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Abstract

Quinoa production in Bolivia's southern Altiplano region takes place under some of the most severe agroecological conditions in the Andes. These include extreme altitude, scarce and variable rainfall, frequent frost, strong winds, and, more recently, widespread soil degradation. Organic soil amendments, such as compost, are promoted to restore soil fertility and improve productivity in certified quinoa systems. However, evidence on their effectiveness under real smallholder farming conditions is limited because existing studies often fail to distinguish agronomic potential from realized impacts shaped by environmental and management constraints. This paper addresses this gap by integrating agronomic diagnostics, intervention design, controlled validation, and impact evaluation within a unified framework. First, the study conducts a detailed soil analysis to identify constraints in certified production plots. Next, a compost intervention is designed and validated under controlled conditions to establish agronomic feasibility and potential. Then, a pilot intervention in randomly selected plots estimates the effects of the intervention under real cultivation conditions, including climatic variability, weed pressure, wind exposure, and varied management intensity. The results show that compost application increases quinoa productivity on average, but realized impacts vary with environmental exposure and management practices. Climatic stress, weed competition, wind intensity, and plot's owner presence influence how much the intervention's potential translates into observed outcomes. Methodologically, the study shows how combining agronomic validation with causal inference principles improves the interpretation and policy relevance of evidence in high-risk agroecological settings.

Keywords: Quinoa Production, Soil Fertility, Compost Application, Field Experiments, Farm Management, Agroecological Constraints.
JEL Codes: C93, O13, Q12, Q15.

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Resumen

La producción de quinua en el Altiplano sur de Bolivia se desarrolla bajo algunas de las condiciones agroecológicas más severas de los Andes. Estas incluyen altitudes extremas, precipitaciones escasas y altamente variables, frecuentes heladas, vientos intensos y, más recientemente, un proceso generalizado de degradación de los suelos. En este contexto, se promueve el uso de enmiendas orgánicas del suelo, como el compost, con el objetivo de restaurar la fertilidad y mejorar la productividad en sistemas de quinua certificada. Sin embargo, la evidencia sobre su efectividad en condiciones reales de la agricultura familiar es limitada, ya que muchos estudios existentes no distinguen adecuadamente entre el potencial agronómico de estas prácticas y sus impactos efectivamente observados, los cuales están condicionados por restricciones ambientales y de manejo. Este trabajo aborda esta brecha mediante la integración de diagnósticos agronómicos, diseño de la intervención, validación controlada y evaluación de impacto dentro de un marco analítico unificado. En primer lugar, se realiza un análisis detallado de suelos para identificar las principales limitaciones en parcelas de producción certificada. Posteriormente, se diseña y valida una intervención basada en compost bajo condiciones controladas, con el fin de establecer su viabilidad agronómica y su potencial productivo. A continuación, se implementa un piloto en parcelas seleccionadas aleatoriamente para estimar los efectos de la intervención en condiciones reales de cultivo, incorporando la variabilidad climática, la presión de malezas, la exposición al viento y la heterogeneidad en la intensidad del manejo. Los resultados muestran que la aplicación de compost incrementa, en promedio, la productividad de la quinua, aunque los impactos observados varían según el entorno ambiental y las prácticas de manejo. Factores como el estrés climático, la competencia de malezas, la intensidad del viento y la presencia del propietario en la parcela influyen en el grado en que el potencial de la intervención se traduce en resultados efectivos. Desde el punto de vista metodológico, el estudio demuestra que la combinación de validación agronómica con principios de inferencia causal mejora sustancialmente la interpretación y la relevancia para la formulación de políticas de la evidencia generada en contextos agroecológicos de alto riesgo.

Palabras clave: Producción de quinua, Fertilidad del suelo, Aplicación de compost, Experimentos de campo, Manejo agrícola, Restricciones agroecológicas.
Códigos JEL: C93, O13, Q12, Q15.

