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OPTIMIZING RESOURCE ALLOCATION AND PRODUCTION TREND IN BANGLADESHI RICE CULTIVATION USING LINEAR PROGRAMMING

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ABSTRACT: *Rice production is a cornerstone of food security and rural incomes in Bangladesh, but seasonal variation in rice production and resource constraints on agriculture are significant challenges to sustained growth of output. This study formulates an LP model to analyze the production trends and resource allocation pattern of three dominant rice cultivation seasons such as Aus, Aman, and Boro, in the region. The model combines important production resources, such as land, labor, fertilizer, and irrigation water, to determine the optimal allocation of these resources so that the total rice output can be maximized and a profit-maximum target for each farm could be achieved within the limits of available resource supply. Season-wise production, area, yield, and input-use data of the reference period (2018-23) were obtained from secondary sources, mostly from the Bangladesh Bureau of Statistics (BBS), BRRI (Bangladesh Rice Research Institute), and DAE (Department of Agricultural Extension). Descriptive trend analysis shows that, while Boro rice dominates due to higher productivity and irrigation used for this crop compared to Aus or Aman, the production of Aus and Aman is highly variable, driven by rainfall and input constraints. The LP findings show that shifting land and resources to the water rice seasons with relatively higher yield return has a significant positive impact on gross margin without increasing the cropped area. The results emphasize the significance of better usage of resources, including water (irrigation water saving) and labor, to improve rice productivity. The developed optimization model represents a useful decision-support system for the policymakers and planners to support sustainable rice production and resource productivity in Bangladesh.*

KEYWORDS: Linear programming; Rice production trends; Resource-use efficiency; Seasonal rice cultivation, Agricultural optimization; Bangladesh.

INTRODUCTION

Rice is the principal food crop of Bangladesh and forms the backbone of national food security, employment creation, and sustaining rural livelihoods. The rice industry plays a crucial role in the agricultural gross domestic product and is a source of earnings to millions of farm households throughout the nation. Rice is grown in Bangladesh in three major seasons—Aus, Aman, and Boro with specific agro-ecological factors causing different input-use efficiency and productivity levels. Though major strides have been made in achieving increased rice production over the past decades, the sector still grapples with a lack of resources, variation in climatic conditions, and poor resource deployment.

The seasonal difference in rice yield has been shown to be more pronounced in the past several years. Boro rice, the highest-yielding type of rice and benefiting from controlled irrigation, dominates total production, but Aus and Aman rice are highly variable and sensitive to uncertain times of rainfall availability as well as labor scarcity and limited availability of modern inputs. High rates of population increase, a decrease in arable lands, and increasing costs of production, coupled with unhealthy competition for the use of water, further constrain rice production capacity. Within this setting, enhancing productivity via increasing the area under cultivation is no longer a possibility, and calls for more efficient utilization of available resources become more salient.

Effective allocation of resources is, thus, crucial to maintaining rice production growth in Bangladesh. The land and labor that farmers provide for, the amount of fertilizer they use, and what they irrigate and how much all affect crop productivity and income. Yet they are frequently taken without an integrated analytical framework that considers resource trade-offs across various rice seasons. Conventional planning methods are generally crop- or season-specific and do not consider the interdependencies between operations involved or resource constraints. This frequently results in less-than-ideal production and farm income.

Linear programming (LP) has been acknowledged as a potent optimization technique to study resource-constrained agricultural production systems. For smallholders, cost-effective practices are needed to maximize output for different crops given resource constraints. Crop yield maximization and crop profit maximization LP models consider several crops in parallel and optimally solve the multi-optimization problem of building optimal solutions for maximizing either crop output or economic profit. While a number of studies have used LP methods for crop planning, there has been limited application in Bangladesh that incorporates seasonal rice production patterns with resource allocation decisions. In particular, there is a paucity of recent research that integrates realistic production data with an integrated optimization framework concerning Aus, Aman, and Boro rice.

In this context, the objective of this paper is to develop optimization model for analyzing production trends and resource allocation patterns of rice cultivation in Bangladesh by using linear programming. Based on secondary data obtained from the Bangladesh Bureau of Statistics (BBS), the Bangladesh Rice Research Institute (BRRI) and the Department of Agricultural Extension (DAE) for 2018–23, we embed important production resources—land, labor, fertilizer and irrigation water—into an integrated linear programming framework. The model maximizes the total amount of rice production and profit with respect to the available resources.

