PRODUCTIVE EFFICIENCY AND AGRICULTURAL SUSTAINABILITY: INTEGRATION OF QUANTITATIVE DATA FOR STRATEGIC PLANNING

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ABSTRACT

Modern agriculture faces challenges related to increasing productivity, conserving natural resources, and reducing environmental impacts. This study uses the robust *Agriculture and Farming Dataset*, available on the Kaggle platform, to explore yield efficiency and sustainability in different combinations of soil type and growing season. Data on agricultural practices, inputs, yield, and economic and environmental sustainability were analyzed. He focused on two contrasting combinations: Loamy-Zaid and Peaty-Kharif. The results indicate that Loamy-Zaid has higher absolute productivity (33.38 tons), but at the expense of higher input consumption (6.36 tons of fertilizers and 68,033.80 m³ of water). On the other hand, Peaty-Kharif demonstrates greater efficiency in the use of fertilizers (5.85 tons per ton of fertilizer) and water (0.00064 tons per m³), with lower cost per ton produced (163.20 currency units, against 197.11 for Loamy-Zaid). These results highlight the trade-offs between productivity and resource efficiency. The analysis of specific soil and season combinations revealed that edaphic and seasonal factors significantly influence yield. The Silty soil in Rabi proved to be ideal, reaching an average yield of 48.02 tons, while Peaty in Rabi exhibited severe limitations (3.86 tons), demonstrating the importance of customized management strategies. In addition, modern irrigation methods such as *drip* and *sprinkler* have shown higher water efficiency, although traditional methods such as manual irrigation have obtained higher yields in small farming systems.

The findings provide subsidies for more sustainable and productive agricultural practices. Optimized management strategies, such as soil amendment, use of biofertilizers, and advanced irrigation techniques, can align productivity, resource savings, and environmental sustainability. This study offers valuable guidance for researchers, farmers, and policymakers, promoting resilient and competitive agriculture in response to growing global demands for food and natural resources.

Keywords: Productive Efficiency. Agricultural Sustainability. Resource Management.

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INTRODUCTION

Agriculture plays an essential role in the global economy and in ensuring food security, being crucial to meet the demands of a growing population against a backdrop of climate change and limited natural resources (Domene et al., 2023). Faced with complex challenges, such as increasing productivity, conserving resources, and mitigating environmental impacts, the agricultural sector requires solutions based on integrated and detailed analysis. In this context, the use of data and quantitative models has become indispensable to understand the dynamics of agricultural systems, support decision-making, and promote practices that combine productive efficiency and sustainability.

This study is based on the *Agriculture and Farming Dataset*, available on the *Kaggle* platform, which offers a wide range of information on agricultural practices, crop yields, input utilization, and economic and environmental indicators. The dataset covers key variables such as crop types, soil characteristics, irrigation methods, and growing seasons, allowing for an in-depth analysis of the interactions between these factors and their effects on agricultural productivity. The wealth of information contained in this dataset provides a unique opportunity to identify patterns and propose strategies that balance productivity and environmental conservation.

Key aspects covered include:

1. Crop types: analysis of the predominant crops and their respective yield rates, considering different conditions.
2. Use of resources: evaluation of the allocation and efficiency in the use of water and fertilizers, with a focus on sustainability.
3. Sustainability indicators: examination of environmental impacts and economic viability of agricultural practices.
4. Economic data: detailed study of costs, revenues and profit margins, offering an integrated view of economic competitiveness.

The main objective of this work is to investigate how soil type and season combinations influence agricultural productivity, efficiency in the use of inputs and the sustainability of adopted practices, proposing strategies to optimize these interactions. To this end, the specific objectives include:

1. Evaluate the efficiency in the use of inputs such as fertilizers and water in relation to the production obtained.
2. Compare operating costs and sustainability between different combinations, identifying critical trade-offs.

3. Propose recommendations that maximize productivity while minimizing economic and environmental impacts.

The analysis focuses on two contrasting combinations of soil and season: Loamy-Zaid and Peaty-Kharif, selected for their distinct characteristics in productivity, input consumption and economic viability. The descriptive and inferential approach adopted explores patterns of resource use, operating costs and production efficiency, seeking to understand determinant factors for agricultural performance and propose practices that optimize the relationship between productivity and sustainability.

The results highlight that Loamy-Zaid has higher absolute productivity, although with high operating costs and significant consumption of inputs. On the other hand, Peaty-Kharif demonstrates greater efficiency in the use of resources, reduced costs per ton produced and greater economic sustainability, proving to be a viable alternative in scenarios of resource constraint. The interaction between soil characteristics and seasonal conditions proved to be decisive, reinforcing the importance of personalized approaches in agricultural management.

This study offers a significant contribution by deepening the understanding of the factors that affect agricultural performance, guiding farmers, researchers, and policymakers in building more resilient, productive, and sustainable agricultural systems. By integrating agronomic, economic, and environmental perspectives, the results provide a solid foundation for practices that meet the growing global demands for environmentally responsible food and economic competitiveness.

LITERATURE REVIEW

The literature on productive efficiency and agricultural sustainability highlights the need for integrated approaches that balance productivity, resource use, and mitigation of environmental impacts. In this context, sustainable management practices, the management of essential inputs, and climate-adaptive strategies emerge as fundamental pillars for building resilient agricultural systems. The analysis of recent studies highlights the complexity and opportunities of the Brazilian agricultural sector, reinforcing the role of strategic planning in promoting solutions that combine economic development with environmental preservation.

Ogino et al. (2021) analyze the interrelationships between mineral fertilizer prices, producers' purchasing power, and consumption in the Midwest of Brazil. Fertilizers are described as crucial inputs for productivity in poor soils, such as those in the Cerrado, but their dependence on imports exposes the sector to market volatility. Policies to stabilize prices and encourage research into alternative technologies are recommended to strengthen productive sustainability.

Castro et al. (2017) investigate the relationship between production value, productivity, and input use in Brazilian states, highlighting that the increase in fertilizer use between 1990 and 2012 boosted agricultural productivity, even in the face of territorial expansion limitations. This intensification, although essential, reinforces the need for practices that maximize efficiency gains without compromising natural resources.

Paz et al. (2002) emphasize the importance of uniformity in sprinkler irrigation as a determining factor to maximize economic efficiency and reduce environmental impact. Optimized water management, saving up to 18.64% of water, is essential to sustain productivity in scenarios of resource scarcity and climate variability.

Montoya and Finamore (2020) discuss the relationship between water resources and agribusiness, highlighting the water dependence of the agricultural sector, responsible for 90% of water consumption in Brazil. The study reinforces the need for practices that optimize the use of water, ensuring greater economic and environmental efficiency in the face of a scenario of growing water scarcity.

Novak et al. (2021) highlight that sustainable management practices, such as planting native species and the absence of mechanization, are key to restoring soil chemical quality and promoting long-term agricultural sustainability. These practices reinforce the importance of ecological stability in productive performance.

França et al. (2021) point out the relevance of soil physical properties, such as texture and porosity, for maintaining fertility and reducing erosion. Proper management of organic matter and preservation of soil aggregates are crucial for production efficiency and environmental balance.

Oliveira et al. (2022) analyze climate change adaptation measures in Nova Friburgo, RJ, highlighting conservation practices such as no-till farming and green manure. These strategies promote climate resilience and minimize environmental impacts, integrating environmental conservation and productivity in a scenario of regional vulnerability.