1 Introduction

Quinoa production by smallholders in the southern Altiplano region of Bolivia is subject to some of the most severe agroecological constraints in the Andean region. Extreme altitude, low and highly variable precipitation, frequent frost, intense solar radiation, and persistent winds sharply limit the viable crop options and exacerbate the effects of soil degradation. In this environment, quinoa has historically played a central economic, nutritional, and cultural role. This has been supported by land-use systems that maintain soil fertility through long fallow cycles, organic nutrient recycling, and integrated livestock management. Over the past two decades, however, these systems have undergone profound alteration. The rapid expansion, driven by international demand of quinoa, mechanization, shortened rotations, and the removal of natural vegetation barriers, has accelerated soil degradation and increased exposure to climatic stressors. Consequently, restoring soil fertility has become essential for sustaining quinoa productivity and rural livelihoods in the region.

Organic soil amendments, especially compost from locally available materials, are widely promoted as a promising response to these challenges. Agronomically, compost replenishes organic matter and nitrogen, improves soil structure, enhances water retention, and supports biological activity. These benefits are especially relevant in sandy, alkaline soils under moisture stress. From a policy perspective, compost is appealing because it aligns with organic and Fairtrade® certification standards and can be produced locally. However, despite its prominence in technical recommendations and development programs, there is limited credible evidence on how much compost actually increases quinoa productivity under real farming conditions. Existing studies often rely on controlled agronomic trials that identify biological potential or on observational field data that struggle to distinguish treatment effects from confounding environmental and management factors. This complicates agronomic decision-making and the design of scalable interventions.

This paper bridges the gap by integrating agronomic diagnostics, intervention design, and validation under controlled field conditions. It also includes a randomized pilot evaluation in multiple real producer plots. Instead of treating impact evaluation as a standalone exercise, the study follows a sequential logic. First, a baseline soil diagnostic identifies binding fertility constraints. Next, a compost intervention is formulated to address those constraints. Then, different compost dosages are validated in a standard agronomic plot to establish biological potential and operational feasibility. Finally, a randomized pilot intervention estimates causal effects under real production conditions with climatic variability, weed pressure, wind exposure, and varied management intensity. This *diagnostic-design-validation-pilot* structure allows the analysis to distinguish between the potential effects of compost application and the realized effects in typical smallholder settings.

The paper makes three main contributions. First, it characterizes the soil fertility of certified quinoa plots in the southern Altiplano through laboratory analysis. This documents the severity and spatial heterogeneity of organic matter depletion, nitrogen deficiency, alkalinity, and micronutrient imbalances. Second, it identifies and validates an optimal agronomic compost dosage. In the validation plot, applying 600 grams of compost per plant increased grain productivity by 48.78% compared to the untreated control. This result sets an *upper-bound* on the intervention's potential when environmental stressors are limited and implementation is tightly controlled. Third, the paper uses a randomized design that combines principles of causal inference with standard agronomic approaches to estimate the effect of compost under real conditions. In the pilot evaluation, average productivity gains converged to 12%, which serves as a conservative *lower-bound* estimate of the expected impact on smallholder plots exposed to multiple climatic and managerial constraints. Higher effects were consistently observed in subsamples with favorable conditions, such as adequate rainfall, lower frost and wind exposure, reduced weed pressure, and a stronger farmer presence. This suggests that realized impacts can approach the validated agronomic potential when constraints are relaxed.

Beyond its substantive findings, the study offers valuable methodological contributions by demonstrating how agronomic diagnostics, validation trials, and principles of causal inference can be integrated to produce policy-relevant evidence in high-risk agroecological environments. The evaluation design ensures internal validity under real production conditions. The preceding diagnostic and validation phases provide benchmarks for interpreting estimated treatment effects as constrained realizations of known biological potential rather than averages in isolation. This framework clarifies why impacts diminish in typical farming settings and identifies conditions in which soil fertility interventions can reach their full productive potential.

The remainder of the paper is organized as follows. Section 2 describes the agroecological and historical context of quinoa production in the southern Altiplano of Bolivia. Section 3 outlines the integrated methodological framework. Section 4 presents the baseline soil diagnostic. Section 5 details the design of the compost intervention. Section 6 reports results from the agronomic validation plot. Section 7 presents the pilot intervention, including average treatment effects and heterogeneity analyses by climatic and management factors. Section 8 concludes by synthesizing the agronomic, methodological, and policy implications of the findings.

