEOM). Estimating efficiency levels primarily relies on production inputs and the related costs, whereas the inclusion of technology adoption and institutional variables as explanatory factors accounts for their impact on cost structures and efficiency outcomes. This combined framework enables the paper to quantitatively assess the effectiveness of integrated measures aimed at the different aspects of the rice value chain in Liberia in terms of productivity and competitiveness.

4. Results

4.1. Descriptive Statistics of the Sample

The demographic and socio, economic characteristics as well as the farm features of the respondents are presented in **Table 2**. The studied group mainly consists of farmers who are in the economically productive phase of their life with the highest proportion of the age group being 2635 years (32.4%) followed by 3645 years (27.8%). Males made up 56.8% of the total respondents while females accounted for 43.2%. Hence, there was a relatively strong participation of women in rice farming.

The data revealed that the level of education was quite low. Therefore, more than half of the farmers had no formal education or only primary education. Besides that, not even one, third of the farmers had college or university, level education. This points to possible difficulties in getting information and adopting new technologies through formal education.

The presence of farmers in the three counties of Bong, Grand Cape Mount, and Montserrado was fairly equal. The study's indications revealed that rice farming was mostly on a small scale, with over 77% of farmers owning less than 5 acres. Old, fashioned manual farming methods prevailed, making up more than 80% of the production techniques, whereas obtaining credit was very restricted as it was reported by less than one, fifth of the respondents.

The output was on average very low. Close to 43% of the farmers yielded less than 500 kg per acre while only a small number of farmers less than 7% managed to get yields in excess of 1,000 kg per acre. Human work was the major element of expenditure, and almost 75% of the farmers mentioned that the cost of labor was between 25% and 50% of the total production costs.

4.2. Relationship between Farming Method and Technology Use

A chi-square test of independence revealed a strong and statistically significant relationship between farming method and technology adoption ($\chi^2 = 141.80, p < 0.001$) Every farmer who used modern production methods had implemented at least one technological application. On the other hand, most traditional farmers (82.8%) indicated not using any technology.

The finding suggests that the type of farming method can greatly influence the decision to invest in technology. It is evident that traditional farming systems are still limited to low, input, low, output modes of operation, whereas modern methods go hand in hand with the use of machinery and the adoption of better techniques.

4.3. The Role of Extension Services in Technology Adoption

Access to extension services was a significant factor in technology adoption. A chi-square test revealed a strong association between having access to extension and the use of technology, $\chi^2 (13, N = 176) = 71.25, p < 0.001$.

The column percentages in the crosstabulation reveal quite a bit. Take a look at the example of farmers who operated a power tiller, 63.6% of them were supported by extension services. Likewise, all farmers who chose to use the combinations that included a reaper had access to extension services, 100% stood at this ratio. On the other hand, 92.7% of the samples that did not use any technology corresponded to a lack of access to extension services as the main reason. In fact, this supports that extension services play an important role in the adoption of agricultural technologies.

4.4. Impact of Farming Method on Crop Yield

A one-way Bayesian ANOVA was used to test whether crop yield (using midpoint

values) varies with primary farming method as shown in **Table 1**. The data strongly supports (Bayes Factor = 20.23) the model with farming method, i.e. yield is dependent on the method of cultivation.

Table 1. ANOVA summary table for yield per kg.

Yield per kg	Sum of Squares	df	Mean Square	F	Sig.	Bayes Factor ^a
Between Groups	777215.928	2	388607.964	8.641	0.000	20.228
Within Groups	7780284.072	173	44972.740			
Total	8557500.000	175				

Both frequentist and Bayesian ANOVA results provide strong evidence that rice yield differs significantly across farming methods. The frequentist ANOVA indicated statistically significant differences in yield ($F = 8.64, p < 0.001$), while the Bayesian analysis yielded a Bayes Factor of 20.23, indicating very strong evidence in favor of the model including farming method.

Farmers of modern production methods were the ones that achieved the highest average yields level, which was followed by those using organic or low, input methods, with traditional farmers gathering the lowest yields. On average, modern methods produced yields that were around 31% higher than traditional practices. These results confirm that the main source of productivity is the management and technology implementation improvement rather than farm size or the demographic characteristics of the farmer.