Magalhães et al. (2021) highlight the relevance of practices such as agroclimatic zoning and sustainable crop management to increase the resilience of the agricultural sector in the face of climate change. Productive diversification and the adoption of innovative technologies are pointed out as strategies to align productivity and environmental preservation.

This literature review shows that productive efficiency and agricultural sustainability depend on strategies based on the integration of technical knowledge, technological innovation and adaptive management. The literature reinforces the importance of public policies and private actions that encourage responsible agricultural practices, consolidating the sector as a pillar of sustainable development

METHODOLOGY

This study was conducted with the objective of evaluating productive efficiency and agricultural sustainability in different combinations of soil types and growing seasons. For this, the *Agriculture and Farming Dataset* was used, obtained from the *Kaggle* platform, which contains comprehensive information on management practices, crop yield, use of inputs and economic indicators. This dataset was essential to identify interactions between agricultural variables and to propose strategies that promote greater efficiency and sustainability.

The variables analyzed included numerical data, such as cultivated area (in acres), fertilizer consumption (in tons), pesticide application (in kilograms), total production (in tons), and water use (in cubic meters), as well as categorical variables, such as crop type, irrigation method, soil type, and growing season. This broad granularity allowed for a detailed study, highlighting the Loamy-Zaid and Peaty-Kharif combinations due to their distinct characteristics in terms of productivity and resource consumption.

The first stage of the study consisted of importing and processing the data using the Python language, with the support of the Pandas and NumPy libraries. Data cleansing techniques were applied to correct inconsistencies, such as missing or outlier values, which were retained if relevant to the analysis. Categorical variables were coded by *label encoding* to enable quantitative and statistical analyses.

The descriptive analysis of the numerical variables was performed using histograms, with the objective of identifying general trends and patterns in the distributions. A Pearson correlation matrix was generated to evaluate relationships between numerical variables, being visualized by heat maps, which allowed to highlight significant interactions, such as the impact of water consumption on productivity. For categorical variables, bar graphs were used to explore distributions and calculate the average productivity associated with different soil types and irrigation methods.

A cross-analysis between soil types and growing seasons was conducted to identify the most productive combinations. Heat mapping was used to represent the interactions between these variables, focusing on the Loamy-Zaid and Peaty-Kharif configurations. These combinations were subjected to detailed analyses of average fertilizer consumption, water use and productivity. The efficiency in the use of inputs was calculated by the ratio between the total production and the inputs applied, allowing the evaluation of the effectiveness of each combination in transforming resources into productive yield.

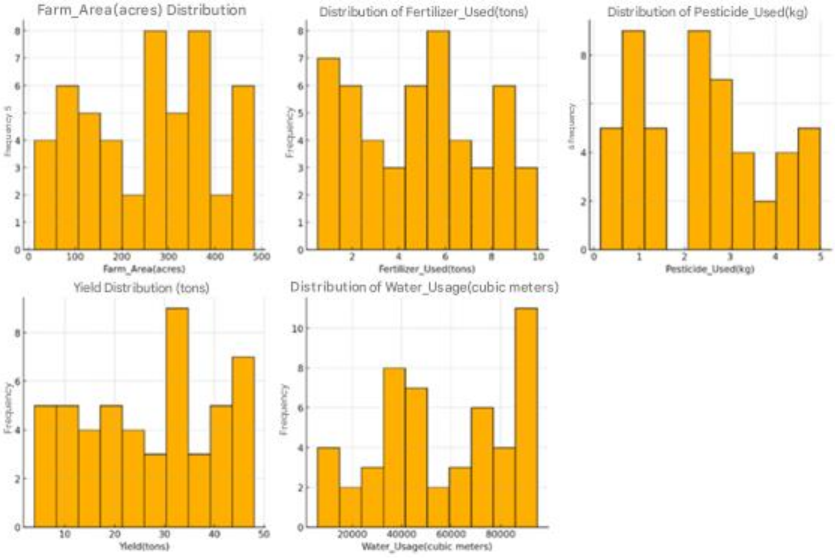
The methodology adopted followed strict principles of scientific reproducibility and ethical compliance, ensuring the proper treatment of data according to the terms of the original platform. Despite limitations, such as the absence of climate variables or agricultural policies, the results obtained provide robust bases for understanding and improving efficient and sustainable agricultural practices in various production contexts.

RESULTS AND DISCUSSION

This chapter presents a detailed analysis of the results obtained from the adjusted model, focusing on agricultural productivity, resource use, and efficiency in different soil and season combinations. Numerical and categorical variables were explored to identify significant patterns, correlations, and trends that can guide more sustainable and effective agricultural practices. The analysis considers the performance of the Loamy-Zaid and Peaty-Kharif combinations, highlighting trade-offs between productivity, costs and sustainability, based on empirical data.

Figure 1 presents histograms that illustrate the distributions of the main numerical variables extracted from the analyzed agricultural dataset. These graphs provide an overview of the dispersion and underlying patterns in variables related to agricultural productivity, inputs, and resources, allowing for a detailed analysis of the behavior of the data and possible correlations with the results obtained.

Figure 1: Distributions of Numerical Agricultural Variables: Area, Inputs, Productivity and Use of Resources



Source: Prepared by the author (2024)

The first graph represents the **distribution of Farm_Area (acres),** indicating that most farms have areas between 100 and 400 acres, with a more significant concentration around 200 and 300 acres. This distribution suggests that small and medium-sized farms predominate in the dataset, which may influence the use of inputs and agricultural productivity.

The second graph addresses the **distribution of Fertilizer_Used (tones).** The analysis shows that the use of fertilizers is relatively uniform, with values ranging from 0.5 to 10 tons, and a slightly higher concentration between 5 and 8 tons. This distribution reflects different management strategies, which may be associated with soil characteristics and the types of crops analyzed.

The third graph shows the **distribution of Pesticide_Used (kg),** highlighting that most farms use less than 3 kg of pesticides. However, there is a longer right tail, with some farms applying up to 5 kg. This pattern may indicate selective pest control practices, possibly related to crop diversity and the severity of infestations.

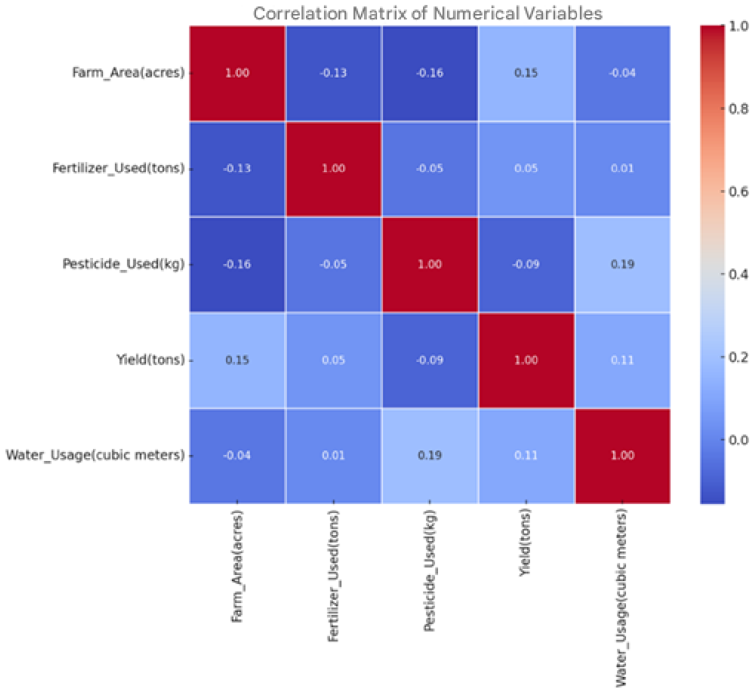
The fourth graph represents the **distribution of Yield (tons),** showing that productivity is predominantly concentrated between 15 and 40 tons, with a more accentuated peak near 30 tons. This result indicates a general consistency in production, although variations can be attributed to differences in management methods and environmental conditions.