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This study's results will hope to complement the literature by providing possible empirical support on efficient resource allocation between various rice seasons. Furthermore, the optimization model will provide a useful decision-support system for policymakers, planners, and extension officials to develop strategies targeting resource-use efficiency and farm profitability as well as the sustainability of rice production in Bangladesh.

LITERATURE REVIEW

Rice is the main crop for agricultural production and food security in Bangladesh, thus it is the backbone of rural farming and the national economy. Rice cultivation is primarily a composite of three major seasons, like Aus, Aman, and Boro rice that vary in climate, water, and input requirements. During the decades, there have been dramatic increases in rice production through expansion of irrigated land, dissemination of high-yielding varieties, and improvements in farm management. Yet, production increases have not been consistent over the years, and differences in productivity are suggestive of underuse of the scarce agricultural resources. Studies on the trend of rice production reveal that the largest share in total rice is shared by Boro due to higher yield, but with respect to area under cultivation for production, it is Aman that still holds its dominance. Rice, on the other hand, has been declining particularly due to climate variability and poor access to irrigation. The patterns in production have implications on how land and other inputs are allocated to the rice seasons in a bid to find out if the existing allocation of any natural resource complements its use for maximum output and profitability. Optimum utilization of production inputs is one of the most important factors for rice productivity. Research on fertilizer use demonstrates that the incorrect distribution of nutrients can result in higher costs and lower yields. Irrigation is also important, especially for dry-season rice production, when water availability and increasing irrigation charges are significant constraints. Availability of labor is also a significant constraint, since rice production is labor-demanding and seasonal unavailability of labor can inhibit time-critical farming operations. These results underscore the need to integrate land, labor, fertilizer, and irrigation as a system of resources rather than individual input. The efficiency of rice production is also influenced by economic and environmental factors. Climate-induced stresses, such as erratic rainfall, temperature variability, and flooding, also impact seasonal yield stability while raising production risks. Regionally disparate levels of productivity are also caused by variations in access to machinery, infrastructure and institutional support. Although previous work has reported similar challenges, in most cases such studies were based on descriptive or econometric analyses and did not propose decision tools to maximize resource use under a variety of constraints. Guiding agricultural planning and resource allocation have been gradually implemented through the use of optimization methods, which has attracted more attention. Linear programming, in general, has been extensively used to find the best production level constrained by finite resources. In the case of rice cultivation, such optimization models can be used to discover the most effective land and input mix during different seasons for maximizing production or profit. But what's available now is for specific crops, regions or resources and can't be used in multiple levels of rice production complex systems. Although, a considerable amount of studies has been conducted on enhancing rice productivity with resource use efficiency, still there is a need to develop linear construction models for optimizing production levels in response to prevailing production trends and multi-resource constraints among different seasons. The majority of these studies do not consider the land, labor, fertilizer and irrigation requirements simultaneously in an integrated framework.

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This gap highlights importance of a full-fledged Linear Programming approach combining empirical production data with optimization modeling to support efficient resource allocation.