4.5. Post-Harvest Losses Across Farming Methods

The primary cause of post-harvest losses for the entire sample was Poor storage (43.8%), followed by Delayed harvesting (21.0%) and Processing losses (15.9%). A chi-square test showed a significant association between farming method and the cause of post-harvest loss, $\chi^2(8, N = 176) = 22.80, p = 0.004$.

Notably, a greater percentage of modern method farmers (20.8%) as compared to traditional farmers (4.8%) identified rodents/pests as one of the main causes. No organic farmer reported poor storage as the cause, but they mentioned rodents/pests (42.9%) and delayed harvesting (28.6%). This means that when farmers increase production level and make better their on-farm practices, the types of their post, harvest problems may change.

4.6. Labor Costs and Technology Adoption

The relationship between labor cost share and technology use was explored to find out if labor intensity is linked with the adoption of mechanization and related technologies. Labor cost share was defined as the fraction of total production costs that is accounted for by hired and family labor, regardless of technology classifi-

cation.

The chi, square results reveal that there is a statistically significant correlation between labor cost share and technology adoption. Farmers who have lower labor cost shares are more likely to acquire mechanized technologies, especially power tillers, whereas those with the highest labor cost shares mostly depend on non, mechanized production systems.

It should be made clear that high labor cost shares are not, by definition, due to the use of manual production methods, but rather they represent the overall economic load of labor, intensive operations such as land preparation, transplanting, weeding, and harvesting. Thus, labor costs are the economic consequence of decisions made in the production process, not the case of a previously established category.

The relationship found is not necessarily a one, way causality. On the contrary, the evidence points to a two, way, self, reinforcing interaction: on the one hand, labor, intensive production systems are likely to have high labor costs, on the other hand, high labor costs will induce mechanization adoption if access and institutional support are available. Studies of smallholder rice systems in Sub, Saharan Africa have revealed similarly patterned mechanization that has both been a response to and a way of mitigating labor cost pressures ([AfricaRice, 2022](#); [Takeshima & Salau, 2010](#)).

Hence, these results are consistent with an explanation where the labor cost stress is the primary economic signal that influences decisions of technology adoption. The latter is in line with the behavior of cost minimization prevalent in smallholder production systems ([Feder et al., 1985](#); [World Bank Group, 2023b](#)).

4.7. Multivariate Predictors of Technology Adoption

Operation of a multinomial logistic regression disclosed that variables like age, years of farming experience, labor cost share, and fertilizer expenditure could significantly predict technology adoption patterns at the farm level. The model taken as a whole was significant statistically when compared to the intercept, only version and showed strong explanatory power, as indicated by high pseudo-R, squared values.

Nonetheless, diagnostic tests unmasked quasi, complete separation being the major problem, which was due to the categories of technology with low, frequency and instances of perfect prediction. To solve this problem, the categories of technology adoption were merged and robustness checks with penalized likelihood estimation were used. These measures increased numerical stability and the main predictors' consistency across model specifications was confirmed.

Although individual parameter estimations have to be taken with a grain of salt, the findings strongly suggest that cost structures and production experience rather than demographic characteristics such as gender, education level, or farm size, are the key factors determining technology adoption. More specifically, larger labor cost shares were invariably linked to greater probability of mechanization

adoption, thus revealing cost pressures as one of the main reasons for technological change.

In general, the regression results give backing to the study's wider statement that technology adoption in Liberia's rice sector is mainly an economic and institutional reaction rather than farmer demographics driven.

4.8. Results on Age, Education and Farm Size

Table 2 and **Figure 1** present a comprehensive analysis of the relationship between age, education level, and farm size among the study participants. The population was divided into five age groups: 1, 20, 21, 30, 31, 40, 41, 50, and 51+. Each age group exhibits different levels of education and correspondingly different average sizes of farms. Thus, the age and education factors may be influencing farm activities and farm management, as revealed by this age group segmentation.

Table 2. Results on age, education and farm size.