Finally, the fifth graph shows the **distribution of Water_Usage cubic meters**, with consumption varying widely between 20,000 and 80,000 cubic meters, but with a slight slope to lower values. This behavior suggests that while water consumption is substantial, there is a considerable fraction of farms that adopt more moderate irrigation practices.

These distributions provide a solid basis for subsequent analyses, allowing us to explore correlations between variables and identify patterns that can guide more efficient and sustainable farming practices. A detailed analysis of the relationships between crop area, inputs and productivity will be key to understanding the trade-offs and proposing strategies that balance economic performance and environmental impact.

Figure 2 presented below consists of a correlation matrix of the numerical variables analyzed in the agricultural dataset. This matrix was constructed using Pearson's correlation coefficient, which measures the strength and direction of linear relationships between variables. The scale ranges from -1 to 1, where positive values indicate direct correlation, negative values indicate inverse correlation, and values close to zero suggest little or no linear relationship.

Figure 2: Correlation Matrix of Numerical Agricultural Variables: Relationships between Inputs, Resources and Productivity



Source: Prepared by the author (2024)

The **Farm_Area (acres)** shows weak correlations with the other variables, with emphasis on its moderate and positive relationship with the **Yield (tones)** (0.15). This suggests that larger farms tend to have slightly higher yields, but other factors may play more significant roles in determining productivity.

The variable **Fertilizer_Used (tons)** shows a weak correlation with **the Yield (tons)** (0.05), indicating that the use of fertilizers has a positive, but not significant, impact on productivity. This observation may reflect the presence of limitations in other production factors, such as soil conditions and water management, which affect the effectiveness of fertilizers.

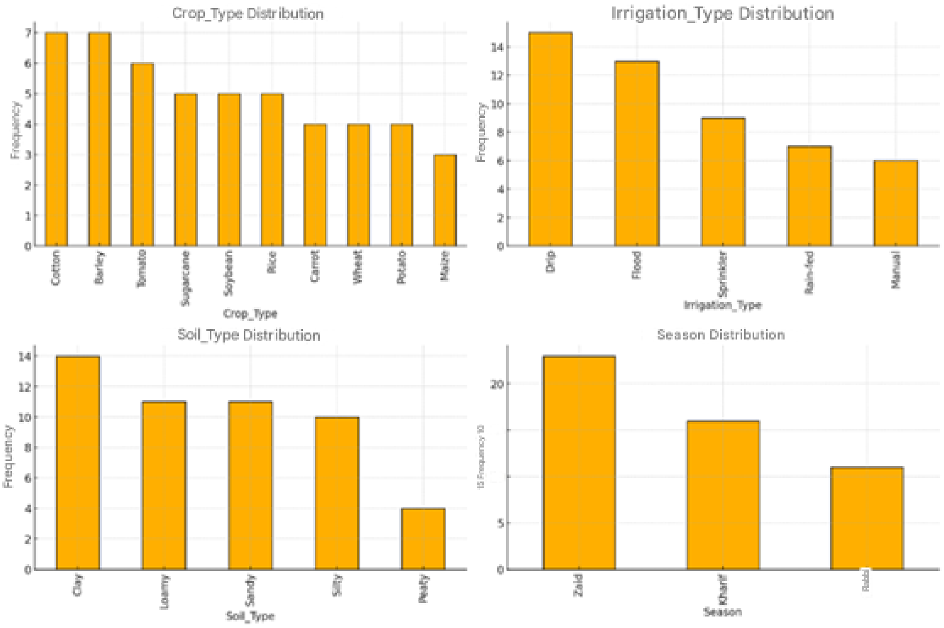
The **Pesticide_Used (kg)** demonstrates a negative, albeit weak, correlation with the **Yield (tones)** (-0.09), suggesting that the increase in pesticide use may not be directly associated with yield gains and, in some cases, may even reflect management problems or pest outbreaks under adverse conditions.

The Water_Usage (cubic meters) shows a weak and positive correlation with the **Yield (tons)** (0.11), indicating that a higher water consumption is related to a slight increase in productivity. However, the low intensity of this relationship reinforces the need for efficient irrigation practices that maximize productivity without significantly increasing water consumption.

The results of the matrix highlight the complexity of the interactions between agricultural variables and suggest that productivity is not defined in isolation by any specific input, but rather by an integrated set of factors. This analysis substantiates the need for multifactorial approaches to optimize agricultural production, considering economic, environmental and resource management aspects. In addition, the low correlation between inputs suggests opportunities for more sustainable practices, where the rational use of resources can be implemented without compromising productivity.

Figure 3 presented below contains four graphs illustrating the distributions of the main categorical variables in the agricultural dataset, addressing **crop type (Crop_Type), irrigation method (Irrigation_Type**), **soil type (Soil_Type)** and **growing season (season)**. Each graph contributes to a better understanding of the relative frequency and predominance of the different categorical factors that influence agricultural productivity.

Figure 2: Distribution of Categorical Variables in Agricultural Systems: Crops, Irrigation, Soil Types, and Growing Seasons



Source: Prepared by the author (2024)

The first graph, referring to the **distribution of Crop_Type**, reveals that the most predominant crops in the data set are *Cotton* and *Barley*, followed by *Tomato* and *Sugarcane*. Crops such as *Rice*, *Wheat*, and *Maize* are less represented. This pattern may reflect prevailing agricultural practices in certain regions or cultural and economic preferences related to market demand.

The second graph, which deals with the **distribution of Irrigation_Type**, shows that the *Drip* irrigation method is the most used, followed by *Flood* and *Sprinkler*. More traditional methods, such as *Manual*, have a lower frequency, indicating a possible transition to more automated and efficient systems. This may be associated with the search for greater efficiency in the use of water, especially in areas where this resource is scarce.

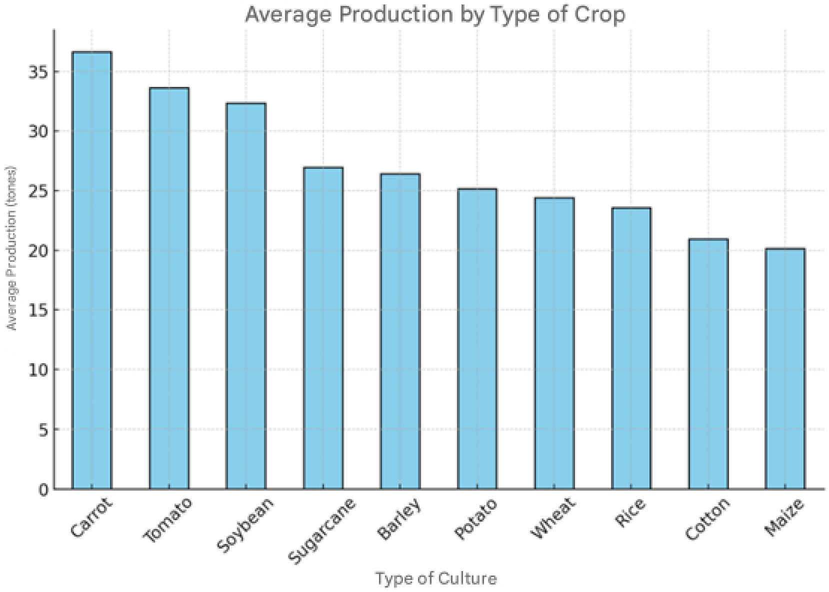
The **Soil_Type distribution**, shown in the third graph, highlights that *Clay* and *Loamy* solos are the most frequent in the dataset, while *Peaty* is the least represented. This distribution can be attributed to the agronomic characteristics of the soils, with *Clay* and *Loamy* often associated with favorable conditions for cultivation. The low frequency of *Peaty soils* suggests that this type of soil is less commonly used or presents specific restrictions for agricultural management.