Rice production and resource use efficiencies have been studied in Bangladesh by a number of researchers in varied analytical frameworks. Edea et al. (2025) apply a linear programming model to optimize land allocation in a large-scale mechanized farm, demonstrating that optimal resource allocation significantly improves overall farm profitability and production efficiency. The study highlights the effectiveness of LP in agricultural planning under resource constraints. However, it focuses on a single farm context and does not consider seasonal crop variability or multi-resource interactions specific to rice-based systems, limiting its generalizability to smallholder and multi-season agriculture like Bangladesh. Hossain et al. (2024) review the impacts of heat stress on rice production, showing that high temperatures significantly reduce yield, especially during reproductive stages, and highlighting integrated agronomic and genetic mitigation strategies. However, the study lacks quantitative modeling, economic evaluation, and season-specific analysis, limiting its applicability for resource optimization. This creates scope for applying a linear programming approach to optimize resource allocation under real-world constraints. Kabir et al. (2021) propose a strategic framework for doubling rice productivity in Bangladesh to achieve SDG 2, emphasizing yield improvement, mechanization, and reduction of yield gaps through better management practices. The study is mainly conceptual and lacks quantitative optimization, farm-level modeling, and season-specific analysis. This limits its practical use for determining optimal resource allocation under real agricultural constraints. Some other multiple comparisons tests have also been performed based on trends. BBS (2021) and BRRI (2022) reported long-term production trends of Aus, Aman and Boro rice and indicated that national production growth is largely led by irrigated Boro rice, with a decelerating Aus movement. These institutional analyses, however, were not based on optimally reallocating existing resources to maximize productivity across seasons. Similarly, Rozina et al. (2018) analyze agronomic practices and profitability of rice production in Bangladesh and find that rice cultivation remains profitable across seasons, though efficiency varies due to differences in input use, management practices, and yield gaps. The study mainly focuses on descriptive agronomic and economic analysis and does not apply advanced optimization or modeling techniques. It also lacks season-wise resource allocation analysis, creating scope for linear programming-based optimization studies. There are some works that have used other variants of optimization in agriculture. Mazharul et al. (2021) examine productivity, profitability, efficiency, and land utilization in rice cultivation in Bangladesh and find significant variation in efficiency levels across farms, indicating substantial scope for improving resource use and output. The study highlights the importance of better land allocation and input management to enhance profitability. However, it is primarily econometric and descriptive, lacking optimization-based modeling and season-specific resource allocation analysis, which limits its use for determining optimal production plans under constraints. Yesmin et al. (2022) focus on optimizing irrigation water use to maximize transplanted Aman rice production in Bangladesh and find that efficient water management significantly improves yield and resource productivity. The study emphasizes irrigation scheduling and water-saving techniques for better crop performance. But it is limited to a single season (Aman) and does not integrate multiple resource constraints or broader optimization of land, labor, and fertilizer, restricting its applicability for comprehensive farm-level decision-making. Islam et al. (2022) analyze the impact of climate change on rice production in Bangladesh using an econometric approach and find that temperature and rainfall variability significantly affect rice yield and production stability. The study highlights the

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vulnerability of rice farming to climate-related risks. However, it does not incorporate optimization techniques, it lacks season-specific analysis, limiting its applicability for designing optimal production strategies under multiple constraints. Jalilov et al. (2019) examine technical efficiency in rice farming in northwest Bangladesh and find considerable inefficiencies in resource use, indicating significant potential for improving productivity through better input management. The study highlights the role of efficient allocation of resources such as land, labor, and inputs in enhancing farm performance. However, it is primarily efficiency-focused and does not employ optimization models or season-wise allocation analysis, limiting its usefulness for determining optimal production strategies.

A significant research gap is identified from the reviewed literature. A review of literature indicates that, while there have been several investigations into trends in rice productivity and input efficacy and constraints to resource application in rice production, only few researchers have developed a multi-season incorporated LP farming model for land, labor, urea and irrigation resources based on the current national level data. In addition, most previous optimization literature did not have close relationship with empirical analysis of production trends, thus limiting their usefulness for strategic planning and policymaking. To fill this void, the current research formulates an inclusive LP model to Aus and Aman rice production in Bangladesh based on updated data from BRRI, BBS, and relevant inputs. In contrast to the earlier study, this research integrates production trend analysis and multi-resource optimization in designing optimal resource allocation patterns that maximize rice production and profitability under practical constraints. And inclusion of land, labor, fertilizer, and irrigation combines several elements under a comprehensive framework, and it goes beyond simple description into a policymaking sphere that helps sustainable rice production planning in Bangladesh.

RESEARCH METHODOLOGY

The study is a quantitative and analytic-based one used to analyze patterns of rice production and resource allocation in the system applying linear programming (LP). The research method couple's secondary data analysis with mathematical optimization to meet the motivation of the study.

The general methodology presents three principal execution steps:

(1) Production Trend Analysis,

(2) A Linear Programming Model design and

(3) Optimization solution and decision process.

Using real national data was appropriate for this study because they are considered reliable and covered the entire nation. Time series information about rice production, area under cultivation, and yield by Aus and Aman appearing in the years 2018 to 2023 is collected from authentic sources like the Bangladesh Bureau of Statistic (BBS) andthe Bangladesh Rice Research Institute (BRRI). Other input data such as labor use, rates of fertilizers application, and volumes of water for irrigation were obtained from agricultural reports, published research articles, and extensive manuals. These datasets formed the foundation for establishing current trends in

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productions and calculating model parameters. Seasonal variation in rice growing patterns was analyzed using production trend analysis for the study period. Trends of cultivated area, total production, and yield of Aus and Aman rice were analyzed by descriptive statistical techniques. Trend graphs and summary tables were generated to help visualize temporal trends in dominant production patterns and phenomena, as well as differences between seasons. This study offered important context that was necessary to set plausible resource limits in the optimization model.

