Optimization of Traditional Crop Yields Through Experimental Design in Puno, Peru

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1 Introduction

1.1 General Context

Importance of traditional crops, particularly potato, quinoa, and cañihua, in Puno's food security and economy. The potato, a staple in Puno's agricultural economy, accounted for 48% of cultivated land in 2001, highlighting its dominance in areas like Lampa and Ayaviri, which are key production zones. Similarly, quinoa plays a vital role due to its resilience and nutritional value: "Quinoa is not only rich in proteins and carbohydrates but also bioactive substances such as saponins, which are distributed mainly in the pericarp of quinoa seeds. These compounds have foaming, emulsifying properties, and several health benefits, making quinoa a valuable crop in high-altitude Andean regions like Puno" [1]. Despite its adaptability, monocropping quinoa can harm soil microbial diversity, essential for sustainable agriculture: "Quinoa's cultivation in Andean regions, including Puno, highlights its ability to adapt to adverse conditions. However, monocropping practices negatively affect soil microbial diversity, which is crucial for sustainable agriculture and soil fertility in these areas" [2]. Native potato varieties, while integral to food security, have seen decreased cultivation due to limited industrial use: "The limited industrial use of indigenous varieties of native potatoes has caused a decrease in their cultivation, confining their production to self-consumption. Native potatoes remain essential to food security and cultural identity in the Andean highlands, including Puno" [3]. Cañihua, a protein-rich grain from the high-altitude Andes, thrives in Puno's semi-arid zones: "The cañihua originates from the Andes region of southern Peru and Bolivia, being distributed in the highest semi-arid regions. The cañihua grain presents high protein content (15-19%), as well as a significant proportion of sulfur amino acids and a balance of amino acids of optimum quality, rich in lysine, isoleucine, and tryptophan. Bioactive compounds like phenolics and carotenoids found in vegetables, fruits, and grains can have antioxidant and anti-inflammatory effects, which make them good candidates for the prevention of chronic diseases such as diabetes" [4]. These traditional crops are central to Puno's sustainability, emphasizing the need for optimized cultivation practices.

1.2 Introduction to the Concept of Experimental Optimization

This approach is particularly useful in agriculture, where multiple factors (fertilizers, water, soil type) interact in complex ways. In the context of agricultural experiments, optimizing the interaction between various factors—such as fertilizers, water, and soil type—is essential for maximizing crop yield while minimizing resource use. Experiment optimization helps address these complexities. A common method involves response surface methodology (RSM), which is used to optimize experimental outcomes by balancing multiple factors: "This study uses the desirability function approach to obtain a compromise optimization between the concentration of ethanol and the profit, which gives a robust solution to the complex problem. The case study emphasizes the importance of sequential nature and provides a useful guidance for engineers to solve complex problems" [5]. Similarly, in agricultural applications, the optimization of variables such as water and soil conditions can be approached through experimental design: "An optimization approach has been introduced to optimize the number of configurations that need to be evaluated to decrease the testing effort. SPL testing optimization reduces the number of configurations in the test suites by using a meta-heuristic algorithm, evolutionary algorithm, and mathematical linear" [15]. Agricultural experiments also rely on fractional experimental designs to streamline the process, as certain factors like protein levels are sensitive to environmental conditions: "The optimization of the procedure was obtained through a fractional experimental design. According to the international literature, and taking into account that proteins are sensitive to the surrounding environmental conditions and are easily denatured, the operational parameters and the relating range of values were considered" [8]. Balancing multiple variables—such as temperature, speed, and material properties—can be optimized using a similar approach: "The study used the hybrid Grey-TOPSIS method to optimize multi-objective criteria, analyzing parameters like extrusion temperature, layer height, and printing speed. This approach enables balancing trade-offs between tensile strength and surface roughness, akin to experimental designs in other fields where multiple factors interact to influence outcomes" [13]. Finally, experiments in pest control demonstrate the need for understanding complex variable interactions, similar to optimizing crop yield: "The management of potato cyst nematodes (PCNs) involves understanding complex interactions between soil types, climatic conditions, and resistant crops like Solanum sisymbriifolium. Field experiments revealed how such variables interact to optimize yield and pest control, echoing the principles of experimental design in agricultural systems" [14]. Thus, the optimization of agricultural experiments in Puno requires considering various interrelated factors, similar to methodologies used in other complex fields, to ensure efficient and sustainable crop production.