Age Group	Education Level	Average Farm Size (acres)
1 - 20	Low (1 - 3)	2.5
21 - 30	Medium (4 - 6)	5.0
31 - 40	High (7 - 9)	7.5
41 - 50	High (7 - 9)	10.0
51+	Low (1 - 3)	3.0

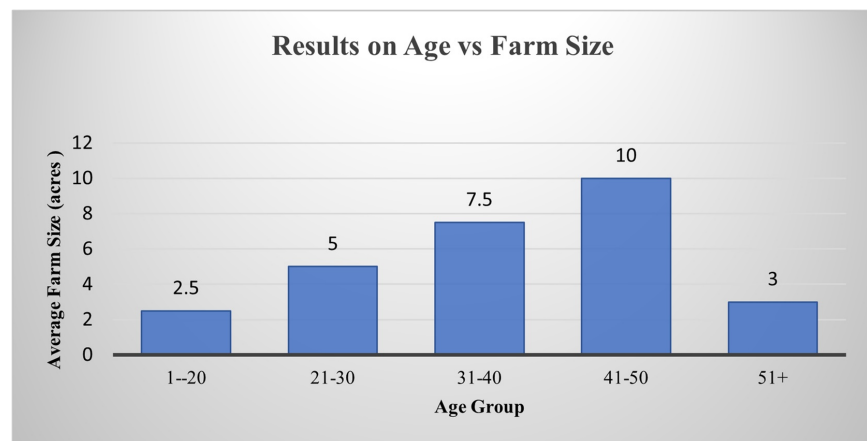


Figure 1. Age vs farm size.

Educational attainment was divided into three ranges: low (1, 3), medium (4, 6), and high (7, 9). Persons with a low level of education had mostly basic knowledge of agriculture or had received informal training; such persons were mostly found among the youngsters (1, 20 years) and the elderly (51+ years). Those falling into the medium education category had the ability to perform the agricultural tasks, had a good grasp of production and marketing concepts and were mainly seen in the age group of 21, 30 years. On the other hand, the highly educated group, re-

flective of a deeper academic background, probably in horticulture or business, is mostly in the 31, 40 and 41, 50 age groups.

There is a strong relationship between a person's age and the average size of the farm he or she owns which shows that with maturity and attainment of higher education, the individual is capable of managing a bigger farm. In fact, the 41, 50 years group, a group that shows evidence of having been educated, has the average largest farm of 10 acres. It has been suggested that both experience and higher education contribute to better farm management and the willingness to enlarge the farm.

On the other hand, the youngest group (1, 20) has the smallest average farm size of 2.5 acres which is probably due to the difficulty of getting experience and resources in early adulthood. Individuals who start farming at a young age have low education and are engaged in a small piece of land which is a likely indication of traditional family of informal farming methods. Later, when they get older and better educated, you will notice that they farm on bigger pieces of land probably meaning they use more modern farming techniques and equipment.

The older and generally more educated farmers operate larger farms; here, the investment in learning and adapting to new farming methods is rounded off. The situation here shows how the financial and material resources were managed by the different age groups after gaining experience from the years of farming. In summary, this analysis has highlighted the extent to which age and education significantly determine the size of farms.

It can be inferred that if young farmers get highly educated, they will be able to efficiently manage their resources to grow larger farms. It thus implies that the route to an increased agricultural output and a more sustainable agricultural environment is through better training, especially of the young farmers.

4.9. Labor Cost Percentage and Main Source of Seeds

Analyzing the breakdown of labor cost percentages, farmers allocate different shares of their production costs to labor according to the figures. Only about 15% of the respondents are reported to be spending 0.20% on labor, thus signaling that they either use family labor extensively or apply farming techniques with low labor demand. On the other hand, as per the data, around 20% of farmers are in the 21, 40% bracket which suggests that there is a moderate level of labor input possibly because of a combination of hired and family labor.