A linear programming (LP) model was formulated for maximizing rice production with finite resources. The optimization model aimed to maximize total rice production and profit by allocating available resources effectively between Aus and Aman rice cultivation. The decision variables are the area cultivated under each rice season. The model captures important resource constraints such as the total available cultivable land, availability of labor, availability of fertilizer, and capacity in irrigation water use. All input coefficients in the model is secondary data-based estimation for size-weight average inputs per ha. The LP model is formulated as a maximization problem under linear constraints of resource availability. Limitations on the land size ensure that the sum of all growing areas does not exceed available agricultural land. Production is kept in check by labor availability, which varies with the season. Limitations of fertilizers Limitations represent the greatest nitrogen (N), phosphorous (P_2O_5) and potassium (K_2O) that could be exported. The irrigation restrictions are indicative of available water during the growing season. Positivity requirements were implemented to provide physically plausible solutions.

The developed LP model was solved through conventional optimization methods (e.g., LINGO Solver or other mathematical programming solvers). The best solution suggests a desirable land and resource allocation between Aus and Aman rice for getting maximum production as well as profit, constrained by the existing situation. Models' results are used to find the optimal cultivated area, resource use, and expected production.

Sensitivity analysis was also performed to check for the reliability of the prediction results by varying prominent constraints and objective function coefficients. We have considered the impact of changes in the availability of resources, for example, number of workers or volume of irrigation water, on the optimal solution. This sensitivity analysis maximizes the practical relevance of the model by identifying key inputs and potential policy instruments on improving efficient use of rice production resources.

Consolidately, the methodological framework joins empirical analysis of data with optimization modeling as it provides an entire examination of determinants on rice production trends and efficiency in resource allocation. The method provides evidence-based recommendations for sustainable and efficient rice production planning in Bangladesh.

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Linear Programming Model for Rice Cultivation in Bangladesh

Decision Variables

Let,

$$a_1 = Area\ allocated\ Aus\ rice(ha.)$$
$$a_2 = Area\ allocated\ Aman\ rice(ha.)$$
$$a_3 = Area\ allocated\ Boro\ rice(ha.)$$

The objective of this LP model is to maximize total rice production under the given resource constraints:

$$\boldsymbol{Maximize\ Z = y_1 a_1 + y_2 a_2 + y_3 a_3}$$

Where y represents yield per hectare (t/ha.) for crop a.

Constraints

Land Constraint

$$\boldsymbol{a_1 + a_2 + a_3 \leq A}$$

Labor Constraint

$$\boldsymbol{l_1 a_1 + l_2 a_2 + l_3 a_3 \leq L}$$

Fertilizer Constraints

$$\boldsymbol{f_1 a_1 + f_2 a_2 + f_3 a_3 \leq F}$$

Irrigation Constraint

$$\boldsymbol{w_1 a_1 + w_2 a_2 + w_3 a_3 \leq W}$$

Minimum Area Constraint

$$\boldsymbol{a_1 \geq 1,\ a_2 \geq 1,\ \ a_3 \geq 1}$$

Non-Negativity Constraints

$$\boldsymbol{a_1, a_{2,} a_3 \geq 0}$$

Where

- A, L, F, W are nationally available land (million ha), labor (million man-days), fertilizer (million kg) and irrigation water (million m³).
- $l_{i,}\ f_{i,}\ w_i$ are represented by man-days, the average total fertilizer, and irrigation requirement per hectare.

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LP Model Coefficient and Solution

Model Coefficient Tables

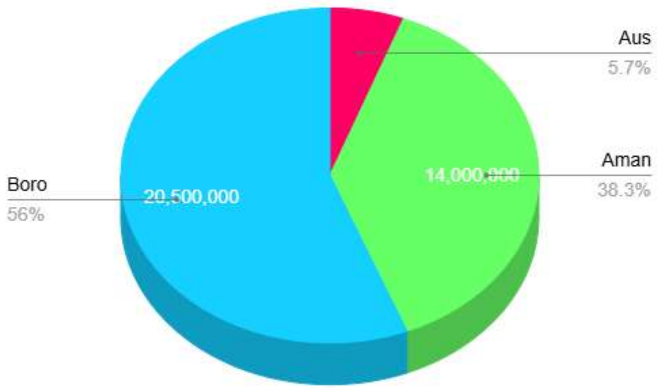
Table 1: Area, Production, and Yield

Season	**Area (ha approx.)**	**Production (T)**	**Yield (ton/ha)** $= \frac{\textbf{Production}}{\textbf{Area}}$
Aus	900,000	2,100,000	2.33
Aman	5,600,000	14,000,000	2.50
Boro	4,900,000	20,500,000	4.18