2 Background

The southern Altiplano region of Bolivia sits at an average altitude of approximately 12,139 feet (3,700 meters) above sea level. Extreme climatic conditions severely limit the availability of agricultural alternatives in this region. Annual rainfall averages 204 millimeters, with approximately 95% falling between December and March. This results in long, dry periods during the rest of the year, which limit soil moisture and intensify evapotranspiration stress (Colque and Muriel, 2024). Additionally, hydrological constraints are exacerbated by significant diurnal temperature fluctuations and frequent frost. Frost occurs up to 200 days per year, exposing crops to repeated thermal shocks (*ibid.*). Strong, persistent winds that stir sandy surfaces and intense solar radiation further increase moisture loss. These extreme environmental factors restrict the range of viable and cultivable crops, favoring only species highly tolerant of drought, cold, and nutrient-poor soils. In this harsh agroecological context, quinoa (*Chenopodium quinoa Willd.*) stands out as the most prominent crop adapted to these extreme conditions. Over the centuries, environmental pressures have shaped land-use systems and social organizations around quinoa cultivation. This has led to low-input, high-resilience agricultural practices that maintain the region's fragile agroecological balance (Colque and

Feliciano, 2025*a*). Understanding this long-term context is essential to grasping the recent changes in production methods, market integration, and land management that have altered the economic role of quinoa and the sustainability of its cultivation.

Historically, quinoa cultivation has been the cornerstone of rural livelihoods in the southern Altiplano region. It serves as a staple food and the main source of cash income for smallholder households (Nina and Wesz, 2018; Del Barco Gamarra et al., 2019; Collao and Muriel, 2024). Its exceptional tolerance to climate stress enables local communities to maintain food security in areas with limited food supplies. Traditionally, surplus production entered local and regional exchange networks through barter and small-scale trade rather than distant, highly commodified markets (Collao and Muriel, 2024). Beyond its economic role, quinoa also has deep cultural significance. It occupies a central place in indigenous agricultural calendars, rituals, and festivals, coordinating planting and harvesting with ceremonial celebrations. These celebrations reinforce community cohesion and support the intergenerational transmission of agronomic knowledge (Villarroel, 2024). Before global demand increased, quinoa prices remained relatively stable. This allowed production decisions to align closely with ecological rhythms rather than short-term market incentives (Collao and Muriel, 2024).

The ancestral and traditional method of quinoa production used multi-year cycles with long fallow periods, crop rotation, and native pastures to restore soil fertility. Planting was synchronized with the rainy season, and labor was organized through reciprocal sociocultural institutions such as *Ayni*, which mobilized collective effort for planting, weeding, and harvesting. These practices integrated biodiversity and avoided monoculture by intercropping with other climate-stress-resistant species, such as tarwi (*Lupinus mutabilis*), often used as green manure. Soil organic matter was replenished by raising camelids (llamas and alpacas) and reserving grazing areas for them near the quinoa plot, so their manure was stored nearby. Quinoa plots relied on camelid manure as their primary source of soil nutrients (Colque and Feliciano, 2025*a*). By avoiding synthetic inputs and maintaining vegetation cover, these practices preserved soil organic matter, promoted nutrient cycling, and reduced the risk of erosion in arid and frost-prone conditions over the long term (*ibid.*).

From 2000 to 2014, quinoa production in Bolivia changed significantly as international demand rose, recognizing it as a "superfood." The international price increased fivefold, rising from the long-term stable price of $500 per metric ton to $3,060, while the cultivated area grew by 222%, from 37,668 to 121,186 hectares (Collao and Muriel, 2024). This rapid demand created strong incentives for monocropping, speeding up cultivation, commercialization, and land conversion. Much of the expansion took place on land previously used as pasture for camelids in a small-scale manure production system that replenished organic matter. This disrupted the ecological balance, reduced herd sizes, and decreased the manure that had traditionally maintained soil fertility (Colque and Muriel, 2024). Agricultural mechanization spread quickly, partly due to investments from extraordinary quinoa revenues (Herrera and Muriel, 2024). Tractors and disk plows replaced manual and animal labor, often without regard for soil structure or erosion risks (Colque and Feliciano, 2025*a*; Collao and Muriel, 2024). While the boom increased some producers' incomes, it also sped up vegetation loss, soil compaction, and the decline of organic matter. These changes weakened the ecological resilience that had supported traditional production systems (Colque and Feliciano, 2025*a*).