A considerable number of respondents, 30% of the total, declared their labor costs to be between 41% - 60%. This scenario contrasts the preceding one and probably depicts a case of intensified farming practices that lead to labor periodically being required for tasks such as planting, harvesting, and the general upkeep of the crops. In addition to this, 25% of the respondents utilize between 61% - 80% of their production costs for labor, which may indicate highly labor, intensive farming systems that depend almost completely on skilled labor for the implementation of agriculture that is both effective and high yielding.

Moreover, the remaining 10% representing a minority, claimed that the costs of labor took up their entire budget. Such a statement either reflects a misunderstanding in the way budget line items are arranged or, at a minimum, illustrates a heavy reliance on labor, driven farming methods without much use being made of other agricultural inputs.

The results also pointed to the main grounds for seed resourcing by farmers and thus demonstrated a range of seed acquisition strategies. Only 15% of the farmers said that most of their seeds were from local markets which may be interpreted as having a preference for convenience as well as price reasons although at the same time they accept the demerits concerning seed viability and quality.

Likewise, a fifth of the farmers depend on government distribution for their seeds which could be an indication of being beneficiaries of special projects by the government that focus on the introduction of certain crop varieties or seed technology improvements. Farmers living side-by-side account for roughly 30% of the total seed purchasers where seeds are obtained from local farmers and thus paving the way for continuation of traditional agricultural practices.

Although the community, level seed exchange system enhances varietal diversity, it is likely to restrict access to high, yielding varieties. Besides that, Jayden (25%) procuring seeds from the cooperatives, manifest the working together scenario that is aimed at improving in terms of quality and getting seeds readily available to the farmers. Lastly, 10% of the farmers depend on commercial seed suppliers which might indicate that these individuals are inclined towards recognized brands and hence higher, quality seeds, albeit usually at a higher price tag.

Table 3. Results on labor cost percentage and main source of seeds.

Percentage of Production Cost to Labor (%)	Main Source of Seeds	Frequency
0 - 20	Local Markets	15
21 - 40	Government Distribution	20
41 - 60	Local Farmers	30
61 - 80	Seed Cooperatives	25
81 - 100	Commercial Seed Suppliers	10

Table 3 shows how the percentage of production costs that are labor, based is related to the main seed sources used by farmers. Knowing this is crucial for evaluating agricultural sustainability and rice production cost management. It is emphasized that the analysis of the interdependence of labor costs and seed sourcing strategies is just one of the factors within the agricultural practices detailed in the article. Farmers with high labor costs use local sources for seeds to the highest degree and farmer cooperatives; over time, they formed the closest bonding among each

other. On the other hand, those who have low labor costs normally use local markets for seeds; thus, their entire production's quality and yield potential may be affected. Developing a deep understanding of these changes is fundamental for creating appropriate agricultural sustainability and efficiency, enhancing strategies.

4.10. Results on Environmental Changes Affecting Rice Farming and Concern Levels

35% of participants identified the increased frequency of droughts as one of the major changes in the environment they are facing. That implies that a trend in water scarcity is emerging which is going to be very detrimental to rice production since rice requires a lot of water.

The effects of this change are likely to be reduced output and increased need for irrigation facilities, thus the cost of production for farmers would go up. Floods and heavy rainfall have been experienced by 30% of farmers among the changes in the weather patterns that have brought about some challenges.

The fact that floods are becoming more frequent consequently crop damage will also be more frequent thus farmer's economic condition will become more unstable if they depend on their harvests for earning.

Some of the respondents (25%) also mentioned soil erosion as an environmental problem arising from farming. Soil erosion, if allowed to continue, will cause the loss of soil nutrients thus crop yields will gradually decline leading to the eventual collapse of agriculture.

Another 20% of the farmers indicated that pest and disease have become more prevalent which they consider as the main problem, this is also closely linked to climate change which creates hospitable conditions for pests.

The result is a heavy dependence on chemicals to get rid of the pests, consequently running the two costs up and interfering with people's health and the environment.

The data shows that about 30% of the farmers admitted being "very concerned" about the environmental impact of farming. This shows that they have an understanding of how their farming activities adversely impact nature cycle and also compromise the macro, level sustainability.