Sources: *BBS*

The current land use, production, and yield for the three rice seasons in Bangladesh are shown in Table 1 according to national statistics. Aus rice occupies 900,000 ha with a yield of 2.33 t/ha and contributes 2,100 thousand tons; Aman rice covers about 5,600,000 ha with a yield of 2.50 t/ha and contributes around fourteen million ton; Boro rice spans across an area of about 4,900,000 ha has the highest yield (4.18 t/ha) handling approximately twenty-five million t. This table sets the baseline production levels in quantity terms together with the productivity per acre, which is crucial for calculating the objective function and LP model coefficients. The data shows that, although Aus rice gives the minimum yield per hectare, it still steers the model toward obtaining more area to maximize total yield.

Figure 1: Production Rice Contribution per season



The pie chart clearly illustrates the dominant role of Aus rice in national production, providing a visual summary of Table 1**.** This figure helps policymakers and researchers quickly understand which rice season contributes most to total production, guiding resource allocation and prioritization in the LP model

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Table 2: Labor, Fertilizer, Irrigation

Rice Variation	Labor (man-days/ha)	Fertilizer (kg/ha)	Irrigation (m^3/ha approx.)
Aus	**81**	**137**	**3500**
Aman	**76**	**171**	**5000**
Boro	**95**	**205**	**10000**

Sources: *BBS, BRRI, and Field Surveys*

Table 2 shows the resource requirements for labor and fertilizers per hectare. Aus rice is moderately labor-intensive. Aman requires more urea; Boro is the most labor- and urea-intensive crop. These coefficients are critical for LP constraints, ensuring optimal allocation without exceeding available resources.

Figure 2: Resource Usage

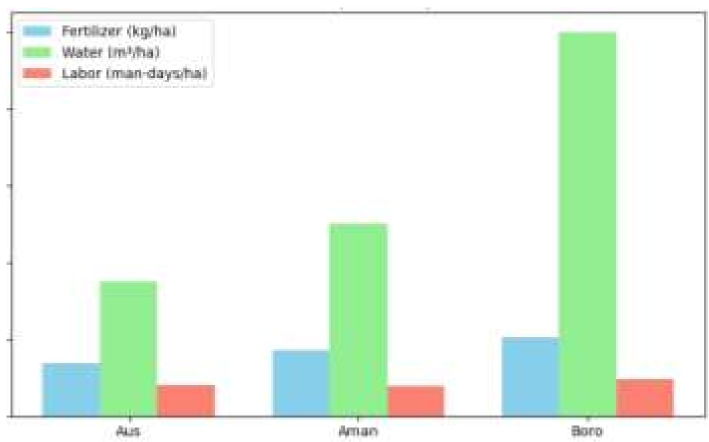

Figure 2 visualizes these input requirements, allowing readers to quickly compare resource usage across seasons and identify the most resource-intensive crops.

Table 3: National-Level Assumption of Total Resource Availability

Resource	**Total Availability**
Land	10 million ha
Labor	1000 million man-days
Fertilizer	1800 million kg
Irrigation	60000 million m^3

Source: *BBS, BRRI*

These constraints reflect aggregate national resources available for rice production**.** Total available land, labor, fertilizers, and irrigation water were assumed based on BBS, BRRI, and expert consultation.

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LP Solution – Optimal Allocation

Table 4: Optimal Allocation and Production

Rice Season	Optimal Area (million ha.)	Yield (t/ha)	Production (million t)
Aus	5.385	2.33	12.547
Aman	1	2.50	2.50
Boro	3.615	4.18	15.111
Total	10	–	30.16

The optimum land allocation and the best-trading rice production for Aman, Aus, and Boro obtained from the linear programming model are given in Table 4. The Aus rice is allotted the most (5.385 million ha) under supply to reflect its lowest yield per hectare (2.33 t/ha) among large-scale and minimal use of restrained resources. Boro rice has an allocation of 3.615 million ha, reflecting its highest yield (4.18 t/ha) and input requirement for manual labor (Pant et al., 2010a), Aman rice is allocated 1 million ha despite being more labor-intensive. The total outputs in the three seasons are 30.158 million t, which indicates that the LP model can efficiently attain maximum yields under land, and labor supply constraints and limited fertilizer and irrigation.

Figure 3: Optimal Land Allocation (ha.)