Finally, the fourth chart addresses the **distribution of Season**, indicating that the *Zaid season* has the highest frequency, followed by *Kharif* and *Rabi*. This prevalence of *Zaid* may be related to favorable water and climate availability during this period, while differences in frequencies at other stations may reflect regional practices or limitations imposed by environmental conditions.

These graphs allow us to understand the predominance of certain categorical factors in the data set and raise hypotheses about how these factors can influence yield and agricultural management. The analysis of these distributions is essential to identify patterns and plan strategies that maximize efficiency and sustainability in agricultural practices.

The graph shown in Figure 4 illustrates the average production (in tonnes) associated with different crop types included in the agricultural dataset. This analysis is essential to understand the variations in yield performance between crops, allowing us to identify those with the highest yield potential and analyze the factors that can influence these differences.

Figure 4: Average Productivity by Crop Type: Comparative Analysis of Agricultural Yield



Source: Prepared by the author (2024)

The results indicate that *Carrot* has the highest average productivity, over 35 tons, followed by *Tomato* and *Soybean*, which also exhibit high yield rates. These crops stand out for their ability to respond more efficiently to the management conditions and inputs used, becoming attractive options for maximizing production in certain regions.

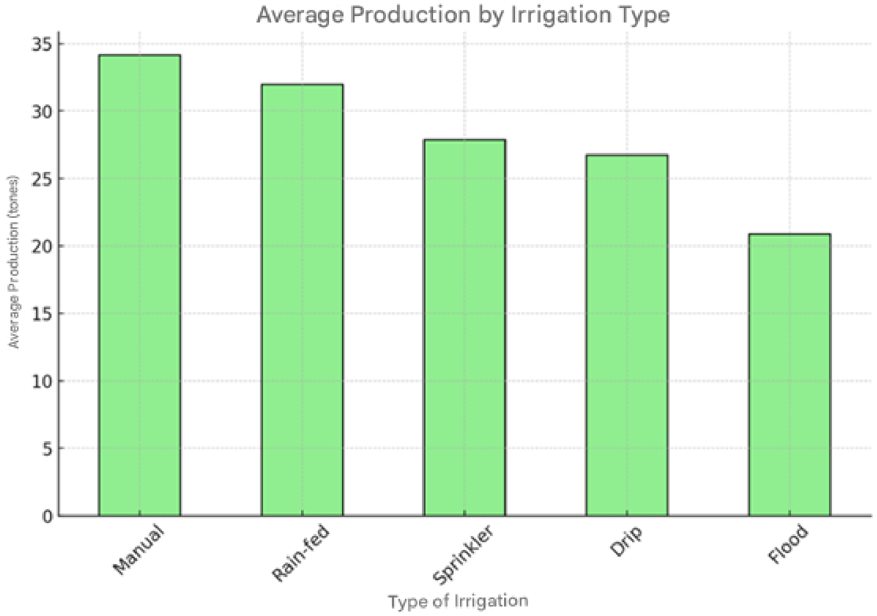
Crops such as *Sugarcane*, *Barley* and *Potato* occupy intermediate positions, with average yields ranging between 25 and 30 tons. These results reflect the competitive potential of these crops, which can be explored in specific contexts depending on economic viability and edaphoclimatic conditions.

At the lower end are *Rice*, *Cotton* and *Maize*, with average yields below 25 tons. The lower productivity of these crops may be associated with factors such as lower input intensity, intrinsic limitations of cultivation, or less advanced agricultural practices. However, these crops have strategic importance in many regions, due to their economic relevance and market demand.

This chart highlights the disparities in productivity between different crops, suggesting that strategic choices should be made based on regional analyses, resource availability, and economic demand. In addition, crops with lower average productivity present opportunities for optimization through the introduction of more advanced technologies and management practices. This analysis reinforces the importance of integrated agricultural strategies to maximize yield and sustainability in diverse production contexts.

The graph presented in Figure 5 analyzes the average productivity (in tons) as a function of the different types of irrigation used in agricultural practices. This graph provides relevant insights into how water management methods can influence yield efficiency in the crops analyzed.

Figure 5: Average Productivity by Type of Irrigation: Analysis of the Impact of Irrigation Techniques on Agricultural Production



Source: Prepared by the author (2024)

The Manual irrigation method has the highest average productivity, reaching values above 35 tons. Despite being a traditional technique, its high productivity may be related to the direct control of water management, allowing precise adjustments to the specific needs of crops. However, it is important to consider that this method can be more labor-intensive, limiting its applicability on a large scale.

The *Rain-fed* system emerges as the second most productive, with an average close to 30 tons. This method, which relies on natural rainfall, can be advantageous in regions with regular rainfall and well distributed throughout the crop cycle. However, its dependence on climatic factors limits its effectiveness in regions with water variability or scarcity.

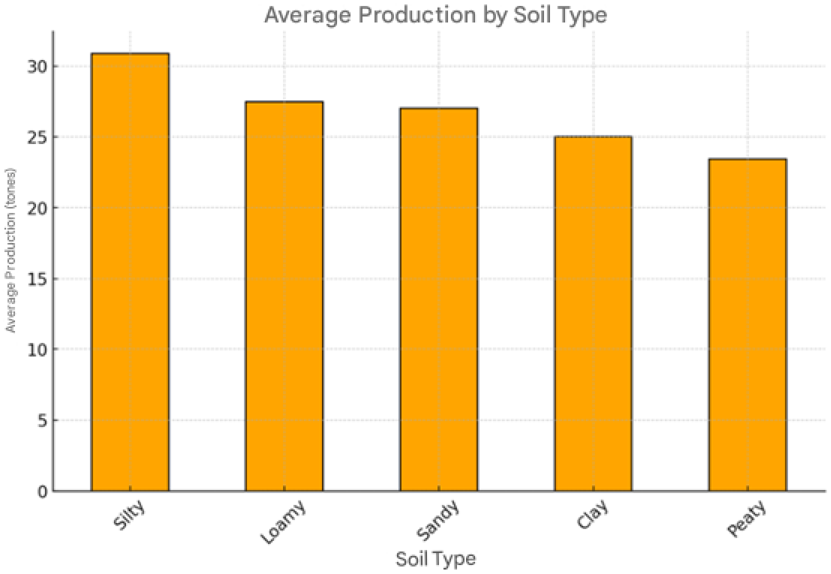
The *Sprinkler* and *Drip* systems exhibit similar average yields, in the range between 25 and 30 tons. Both represent modern and highly efficient methods in the use of water, reducing waste and improving irrigation uniformity. The moderate productivity observed in these methods can be attributed to external variables, such as soil type and crop cultivated, which affect the response to management.