25% of farmers reported a moderate degree of concern ("moderately concerned") which can be interpreted as them being aware of the environmental problems but feeling powerless in making any significant changes. A small percentage (10%) of respondents considered themselves as "not concerned" with the environmental impacts of their farm works at all.

This scenario probably shows either ignorance or the trust of the traditional agriculture not only to be a practice still feasible but to be a source of environmental improvements as well.

Figure 2 and **Figure 3** below summarize feedback from farmers regarding observed environmental changes impacting rice farming and their levels of concern about the environmental effects of agricultural practices.

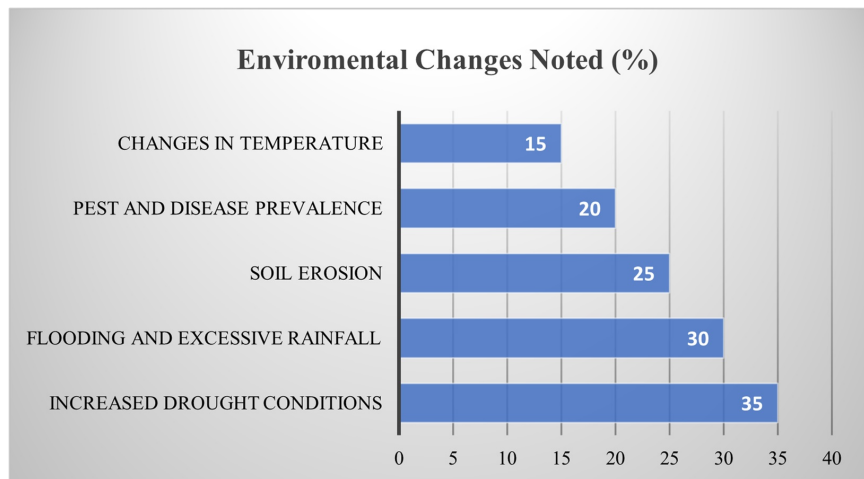


Figure 2. Results on environmental changes affecting rice farming.

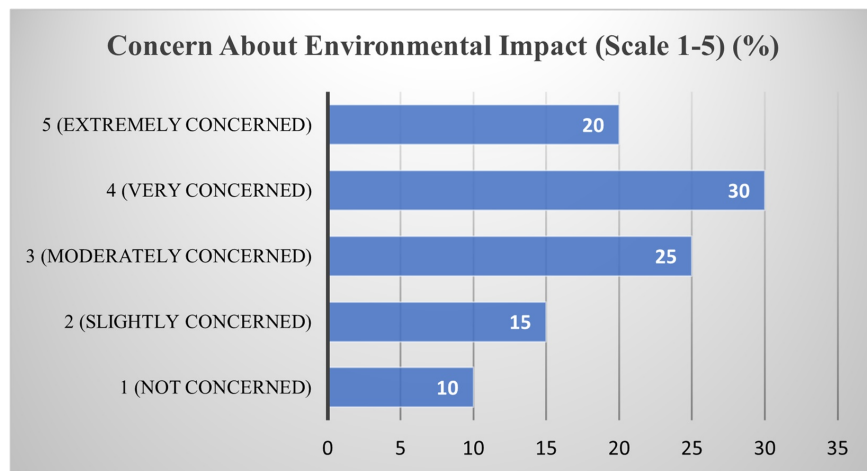


Figure 3. Results on environmental changes concern levels.

5. Discussion

The objective of this research was to discover sustainable means of lowering production costs and increasing technical efficiency in the rice sector of Liberia via an integrated analytical framework. The findings present compelling empirical evidence that the rice production system in Liberia is marked by significant inefficiencies, heavy reliance on labor, and poor institutional support. Besides, data reveal that there is considerable unused potential for productivity growth through the utilization of the same existing resources.

5.1. Technical Efficiency and Yield Gaps

An average technical efficiency score of 0.55 reveals that rice producers in Liberia are quite inefficient and their level of output is greatly lower than the production frontier. This is in line with the efficiency of other rice systems of Sub-Saharan Africa that have similarly reported efficiency scores mostly within the range of 40 to 70 percent as estimated by the [World Bank Group \(2023a\)](#). Thus, it can be con-

cluded that almost 50% of the present production losses are not due to the scarcity of land or climatic constraints, but rather to managerial, technologic and institutional inefficiencies.