As Section 4 will detail, soil degradation became a central constraint to quinoa production in the southern Altiplano during the post-boom period. The soils are nowadays mainly sandy and alkaline, with high potassium and calcium, moderate magnesium, and low phosphorus. Nitrogen is now the most critical limiting nutrient, closely linked to the loss of organic matter from overcultivation and intensive mechanical disturbance. From 2008 to 2023, the estimated loss of organic matter averaged 65 tons per hectare (Cárdenas and Choque, 2008; Colque and Muriel, 2024). Soil organic matter content declined by 82%, from 2.64% to 0.47% (Colque and Muriel, 2024). This degradation reduces nutrient availability, water-holding capacity, and microbial activity, all of which are essential for crop growth under extreme climatic conditions (Aliaga et al., 2024; Colque and Feliciano, 2025*a*). Continuous monoculture, reduced manure inputs from declining camelid populations, and shorter or eliminated fallow periods have further intensified soil depletion (Collao and Muriel, 2024). Compared to traditional systems with higher organic matter, more diverse crops, and less intensive tillage, current soils show greater degradation, posing significant challenges to sustainable quinoa production.

The recent emergence of alternative production systems in the region, such as certified organic and Fairtrade® quinoa schemes, reflects the need for ecological sustainability after the quinoa boom and changing market preferences (Jiménez and Romero, 2022; Collao and Muriel, 2024). Although organic certification aligns with traditional low-input practices, it introduces formal documentation, traceability, compost application, and crop rotation requirements. Fairtrade® certification aims to stabilize incomes and improve social conditions by establishing associative structures that negotiate price premiums and secure market access (Fairtrade, 2023). These schemes encouraged the reintroduction of green manures and more systematic soil management. However, adoption varied across communities depending on resource availability and institutional capacity (Collao and Muriel, 2024). Before the intervention evaluated in this study, quinoa production in the southern Altiplano existed in a fragile equilibrium. Quinoa production was deeply embedded in local culture and livelihoods, but it was increasingly constrained by ecological degradation that threatened its long-term sustainability.

3 Methodological Approach

This study employs a research strategy that combines agronomic field methods and causal inference principles in a sequential, integrated manner. The goal is to obtain agronomically valid and causally robust empirical evidence under real production conditions in the southern Altiplano. The approach has four phases: (*i*) a baseline laboratory soil analysis, (*ii*) designing the agronomic intervention based on the baseline, (*iii*) an initial evaluation under controlled conditions (a validation agronomic plot), and (*iv*) a pilot evaluation in real producer plots to capture heterogeneity in the effect under different climatic and plot management factors. Each phase builds on the previous one to ensure coherence between diagnosis, intervention design, agronomic validation, and causal identification.

The first phase, described in Section 4, includes a baseline diagnostic to characterize the initial agroecological and production conditions of quinoa cultivation. This diagnostic involves laboratory soil analyses of quinoa-producing plots in the region, a rare practice in the area. The last documented evidence of such analyses dates back over 15 years, and many plots in this study have never been analyzed (Colque and Muriel, 2024). The analyses document soil texture, pH, nutrient availability, organic matter content, and indicators of physical degradation. Emphasis is placed on nitrogen availability and organic matter levels, given their critical role in limiting quinoa productivity in the post-boom context. This phase establishes a strong reference point for evaluating changes and ensures the intervention addresses the key agronomic constraints identified in the field.

The second phase, described in Section 5, involves designing and formulating the intervention. This phase focuses on developing a compost adapted to the area, based on baseline diagnostics and knowledge of suitable organic amendments for sandy, alkaline soils with low organic matter. Using standardized composting protocols, we combine locally available materials, mainly camellid and ovine manure and crop residues, with other agronomic inputs approved for certified production to ensure proper decomposition, nutrient stability, and sanitary quality. The formulation prioritizes replenishing organic matter and nitrogen while remaining compatible with organic certification and feasible for small-scale farmers. Guided by the research-action paradigm, the intervention was validated through roundtable discussions with quinoa production experts and local producers. This phase turns diagnostic evidence into a concrete agronomic treatment that can be consistently applied.

The third phase, presented in Section 6, involves an initial agronomic evaluation in a validation plot. This stage validates how quinoa responds to different compost dosages under controlled yet realistic field conditions. The validation plot was in the municipality of Santiago de Huari in the Oruro Department of Bolivia. It followed established agronomic standards and included systematic measurements of key variables, such as plant lifespan, plant height, and grain yield. By isolating the effects of different dosages in a closely monitored setting, this phase identifies an agronomically effective and operationally feasible compost application rate. Results from this phase inform the final specification of the intervention to be evaluated on a larger scale, reducing uncertainty before deployment in heterogeneous producer plots.