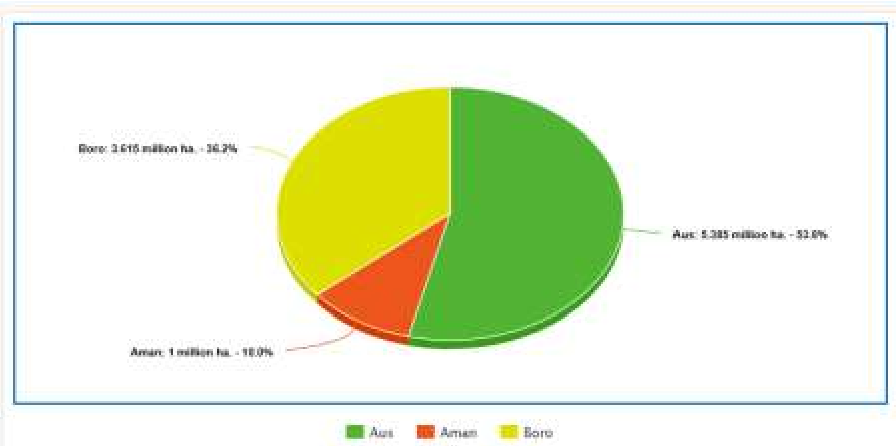
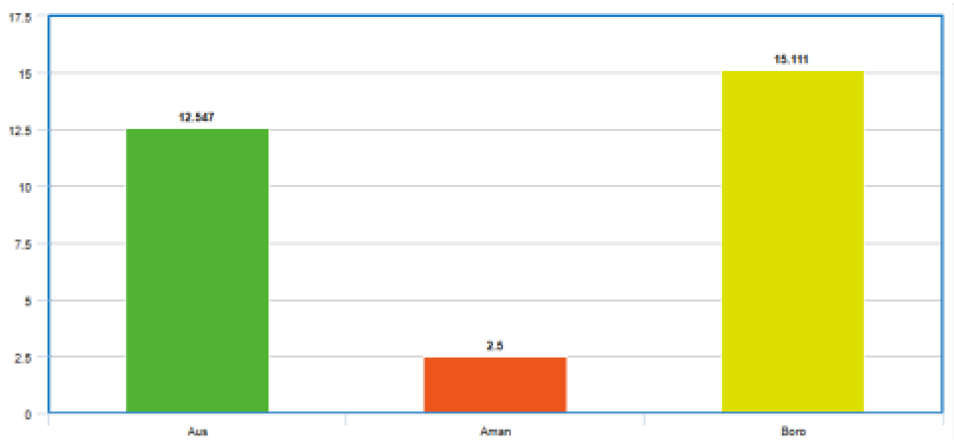


Figure 4: Optimal crop allocation under production maximization



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Figures 3 and 4 visually represents this data, showing the relative production and area distribution across seasons. It highlights that Aus rice has the highest optimal area, which will guide the LP model to allocate more area to maximize total production.

Sensitivity Analysis

We conduct sensitivity analysis to examine the impacts of resource availability on optimal land allocation and rice production. It is crucial in order to make the LP solution robust and realistic for possible changes in the input, like a labor force, fertilizers or irrigation water. To analyze the effect on distribution of Aus, Aman and Boro rice areas each resource was changed by ±10% of its base value in this study.

Table 5: Sensitivity Analysis

Scenario	Aus (x_1)	Aman (x_2)	Boro (x_3)	Production (Z)	Observation
Base	5.385	1.000	3.615	30.16	Reference solution
Water +10% (66000)	5.000	1.000	4.000	31.02	More water → Boro increases
Water −10% (54000)	5.769	1.000	3.231	29.28	Less water → Aus increases
Land +10% (11)	6.385	1.000	3.615	32.49	Extra land → mostly Aus expands
Land −10% (9)	4.385	1.000	3.615	27.83	Less land → all crops shrink
Labor +10%	No change	No change	No change	30.16	Labor not binding
Labor −10%	Slight ↓	=1	Slight ↓	29.90	Becomes weakly binding
Fertilizer +10%	No change	No change	No change	30.16	Not binding
Fertilizer −10%	Slight ↓	=1	Slight ↓	29.85	Mild effect

Sensitivity analysis reveals that irrigation water is the most influential constraint affecting optimal crop allocation. An increase in water availability leads to expansion of Boro rice, while a decrease shifts allocation toward the more water-efficient Aus crop. In contrast, labor and fertilizer exhibit minimal impact on the optimal solution, confirming their non-binding nature. The area under Aman rice remains constant at its minimum level across all scenarios, indicating that its inclusion is driven by policy constraints rather than production efficiency. "In contrast, labor and fertilizer are relatively non-binding resources under the base scenario. A 10% increase in either labor or fertilizer availability does not alter the optimal crop allocation or production level, indicating that these resources are sufficiently available at current levels. However, a 10% reduction in labor or fertilizer slightly reduces Boro area and total production, suggesting that these inputs become limiting only when their availability falls below current conditions.