On the other hand, the Flood irrigation method has the lowest average productivity, below 25 tons. This technique, characterized by large volumes of water flooding the cultivated area, is often associated with significant water losses and an increased risk of nutrient leaching. Although it is widely used in certain crops, such as rice, its low water efficiency can compromise production results in other contexts.

The analysis presented in the graph highlights the importance of aligning irrigation methods with the characteristics of crops, soil and environment, seeking to maximize water efficiency and productivity. Methods such as *Sprinkler* and *Drip* offer sustainable alternatives to traditional water management, while practices such as manual irrigation can be optimized in specific situations. Thus, the choice of the ideal irrigation system depends on an integrated assessment of agricultural needs and resource availability.

The graph shown in Figure 6 below shows the average production (in tons) as a function of the different soil types included in the data set. The analysis highlights the influence of soil physical and chemical characteristics on agricultural yield, offering valuable insights for management practices and soil selection for specific crops.

Figure 6: Average Productivity by Soil Type: Impact of Soil Characteristics on Agricultural Yield



Source: Prepared by the author (2024)

Silty *soil* has the highest average productivity, exceeding 30 tons. This type of soil is widely recognized for its fine texture and excellent water and nutrient retention capacity, characteristics that favor the healthy development of plants and, consequently, a high productive yield. This superiority suggests that, when available, *Silty* soil may be a preferred option for intensive crops.

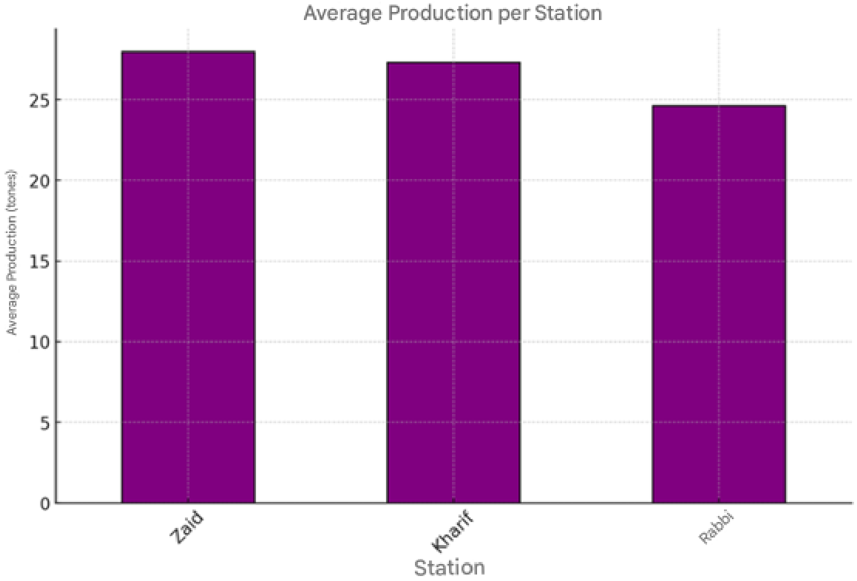
The *Loamy* and *Sandy* soils continue to be productive, with average values around 27 to 28 tons. *Loamy* soil is often considered ideal for agriculture due to its balance of sand, silt, and clay, providing good drainage and nutrient retention. The *Sandy* soil, in turn, despite having low water retention, can be advantageous in crops that require good drainage and efficient water management.

The Clay *and* Peaty *soils* exhibit the lowest average yields, with yields of less than 27 tons. *Clay* soil, due to its heavy texture and low permeability, can hinder root growth and water infiltration, especially in improper management conditions. *Peaty soil*, on the other hand, although rich in organic matter, presents challenges such as high acidity and lower availability of essential nutrients, which can limit its productive potential in certain crops.

These results highlight the importance of aligning soil type with specific crop demands and management practices. High-productivity soils, such as *Silty* and *Loamy*, may be preferred for maximizing yield in intensive farming systems, while soils with limitations, such as *Clay* and *Peaty*, require specific interventions, such as pH corrections, proper fertilization, and conservation practices. Thus, the choice of soil must be based on detailed edaphic analyses, considering both the productive potential and the economic and environmental viability.

Figure 7 shows the average yield (in tons) associated with the three main growing seasons: *Zaid*, *Kharif* and *Rabi*. This analysis allows us to understand how seasonal conditions influence the yield of agricultural crops, providing subsidies for the strategic planning of management practices and resource allocation.

Figure 7: Average Productivity by Growing Season: Analysis of the Seasonal Influence on Agricultural Yield



Source: Prepared by the author (2024)

The *Zaid* station has the highest average productivity, slightly over 25 tons. This performance can be attributed to the favorable climatic conditions of this season, characterized by moderate temperatures and adequate water availability, which favor plant development. Additionally, the lower incidence of pests and diseases during *Zaid* can contribute to the increase of production efficiency.

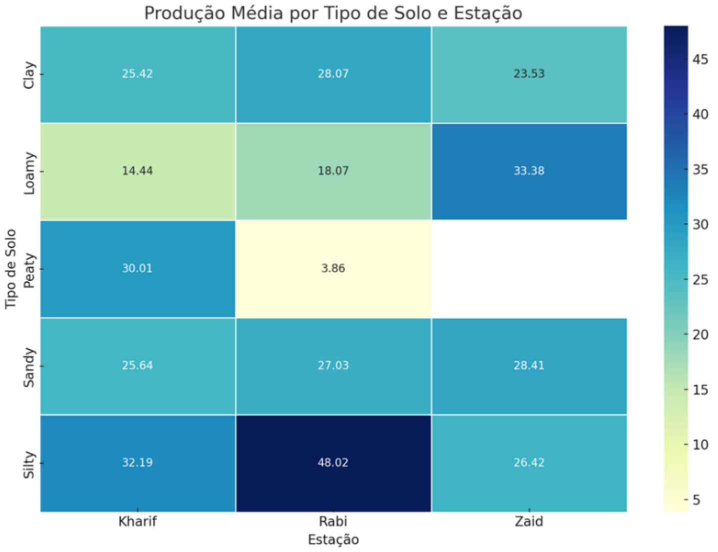
Kharif *Station* closely follows *Zaid*, with a similar average yield. *Kharif* coincides with the monsoon season in many regions, providing plenty of water through the rains. However, challenges associated with excess precipitation, such as soil waterlogging and nutrient leaching, can limit the performance of some crops. Additionally, the high humidity during *Kharif* can increase the incidence of pests and diseases, which necessitates more stringent management strategies.

The Rabi *station* has the lowest average productivity, although the difference in relation to the other stations is relatively small. *Rabi* is characterized by lower temperatures and lower water availability, which can restrict the growth of crops sensitive to these conditions. However, irrigation systems and management practices adapted for this season can partially mitigate the impacts of climate limitations, allowing for competitive yield in many situations.

This chart highlights the importance of considering seasonal characteristics in crop choice and crop management strategies. While *Zaid* and *Kharif* offer ideal conditions for many crops, *Rabi* calls for greater attention to the availability of resources and irrigation techniques to achieve satisfactory productive results. Seasonal analysis, therefore, is essential to optimize agricultural planning and promote sustainability in different production contexts.