Finally, the fourth and last phase, presented in Section 7, is a pilot intervention in representative quinoa-producing plots. These plots were randomly selected using statistical power calculations to capture the diversity of agroecological conditions and management practices in the study area. In each randomly selected plot, treatment and control subplots were defined, and the compost intervention was assigned at the subplot level. Outcome variables were measured using standardized agronomic protocols. This data structure enables us to estimate the intervention's causal impact across diverse real-world quinoa production conditions. Unlike the controlled agronomic validation plot, these on-farm plots let us examine the heterogeneity of treatment effects across different levels of climatic stress and management protocol compliance.

This methodological approach bridges experimental agronomy and causal inference by combining diagnostic-driven intervention design, agronomic validation, and pilot intervention evaluation in a single analytical framework. It enables us to move beyond describing soil degradation or yield performance to identifying the causal effects of organic soil amendments on quinoa productivity. It also accounts for environmental variability and management heterogeneity, which characterize agriculture in the southern Altiplano of Bolivia.

4 Baseline Soil Diagnostic

This study begins with a baseline soil diagnosis, based on a thorough laboratory assessment of soil fertility.[1] The assessment covered seventy-five plots of Fairtrade®-certified quinoa production in Bolivia's southern Altiplano region.[2] The diagnosis was conducted before the agronomic intervention to identify soil structure constraints affecting productivity. As described previously in Section 2, the study area faces extreme agroclimatic stress, including low and highly variable rainfall, intense solar radiation, cold temperatures, and frequent frost. These factors worsen soil degradation and limit the soils' ability to sustain crop production. The diagnosis aimed to provide an empirical characterization of soil conditions to guide the design of a targeted fertility restoration strategy.

Soil sampling took place from October 2022 to May 2023 on seventy-five certified organic quinoa plots in communities across Oruro and Potosí. Figure A.1 in the Appendix shows the area of the sampled plots, and Table A.1 lists the communities. Sampling followed a rigorous, standardized protocol to ensure representativeness and analytical reliability. In each plot, 20 subsamples were collected in a zigzag pattern to a depth of 20 centimeters. The subsamples were homogenized and reduced to a composite sample of about 500 grams using the quartering method. The composite sample was sealed and sent to CETABOL[3] for laboratory analysis. The analysis measured 19 soil properties, including pH, macro- and micronutrient availability, organic matter, total nitrogen content, and soil texture. Laboratory analyses used rigorous, standardized agronomic methods, such as the Walkley–Black method for organic matter content and spectrophotometric techniques for nutrient quantification. To capture spatial heterogeneity, geostatistical interpolation with Kriging generated spatial representations of key soil properties across the study area, as shown in the Appendix maps.

Laboratory results, summarized in Table A.2 in the Appendix, reveal significant limitations in plot fertility and substantial variability between plots. This results from the interaction of climatic conditions, underlying geological material, and intensified agricultural practices. As seen in Figure A.2, soil texture analysis shows that 96% of the plots have *sandy loam, loamy sand*, or *sandy* textures, which are linked to low nutrient retention, rapid drainage, and limited water retention. These characteristics increase nutrient leaching, speed up organic matter decomposition, and reduce cation exchange capacity. This limits nutrient uptake by cultivated plants and increases their vulnerability to climate stress. Although texture showed relatively low variability between plots, other properties described below showed high variability. This indicates different susceptibility to environmental and agricultural management influences across plots.