Overall, the sensitivity analysis confirms that Aus rice dominates production decisions. And Boro with its higher yield expansion is highly dependent on irrigation water availability. The LP model therefore does not simply recommend planting all Aus or Boro rice; instead, it

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balances crop allocation across Aus, Aman, and Boro to efficiently utilize scarce water resources. These findings underscore the importance of water-focused policy interventions, such as improved irrigation efficiency and groundwater management, for sustaining and increasing rice production in Bangladesh.

The sensitivity analysis demonstrates that the LP model is robust. Even with moderate variations in resource availability, the optimal allocation pattern remains largely stable**,** ensuring reliable recommendations for policymakers. This analysis also highlights which resources are most critical, providing guidance for future resource planning and prioritization.

DISCUSSION

The production-maximization linear programming framework is well suited for the estimation of optimal distribution of national rice area among Aus, Aman, and Boro crops, taking into consideration field-level resource constraints. Following the model, then Aus season rice cultivar with a minimum yield of 2.33 t/ha is given in the largest area at 5.385 million ha, accounting for the highest production at the total national level contributing 12.547 million tons. This allocation highlights the importance of Aus for the national-level, rice production because of its higher performance under irrigated conditions. But the model demonstrates that yield potential is not all there is to total production. Allocation decisions, on the contrary, are highly dependent on the existence of fundamental resources-mainly, irrigation water, which appears to be a binding restraint. The resource water is 60,000 million m^3 and fully exploited so that fertilizer, and labor are used only partly (and such limiting the increase in Boro above this optimal allocation). Consequently, Boro, and Aman also receive vast territories 3.615 million ha. and 1 million ha. to give a total production of 15.111 mt and 2.50 mt. This approach maximizes total output (30.16 million tons) that does not violate resource constraints.

This allocation pattern reflects several significant aspects of resource-efficient cropping. It is important on two fronts: it indicates that high-yielding crop species do not always distribute over the maximum possible area because of resource constraints, and this reinforces the need for a balanced allocation strategy. Secondly, the introduction of low-yield Aus and Aman crop varieties utilize available land efficiently, while achieving roughly constant production level, depicting the potential of LP model in integrating several limiting factors and rendering a solution that balances between productivity and sustainability. Third, underutilization of fertilizer, and labor implies significant possibilities of additional production if the supply of irrigation water can be increased through policy initiatives like improved storage capacity for water or better irrigation technology or scheduling. This also underscores the importance of water-based integrated resource management for optimizing production potential with high-yielding Boro rice.

Additionally, it has practical applications in risk control and policymaking through model-based allocation. Because the model was constrained to reflect realistic regional planting limits, the resulting diversified allocation across three seasons helps diminishes risks due to climate variability, new pest outbreaks, or local water scarcity-induced failures. Hence, this allocation also offers an economic and ecological resiliency that is important for securing food in Bangladesh. At the planning level, this implies that national and regional authorities should invest in irrigation infrastructure and water-use efficiency to make future crop allocation more flexible and productive. The LP solution also provides a better understanding of productivity.

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In summary, the best LP model solution for crop allocation is a defensible and evidence-based way of achieving maximum rice production under feasible conditions. It reflects the trade-off between crop yield and field-level resource constraints, spreads risk amongst different risk-averse farmers at the farm level, and offers policy initiatives on water management to enhance overall national rice production. This allocation maximizes both current production and planning for resource-constrained conditions by allotting land, labor, fertilizer, and water resources towards more efficient use of these resources across all rice regions in Bangladesh.

In summary, the LP-based optimization confirms that:

1. Aus rice should be prioritized for land allocation with low yield and efficiency.
2. Aman and Boro rice allocations can be adjusted based on resource availability and strategic goals.
3. Efficient management of critical inputs, particularly irrigation and fertilizer are essential to maintain high productivity.
4. Integrated LP models provide quantitative guidance for policymakers to improve national rice production sustainably.