The heat graph shown in Figure 8 illustrates the average yield (in tons) for different combinations of soil types and growing seasons. This visual representation facilitates integrated analysis by highlighting the interactions between edaphic and seasonal conditions in agricultural yield. Each cell of the graph reflects the productive average of a specific combination, allowing the identification of ideal scenarios and limitations associated with these variables.

Figure 8: Interaction between Soil Type and Growing Season: Average Productivity by Combination



Source: Prepared by the author (2024)

The Silty *soil combination* during the *Rabi* season has the highest average yield, reaching 48.02 tons. This result highlights the excellent ability of *Silty soil* to retain nutrients and water, combined with Rabi's moderate climatic conditions, which favor crop development. However, Silty's performance in other seasons, such as *Kharif* and *Zaid*, is less expressive, suggesting that its productive response depends on adequate seasonal management.

Loamy *soil*, recognized for its balance between drainage and nutrient retention, has the highest average productivity during *Zaid* (33.38 tons). This combination benefits from this season's favorable weather conditions and the consistent performance of *Loamy* soil, demonstrating its versatility as an agricultural substrate. On the other hand, *Loamy's yield* in *Kharif* and *Rabi* is considerably lower, at 14.44 and 18.07 tons, respectively, indicating that his productivity may be limited in harsher conditions.

Peaty *soil* exhibits contrasting behavior, with its highest productivity observed in *Kharif* (30.01 tons) but an extremely reduced performance in *Rabi* (3.86 tons). This suggests that *Peaty* soil, while rich in organic matter, faces significant limitations under Rabi's drier climatic conditions, likely due to low water-holding capacity and high acidity.

The Clay *and* Sandy *soils* show moderate and relatively consistent yields between seasons, with slight variations. However, in *Zaid*, the Clay soil shows a drop in productivity (23.53 tons), while *Sandy* shows a slight improvement (28.41 tons). These variations reflect the physical characteristics of these soils, such as the low permeability of *Clay* and the good drainage of *Sandy*, which respond differently to seasonal conditions.

This heat chart provides an integrated view on how soil type and season combinations influence agricultural productivity. The results highlight that strategic decisions about crop allocation must consider both edaphic and seasonal conditions to maximize production and efficiency. In addition, specific combinations, such as *Silty* in *Rabi* and *Loamy* in *Zaid*, represent ideal scenarios for optimized farming systems, while soils such as *Peaty* in unfavorable seasons require specific management strategies to mitigate their limitations. The analysis underscores the importance of tailored approaches in modern agriculture, promoting a balance between productivity, sustainability, and economic viability.

Table 1 compares the resources employed and the productive results for two distinct combinations of soil and season: *Loamy-Zaid* and *Peaty-Kharif*. The variables analyzed include average fertilizer use (in tons), water consumption (in cubic meters), and average productivity (in tons), providing a clear view of trade-offs between inputs and agricultural yield.

Table 1: Comparison of Resource Usage and Productivity Between Loamy-Zaid and Peaty-Kharif Combinations

Combination	**Fertilizer_Used(tons)**	**Water_Usage(cubic m)**	**Yield(tons)**
Loamy-Zaid	6,355714	68033,7957	33,38
Peaty-Kharif	5,133333	46602,47333	30,006667

Source: Prepared by the author (2024)

The *Loamy-Zaid* combination has the highest average yield, reaching 33.38 tons. However, this productive advantage is associated with a higher consumption of inputs, such as 6.36 tons of fertilizers and 68,033.80 cubic meters of water. These values indicate a high demand for resources to sustain superior productivity, which can negatively impact operating costs and environmental sustainability, especially in regions with water resource constraints.

On the other hand, the *Peaty-Kharif* combination demonstrates slightly lower productivity, averaging 30.01 tons, but uses significantly fewer resources. The consumption of fertilizers is 5.13 tons, while the use of water is 46,602.47 cubic meters. These data reflect a comparatively higher efficiency in the use of inputs, making this combination an attractive alternative in scenarios where costs or resource availability are limiting.

The comparative analysis shows that the *Loamy-Zaid* combination, despite being the most productive, has a lower efficiency in the use of resources. For every ton of fertilizer applied, the yield is approximately 5.25 tons in *Loamy-Zaid*, while *Peaty-Kharif* achieves an efficiency of 5.85 tons. The same pattern is repeated in water consumption, where *Peaty-Kharif* also surpasses *Loamy-Zaid* in terms of water efficiency.

These results raise important considerations about the feasibility of each combination. *Loamy-Zaid* is ideal for maximizing production in conditions where inputs are readily available and environmental impact is not a critical factor. *Peaty-Kharif*, on the other hand , stands out as a more sustainable and economical choice, especially in regions where resource conservation is a priority.

The table highlights the need for a balanced approach to agricultural decision-making. Strategies that optimize fertilizer and water use in *Loamy-Zaid* can improve its efficiency and reduce its environmental impacts. On the other hand, investments in technologies and specific management can raise the performance of *Peaty-Kharif*, making it even more competitive. These insights reinforce the importance of integrated analytics to align productivity, cost, and sustainability across diverse farming systems.

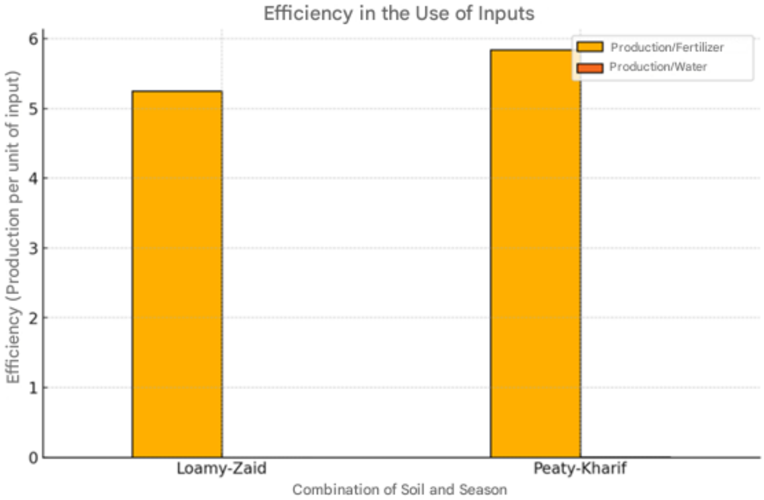
Table 2 and Graph 9 below analyze the efficiency in the use of inputs for two distinct combinations of soil and season: *Loamy-Zaid* and *Peaty-Kharif*. The table quantifies the production per ton of fertilizer (*Yield_per_Fertilizer*) and per cubic meter of water (*Yield_per_Water*), while the graph comparatively visualizes these efficiency indexes, highlighting the disparities between the combinations.

Table 2: Efficiency in the Use of Inputs: Comparison between Loamy-Zaid and Peaty-Kharif

Combination	**Fertilizer_Used (tons)**	**Water_usage (cubic m)**	**Yield (tons)**	**Yiel_per_Fertilize**	**Yield_per_Water**
Loamy-Zaid	6,3557	68033,7957	33,38	5,2519	0,00049
Peaty-Kharif	5,1333	46602,4733	30,0066	5,8454	0,00064

Source: Prepared by the author (2024)

Graph 9: Comparative Efficiency in Fertilizer and Water Use Between Soil and Season Combinations



Source: Prepared by the author (2024)

In the *Loamy-Zaid* combination, the production per ton of fertilizer is 5.22 tons, while the water efficiency is 0.00049 tons per cubic meter of water. These values reflect a high productivity, but associated with a considerably higher use of inputs, indicating that, although effective in maximizing absolute production, *Loamy-Zaid* has a limited efficiency in the use of the resources employed.