The 31% yield advantage derived from modern farming methods over the traditional ones, which was also observed by farmers, thus, further confirms this conclusion. Modern methods consisting of improved land preparation, proper spacing, timely operations as well as some mechanization, help farmers to make the best use of their inputs to produce more output. One additional strong Bayesian evidence favoring yield differences across farming methods was that these gains are statistically proven and not due to chance.

Moreover, the results indicate that there is no need to increase the size of the cultivated area in order to improve productivity. This is especially the case with Liberia, where the expansion of land for agriculture would lead to environmental degradation as well as social conflicts. Hence, efficiency, enhanced intensification is a better and more sustainable development option than extensification (FAO, 2021b).

5.2. Cost Structures and Labor Dependence

Labor costs were found to be the largest single factor in determining the overall cost of rice production, where for most farmers, it was between 25 and 50 percent of the total production costs, and for a substantial minority, it was more than 50 percent. Such high dependence on labor reflects the continuation of manual production methods and the lack of mechanization especially in the stages of land preparation and weeding.

These results correspond well with general data on African rice production systems, where it has been observed that increasing labor costs make the systems less competitive (AfricaRice, 2022). On the other hand, rice economies in Asia have been able to bring down the cost of production per unit by means of mechanization service markets and collective action. Liberia demonstrated a case where it was shown that not only does labor intensity increase the cost but also it is a source of inefficiency due to delays in critical operations like planting and weeding which in turn lowers the yield potential.

The correlation between labor costs and technology adoption should be seen as one of association instead of being strictly causal. It is true that mechanization leads to fewer labor requirements, however, high labor costs can also come before and be the factor that drives technology adoption when institutional conditions are favorable. Such a two, way relationship has been documented on numerous occasions in African smallholder systems where the shortage of labor and the increase in wage rates at the same time limit production and create demand for labor, saving technologies (AfricaRice, 2022; Takeshima & Salau, 2010).

The findings imply that lowering costs and increasing efficiencies are not two distinct goals but are in fact complementary and can reinforce one another. Mechanization decreases labor costs and at the same time raises the level of work in

terms of timeliness and productivity, this combination being a key feature of the Cost-Efficiency Optimization Model presented in this paper.

5.3. Institutional Factors and Technology Adoption

It is also crucial that, due to some quasi, complete separation in the adoption models, the regression results here are mostly about the presence of robust directional relationships and institutional patterns between the variables rather than strict causal effects.

Among the most important discoveries, the highly significant relationship between the availability of extension services and technology adoption stands out. Farmers who had regular contact with extension services were far more likely to adopt improved practices and consequently achieve higher productivity. This reaffirms the vital role of knowledge transfer in determining the true effectiveness of agricultural technologies which is in line with the findings of the [FAO \(2021a\)](#).

Interestingly, age, level of education, and farm size did not emerge as significant predictors of either productivity or adoption in this research. This implies that production results are more influenced by institutional and structural factors that limit them. That is to say, even the young and educated farmers can hardly manage to perform better if they lack access to information, services, and finance.

Moreover, limited access to credit is a further factor that hampers adoption. Since only 18.2% of farmers indicated having access to formal financial institutions, many are, therefore, unable to invest in technologies that reduce cost and increase efficiency, even though the benefits have been proven. Thus, this finding also supports the assertion that being financially included is a pre-requisite to transforming agriculture in smallholder systems ([World Bank Group, 2023a](#)).

5.4. Implications for the Cost-Efficiency Optimization Model (CEOM)

The empirical findings provide strong evidence that the CEOM framework suggested in this study is correct. The main argument of the model is that sustainable productive growth is the result of a combination of factors that include simultaneously coordinated changes in cost structure, efficiency, technology, and institutional framework.

Simply giving out better seeds without providing extension services or promoting mechanization without developing service markets, will probably be ineffective for a long, term impact. On the contrary, integrated approaches which at the same time tackle the issues of cost and efficiency, have the highest potential for the transformation of the rice sector of Liberia.