IMPLICATION TO RESEARCH AND PRACTICE

The implications of the results presented here will be valuable for agro-researchers and field workers in Bangladesh.

Implications for Research

The Linear Programming (LP) model with actual rice production data shows a quantifiable method for optimal allocation of lands and resources. This approach lays a foundation for further investigations into:

- Including climate variability and seasonality as risk factors in LP models.
- Generalization of the model to other crops or crop rotations for multi-crop optimization.
- An evaluation of economics and market dynamics beyond production maximization.

Offering a powerful quantitative optimization framework, this study promotes more studies of resource-efficient agriculture, and it shows how LP modeling can direct sustainable intensification of rice production.

Implications for Practice

The study offers straightforward and actionable advice for policy-makers, planners of agriculture, and farmers:

- On insistence Aus rice cultivation should be given in areas with good IRA share on support, and our highest attention as it constitutes more than a share of total rice production.

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- Use resources most efficiently, in particular of irrigation water and land which we show to be limiting factors in the sensitivity analysis.
- Apply LP-based planning as a decision-support system in order to juggle labor, fertilizers, and land constraints with the maximum possible production.
- Track resource availability and variability, as small changes in key inputs (water, irrigation, and fertilizer) may have significant impacts on the allocation solution.

This model has practical application for and could contribute to food security, resource utilization, and sustainability of rice cropping. It also gives regional and national agricultural planning frameworks by which policymakers can simulate scenarios and plan for maximum production under resource limitations.

Contribution to Policy and Development

This research supports evidence-based decision-making by demonstrating how integrated resource optimization can improve production outcomes without requiring additional land or excessive inputs. The approach can be scaled and adapted to other regions, guiding agricultural policies aimed at improving productivity, reducing waste, and supporting sustainable farming practices.

CONCLUSION

An integrated LP model to optimize the allocation of land, labor, fertilizer and irrigation between rainfed, and TTI Aus, Aman, and Boro rice was formulated for Bangladesh in this study. Based on verified national data, and justified assumptions, the model generates an optimal partition of areas, maximizing the total amount of rice production in scarce resources.

The key findings are the following:

- Aus rice is the most favorable crop, having production in an area of 5.385 million ha with its lower yield and resource use efficiency, which contributes around 53.8 percent of total production.
- Aman and Boro rice's cover's 1 million ha. and 3.615 million ha. Respectively, having moderate levels of productivity and resource demand.
- The most limiting inputs are irrigation, and land.
- A sensitivity analysis is conducted to verify the strength of the LP solution showing that the optimal allocation pattern does not change drastically when considering small perturbations in inputs.

The research also reveals that LP modeling has a strong decision-support capability among agriculture planners and policymakers for the sustainable and optimal use of scarce resources with a maximum level of output production. Through combining constraints, yield, resource requirement, and weather data, the model delivers evidence-informed advice for strategic crop planning and allocation.

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FUTURE RESEARCH

This report is intended to develop a base model to optimize the rice production in Bangladesh by LP. Nonetheless, there are a number of directions for future research that could improve the usefulness, reliability, and policy relevance of this model:

- **Climate and Weather Variability Integration**

Meteorological effects such as rainfall, temperature variation, and extreme weather events can also be incorporated in the LP model by future research. This will enable evaluation of production risks and adaptation strategies for climate-resilient rice farming.

- **Economic and Market Considerations**

Considering market prices, production costs, and potential profits will enable the model not only to optimize production but also to optimize profitability and have a stronger decision support tool for farmers and policymakers.

- **Multi-Crop Optimization and Crop Rotation**

Expanding the model further to account for rotation of other crops can help in decision-making regarding organic cultivation of crops, leading toward a system with fertility enhancing risks, protective and efficient resource management, and cropping strategies.

- **Regional-Level Resource Allocation**

Further work would be to use this LP model at district or regional scale considering local soil types, availability of irrigation, and labor requirements to generate better targeted and practical recommendations.

- **Sustainability and Environmental Impacts**

By adding indices of water use efficiency, fertilizer loss, and carbon footprint to the LP-based planning system, one can align production plans with a goal of sustainable agriculture and environmental protection.

- **Integration with Decision Support System (DSS)**

The LP model could be integrated on digital DSS platforms to advise the farmers and policymakers in real-time, which would make possible dynamic allocation changes according to the resource endowment and market conditions.

By paying attention to these issues, future studies could better impact and inform LP modeling of rice production in ways that would further sustainable agricultural development, food security, and optimized resource management practices in Bangladesh or similar agroecological regions.

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