On the other hand, the *Peaty-Kharif* combination demonstrates greater efficiency in both metrics. For each ton of fertilizer used, the average yield is 5.85 tons, surpassing *Loamy-Zaid*. Similarly, water use efficiency reaches 0.00064 tons per cubic meter, representing a significant improvement over the other combination. This data highlights *Peaty-Kharif* as a more sustainable alternative in scenarios where resource availability is limited.

Graph 9 visually reinforces the differences pointed out by the table, showing that *Peaty-Kharif* consistently outperforms *Loamy-Zaid* in both efficiency metrics. The disparity is particularly pronounced in water efficiency, suggesting that *Peaty-Kharif* may be a more viable choice in regions where access to water is restricted or where sustainable agricultural practices are a priority.

The analysis presented emphasizes the trade-offs between absolute productivity and efficiency in the use of inputs. While *Loamy-Zaid* is best suited for contexts where maximizing yield is the primary goal, *Peaty-Kharif* offers a balanced approach between production and resource conservation. Strategies that combine optimized management practices in both combinations can help align sustainability and economic competitiveness, promoting more resilient and efficient agricultural systems.

Table 3 and Graph 10 presented below provide a detailed view of the costs associated with the use of fertilizers and water, as well as the productive efficiency of the

Loamy-Zaid and *Peaty-Kharif combinations*. The analysis examines total costs, costs per ton produced, and sustainability factors that guide agricultural practices.

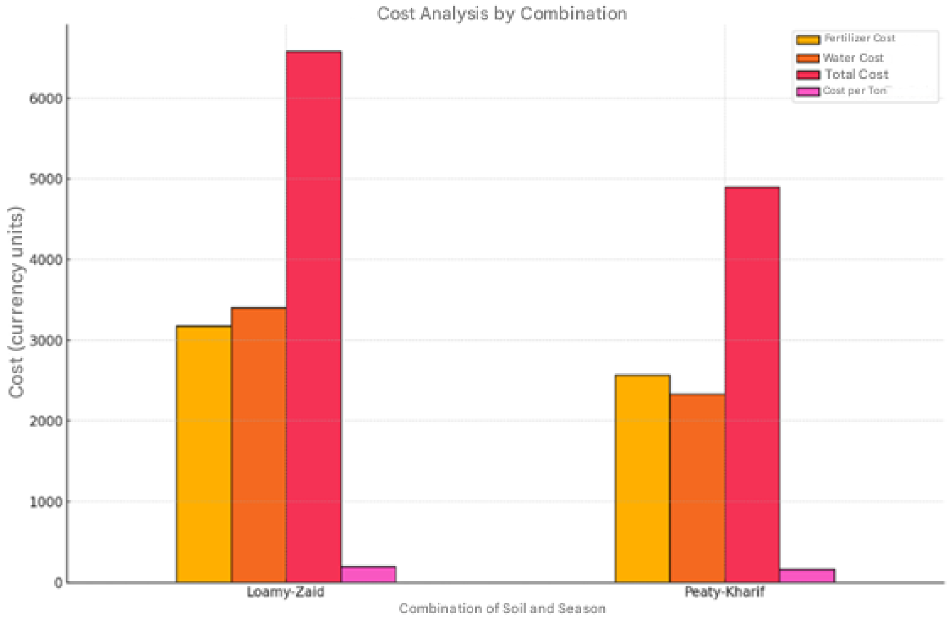
Table 3: Cost and Sustainability Analysis for the Loamy-Zaid and Peaty-Kharif Combinations

Combination	**Fertilizer_Used (tons)**	**Water_Usage (cubic meters)**	**Yield (tons)**	**Yield_per_Fertilizer**	**Yield_per_Water**	**Fertilizer_Cost**	**Water_Cost**	**Total_Cost**	**Cost_per_Ton**
Loamy-Zaid	6,36	68033,80	33,38	5,22	0,00049	3177,86	3401,69	6579,55	197,11
Peaty-Kharif	5,13	46602,47	30,00	5,85	0,00064	2566,67	2330,12	4896,79	163,20

Source: Prepared by the author (2024)

Table 3 highlights that the *Loamy-Zaid* combination has a total cost of 6,579.55 monetary units, significantly higher than the total cost of 4,896.79 *Peaty-Kharif* monetary units. This difference is mainly due to the higher consumption of water (68,033.80 cubic meters against 46,602.47 cubic meters) and fertilizers (6.36 tons against 5.13 tons) in *Loamy-Zaid*. Consequently, the cost per ton produced in *Loamy-Zaid* (197.11 currency units) is higher compared to *Peaty-Kharif* (163.20 currency units), which reinforces the lower economic efficiency of this combination.

Graph 10: Comparison of Costs and Efficiency by Soil and Station Combination



Source: Prepared by the author (2024)

Graph 10 shows the distribution of costs in each combination, showing that *Loamy-Zaid* has higher expenses in all categories: fertilizer cost, water cost and total cost. Despite this, the production of 33.38 tons at *Loamy-Zaid* is only slightly higher than the 30.00 tons seen at *Peaty-Kharif*. This disparity between costs and production reinforces *Loamy-Zaid's lower overall efficiency*.

Peaty-Kharif's *sustainable efficiency* stands out especially in the cost per ton produced, which is approximately 17% lower than *Loamy-Zaid*'s. This combination also demonstrates greater efficiency in the use of inputs, with a better relationship between inputs applied and productivity achieved, as already highlighted in previous analyses.

These results have important practical implications. While *Loamy-Zaid* may be preferred in scenarios where the priority is to maximize absolute production, *Peaty-Kharif* offers a more balanced alternative between cost, efficiency, and sustainability. In contexts where water resources are limited or where cost reduction is crucial, *Peaty-Kharif* has clear advantages.

The analysis in Graph 10 reinforces the importance of adapting agricultural strategies to local conditions. Investments in practices that optimize the use of resources in *Loamy-Zaid* can make it more competitive, while additional techniques such as biofertilizers can further increase the efficiency of *Peaty-Kharif*. The decision between these combinations must consider not only productivity, but also economic costs and environmental impact.

The analyses presented throughout the graphs and tables provide a comprehensive view on the factors that influence agricultural productivity, input use, and economic and environmental sustainability across different combinations of soil, season, and agricultural practices. This integrated approach allows you to identify fundamental patterns and trade-offs for the optimization of agricultural systems.

The distribution graphs **of categorical variables** highlighted the predominance of certain types of crops, soils and irrigation methods, suggesting that regional practices and agronomic characteristics influence the choice of inputs and management. Crops such as *Carrot* and *Tomato* had the highest average yields, reinforcing their economic relevance. More traditional irrigation methods, such as *Manual*, have shown high yields, but raise questions about scalability and resource efficiency. Silty soil and *Rabi* station stood out as scenarios of high productivity in their respective contexts.

Analysis of the correlation matrix revealed weak interactions between inputs such as fertilizers and pesticides with yield, suggesting that yield efficiency depends on a broader set of factors, including soil characteristics and seasonal conditions. This complexity reinforces the need for customized management practices to maximize yields.