1.3 Role of Experimental Design (DOE)

In the context of optimizing traditional crop yields in Puno, Peru, the careful selection of appropriate Experimental Design (DOE) techniques is crucial for obtaining precise and consistent results. The correct choice of DOE techniques can significantly influence the success of a study, allowing for meaningful conclusions that are applicable in agricultural contexts. Key factors like environmental conditions, soil quality, water availability, nutrients, and cultivation methods must be defined and carefully controlled throughout the experiment. Once these factors are identified, their potential interactions and individual impacts on crop performance must be determined. Various DOE techniques have proven essential in optimizing complex systems, including agriculture. One such technique is factorial experiments, which allow for the evaluation of multiple factors simultaneously and their interactions: "The study utilizes factorial experiments and statistical analysis, with particular emphasis on the innovative application of the arcsine transformation. Two 2k factorial designs were developed to account for warm and cold weather. The experiments evaluated factors such as the operator's experience, wedge sealing temperature, sealing speed, and extruder temperature. The effects on the response variables were analyzed, which included overheating, resistance, and leaks. The research emphasizes the importance of optimizing the thermofusion process for biodigester construction, highlighting the role of arcsine transformation in improving statistical analysis" [6]. A full factorial design can also be used to evaluate key variables, ensuring all relevant factors are considered in the optimization process: "A 24 full factorial design experiment was performed to determine the effects of the flocculant dosage, settling time, and mixing time on the Zetag 8185 harvesting efficiency. The harvesting efficiency of Chlorella vulgaris was optimal at a dosage of 100 mg $L - 1$ and 3 min of rapid mixing. Factorial design of experiments proved essential in optimizing the chemical flocculation process for microalgae harvesting, achieving significant cost and process efficiencies" [7]. Similarly, fractional factorial designs combined with response surface methodology (RSM) help evaluate the interactions between various factors affecting outcomes, improving the efficiency of experimental processes: "Using a fractional factorial design and response surface methodology (RSM), this study evaluated multiple factors influencing biomass production of three Sphagnum species. Key variables such as pH, light intensity, and nutrient concentration were optimized. DOE facilitated the identification of interactions between variables, enhancing the efficiency and predictability of biomass cultivation processes" [9]. Thus, applying appropriate DOE techniques, such as factorial and fractional designs, is critical for optimizing agricultural processes and understanding the complex interactions between factors that influence crop yield in Puno.

1.4 Problem Statement

Farmers in the Puno region face significant challenges in improving agricultural productivity due to both climatic conditions and a lack of technical resources. Adverse weather patterns, such as extreme droughts and floods, exacerbate difficulties, while the lack of advanced technological tools and specialized personnel for agricultural research and improvement further complicates efforts. Inadequate access to financial resources prevents small-scale farmers from engaging in research and technology transfer to optimize production systems, which could enhance plant nutrition, post-harvest management, and agrochemical application. Climatic conditions play a primary role in agricultural productivity, impacting both crops and livestock: "The natural climatic conditions are the primary determinant of agricultural productivity. Climatic factors such as temperature, rainfall, and extreme events like droughts and floods significantly influence crop yields and livestock production. These conditions can also increase production costs, reduce income for farmers, and exacerbate poverty and seasonal unemployment rates" [10]. Climate change further worsens food security and agricultural productivity, particularly for small-scale farmers who lack access to resources: "Climate change impacts food security through increasing temperatures, altered precipitation patterns, and extreme weather events like droughts or floods, reducing water availability and agricultural productivity. Small-scale farmers face challenges due to reduced resilience of ecosystems and a lack of access to resources like organic fertilizers or irrigation systems to counter these effects" [11]. Environmental shifts also directly affect biomass and food production: "Environmental conditions, especially changes in precipitation and temperature, directly affect biomass availability and agricultural productivity. Seasonal shifts, such as those observed in Lake Titicaca, reduce the capacity of local producers to sustain adequate levels of food production without external support" [12]. Thus, the combination of adverse climatic factors and insufficient technical and financial resources hampers farmers' ability to enhance crop yields in Puno.

1.5 Objective of the Article

The main objective of this research is to optimize the productivity of traditional crops in the Puno region of Peru by applying Design of Experiments (DOE) techniques. This study aims to identify and evaluate the key factors such as soil quality, water availability, environmental conditions, and cultivation methods that influence crop yield. Additionally, it seeks to address the challenges posed by climatic variability and the lack of technical resources, proposing optimized solutions to improve agricultural productivity and sustainability in the region.

2 References

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