6. Policy and Managerial Implications

The findings of this study have important implications for policymakers, development partners, agribusiness actors, and farmer organizations seeking to enhance rice self-sufficiency and sector competitiveness in Liberia.

6.1. Policy Implications

First, policy efforts should focus more on developing markets for mechanization services rather than on individual equipment ownership. Service, provider models where cooperatives or private entrepreneurs offer land preparation and harvesting services can reduce labor costs, allow better timing of operations, and increase efficiency without smallholders facing the burden of very high capital costs (AfricaRice, 2022).

Second, expansion of lowland and inland valley development should be part of the strategic investment package. With better water control, crop yields become more stable, plants can make better use of inputs, and modern farming methods can be adopted. Data from Liberia and the neighboring countries reveal that re-vamping inland valleys at a relatively low cost can highly increase productivity (FAO, 2021a).

Third, extension services should be not only strengthened but also modernized. The strong relationship between the availability of extension services and the adoption of innovations indicates that there is a need for more personnel, better training, and increased utilization of farmer field schools and demonstration plots. Besides, digital extension setups can be a good complement to the conventional methods and also lead to a better outreach in isolated areas.

Fourth, access to finance has to be widened through agricultural credit products designed and targeted at farmers. Public, private partnerships between banks, microfinance institutions, and agribusinesses can lower the risks and make financing more affordable. Among rice value, chain finance models, those where the credit is tied to the sale of output are very promising (World Bank Group, 2023b).

6.2. Managerial and Agribusiness Implications

Agribusinesses can take advantage of the findings to create new markets for input supply, provision of mechanization services, and post, harvest processing. Better milling and storage facilities will not only cut down on losses but also improve grain quality. At the same time, the resulting rice will be more competitive in terms of price and quality compared to imported rice.

Farmer groups and cooperatives can help structurally in management by providing bulk input procurement, organizing the use of farm machinery services, and building market linkages. By acting as a group, farmers can cut down on the cost of transactions and increase their negotiating power, thus not only bringing down the costs but also improving overall efficiency.

7. Conclusion, Limitations, and Future Research

7.1. Conclusion

The findings of this research offer substantial empirical evidence that the rice sector in Liberia is severely underperforming in relation to its productive capacity mainly because of high production costs, low technical efficiency, and weak institutional support. The study reveals that the average rice output could be raised by

about 45% without changing the input if the efficiency gaps were eliminated.

By integrating the cost structures and efficiency analysis in the Cost, Efficiency Optimization Model (CEOM), the paper made a significant contribution to the understanding of how collaborative interventions can revolutionize smallholder rice systems. The findings highlight that a sustainable rice self-sufficiency in Liberia is within the reach. Nevertheless, it can only be realized through integrated strategies that simultaneously tackle issues of labor dependence, technology adoption, extension delivery, and financial access.

7.2. Limitations

The research work has some limitations which can be stated here. Firstly, the study is based on cross-sectional data that only allow for capturing the efficiency levels at the time of study but not over different periods.

Secondly, the efficiency figures are derived from farms reported data of inputs and outputs that are liable to have some degree of error.

Thirdly, the research is carried out in three counties, which, though they represent the setting, possibly do not include all the locational variations of the rice sector in Liberia. Even though the number of respondents was adequate for the performance and inferential analytical work done, a larger survey would increase statistical strength and external validity. Hence, one should be careful when generalizing the findings to other rice production areas in Liberia.

Since the data used is cross-sectional, it is not possible to definitively determine cause and effect between labor costs and the use of technology. Therefore, the results are taken as evidence of the existence of structural linkages rather than the demonstration of cause and effect.

7.3. Future Research

Future studies could extend their research by looking at efficiency changes over several production seasons using panel data. Additionally, integrated interventions' sustainable impact can be gauged in the long run.

Another research area is the economic feasibility analysis of mechanization and irrigation models tailored to various agro-ecological zones. Moreover, a study focusing on gender issues and youth's role in rice value chains might open up new insights into inclusive development routes in the sector.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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