Analyses of specific combinations, such as *Loamy-Zaid* and *Peaty-Kharif*, showed significant contrasts. *Loamy-Zaid* stood out for the highest absolute productivity, but at the expense of higher resource consumption and operating costs. On the other hand, *Peaty-*

Kharif demonstrated greater efficiency in the use of fertilizers and water, in addition to significantly lower total costs and per ton produced, evidencing its feasibility in scenarios where sustainability and resource savings are a priority.

The heat graphs that crossed the soil type and the growing season illustrated that productivity does not depend on one factor alone, but on specific combinations. The performance of *Silty soil* in *Rabi* and *Loamy soil* in *Zaid* are examples of optimal interactions that can guide agricultural planning in different regions.

Finally, the analysis of costs and sustainability showed that economic and environmental efficiency varies substantially between the combinations. The higher productivity of *Loamy-Zaid* was achieved at a considerably higher cost, while *Peaty-Kharif* proved to be a more sustainable alternative, with lower operating costs and lower environmental impact. These results emphasize the need to balance productivity, costs, and sustainability to meet modern agricultural demands.

The results show that the Loamy-Zaid combination offers higher absolute productivity, but presents high demand for inputs, especially water and fertilizers. On the other hand, Peaty-Kharif stands out for its efficiency in the use of resources and lower cost per ton produced, emerging as a more sustainable alternative. The analyses suggest that strategic decisions must balance productivity and sustainability, considering specific contexts of resource availability and economic priorities. These conclusions provide valuable subsidies for efficient agricultural planning.

However, the analyses reinforce that there is no single or universal solution for maximizing agricultural productivity. Choosing the ideal combinations of soil, season, and farming practices should take into account local conditions, resource availability, and the producer's priorities, whether economic or environmental. Additionally, adaptive management strategies and the use of innovative technologies, such as biofertilizers and optimized irrigation systems, can improve the overall performance of the analyzed combinations.

These results provide a valuable guide for researchers, farmers, and policymakers, allowing for more informed decisions to be made in pursuit of sustainable and competitive agriculture. The next step will be to apply these analyses in other contexts, validating the findings and expanding the possibilities for different agricultural production systems.

CONCLUSIONS

This study comprehensively analyzed the interactions between agricultural productivity, input use, and sustainability across different combinations of soil types and growing seasons. The results elucidated critical patterns that guide strategic decisions aimed at productive efficiency and resource conservation.

The analyses revealed that categorical variables, such as soil type and irrigation method, exert a determining influence on productivity. Crops such as *Carrot* and *Tomato* demonstrated higher average yield, evidencing their adaptability and economic relevance. *Silty* and *Loamy* soils stood out as suitable substrates for intensive crops, while *Peaty* soil showed significant limitations in less favorable conditions, such as in the Rabi season. The Zaid station emerged as the most conducive to maximizing yield, reinforcing the importance of suitable climatic conditions.

The specific interactions between soil and season reinforced the need for personalized management strategies. The *Silty* soil at the Rabi station showed the highest absolute yield, while the Loamy-Zaid combination was balanced in terms of inputs and yield. On the other hand, combinations such as Peaty-Rabi highlighted the urgency of adjustments in management or the strategic replacement with soils more suitable for challenging conditions.

Regarding the efficiency in the use of inputs, the differences between combinations were striking. Although Loamy-Zaid achieved higher absolute productivity, its efficiency per unit of input was lower than that of Peaty-Kharif, which demonstrated greater efficiency in the use of fertilizers (5.85 tons per ton of fertilizer) and water (0.00064 tons per cubic meter). Thus, Peaty-Kharif emerges as a more sustainable choice in resource-constrained settings.

The cost analysis reinforced Peaty-Kharif's economic superiority in terms of feasibility, with total costs 34% lower than Loamy-Zaid's. The cost per ton of Peaty-Kharif (163.20 currency units) was significantly lower, standing out in contexts where economic efficiency is a priority.

The findings indicate that Peaty-Kharif is ideal for systems that prioritize sustainability and resource savings, while Loamy-Zaid may be advantageous in scenarios where maximizing productivity is essential, as long as it is offset by higher added value. Investments in management technologies, such as biofertilizers, optimized irrigation, and soil amendments, are recommended to increase the efficiency of these combinations in different production scenarios.

The contributions of this study provide a solid basis for data-driven agricultural decisions, with applicability for producers and public policy makers. However, it is necessary to validate the results in other regions and cropping systems to ensure their generalization. The integration of productivity, sustainability, and economic viability is indispensable to promote resilient agricultural systems in line with the growing global demands for food and natural resources.

REFERENCES

1. Castro, N. R., Spolador, H. F. S., & Gasques, J. G. (2017). Valor da produção, produtividade e uso dos insumos na agricultura – uma análise descritiva para alguns estados brasileiros. *Perspectiva Econômica, 13*(1), 1-23. https://doi.org/10.4013/pe.2017.131.01

2. Domene, S. M. A., et al. (2023). Segurança alimentar: reflexões sobre um problema complexo. *Estudos Avançados, 37*, 182-206. https://doi.org/10.1590/s0103-4014.2023.37109.012

3. França, D. V. B., Costa, C. M., & Silva, Q. D. (2021). Propriedades Físicas dos Solos: Uma Abordagem Teórico-Metodológica. *Ciência Geográfica*, *XXV*(4), 1571-1587. https://www.agbbauru.org.br/publicacoes/revista/anoXXV_4/agb_xxv_4_web/agb_xxv_4-25.pdf. Acesso em: 10 nov 2024.

4. Magalhães, G. O., et al. (2021). Agricultura e Sustentabilidade: Mudanças Climáticas e Modificações no Desenvolvimento Agropecuário. *Divers@ Revista Eletrônica Interdisciplinar, 14*(1), 100-112. https://doi.org/10.5380/diver.v14i1.80514

5. Montoya, M. A., & Finamore, E. B. (2020). Os recursos hídricos no agronegócio brasileiro: Uma análise insumo-produto do uso, consumo, eficiência e intensidade. *Revista Brasileira de Economia, 74*(4), 441-464. https://doi.org/10.5935/0034-7140.20200021

6. Novak, E., Carvalho, L. A., Santiago, E. F., Ferreira, F. S., & Maestre, M. R. (2021). Composição química do solo em diferentes condições ambientais. *Ciência Florestal, 31*(3), 1063-1085. https://doi.org/10.5902/1980509828995

7. Oginho, C. M., Costa Junior, G., Popova, N. D., & Martines Filho, J. G. (2021). Poder de compra, preço e consumo de fertilizantes minerais: Uma análise para o centro-oeste brasileiro. *Revista de Economia e Sociologia Rural, 59*(1), e220367. https://doi.org/10.1590/1806-9479.2021.220367

8. Oliveira, S. F., Prado, R. B., & Monteiro, J. M. G. (2022). Impactos das mudanças climáticas na produção agrícola e medidas de adaptação sob a percepção de atores e produtores rurais de Nova Friburgo, RJ. *Interações, 23*(4), 1179-1201. https://doi.org/10.20435/inter.v23i4.3548

9. Paz, V. P. S., Frizzone, J. A., Botrel, T. A., & Folegatti, M. V. (2002). Otimização do uso da água em sistemas de irrigação por aspersão. *Revista Brasileira de Engenharia Agrícola e Ambiental, 6*(3), 404-408. https://www.scielo.br/j/rbeaa/a/Gzvj5WjJDQBKNQMvWGMKRFm/?format=pdf&lang=pt. Acesso em: 10 nov 2024.