Soil hydrogen potential (pH) was identified as a major constraint on soil fertility. As Figure 1 shows, about 67% of the sampled plots had very highly alkaline conditions, with pH values above 8.0[4]. Only

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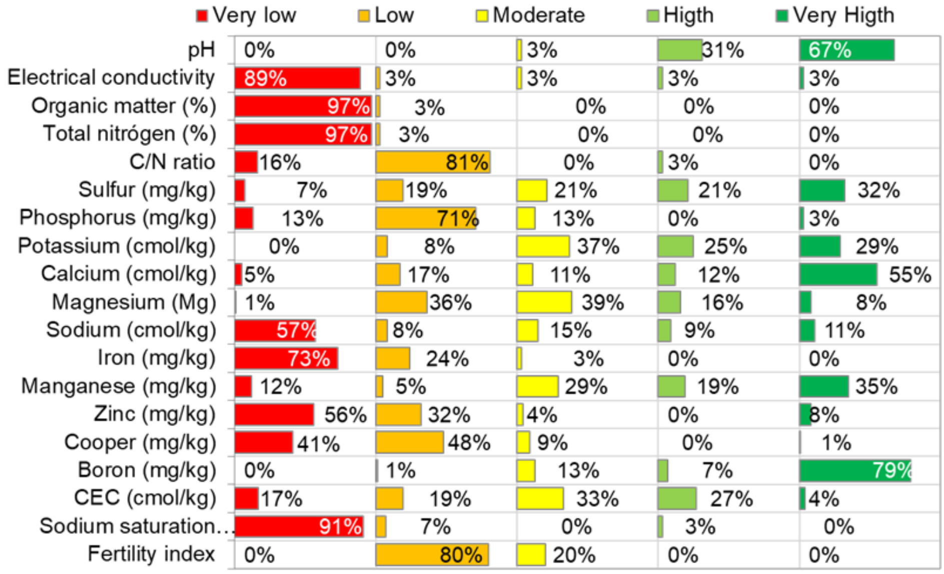
[1] See Colque and Muriel (2024) for a more detailed technical description of the baseline soil analysis results.

[2] This study focuses on Fairtrade®-certified quinoa production, as it is embedded within an action-research project conducted with the informed consent, formal authorization, and institutional endorsement of Fairtrade®-certified quinoa producers' associations in Bolivia's southern Altiplano. These associations are coordinated through RED-QUINUA. For further details and justification, see Fundación INESAD (2023).

[3] The CETABOL Foundation (Agricultural Technology Center in Bolivia) is located in Okinawa, Santa Cruz. CETABOL operates SENASAG-authorized laboratories that analyze plant nutrition, pesticides, and fertilizers, and provides soil, water, plant tissue, and fertilizer analysis services. This laboratory was chosen for its quality standards.

[4] The pH scale ranges from zero to fourteen, showing how acidic or basic a substance is. A value of seven is neutral,

Figure 1: Summary of Laboratory Soil Diagnostics in Certified Quinoa Plots



Source: Own elaboration based on laboratory soil analyses.

Note: The figure summarizes the distribution of key soil diagnostic indicators across sampled plots, grouped by qualitative categories of constraint severity (from *very low* to *very high*). Percentages reported inside bars indicate the share of plots falling into each category for the corresponding indicator.

3% of the plots had a pH within the moderate range for quinoa cultivation, typically between 5.5 and 7.8 (see Colque and Muriel, 2024). Elevated alkalinity reduces the availability of key nutrients such as phosphorus, zinc, copper, and iron. This limits plant uptake, even when these nutrients are present in the soil. These conditions reflect the geochemical characteristics of the southern Altiplano and the limited leaching in arid climates. High soil pH is a structural constraint on fertility that must be explicitly addressed in the intervention design.

Deficiencies in soil organic matter and nitrogen were widespread and severe. As shown in Table A.2 and Figure A.3, the average organic matter content across the seventy-five sampled plots was only 0.47%, and the average total nitrogen content was just 0.03%. Nearly all of the plots, around 97% as shown in Figure 1, were classified as having very low levels of both indicators, suggesting generalized depletion of soil organic carbon and nitrogen reserves. Given the central role of organic matter in nutrient cycling, water retention, and soil structure, this depletion poses a significant challenge to the sustainability of quinoa production. Additionally, phosphorus deficiency was identified in 84% of the plots, further limiting the growth and yield potential of quinoa production in the study region.

As also seen in Figures 1, micronutrient imbalances were widespread. Deficiencies in zinc, iron, and copper were found in 88%, 97%, and 89% of the samples, respectively. Most plots fell into the low or very low category for these nutrients. In contrast, 79% of the plots had excessively high boron concentrations, likely due to the fact that high soil pH increases boron solubility. These imbalances complicate nutrient management because excess boron can cause toxicity, and deficiencies in other micronutrients can restrict essential physiological processes necessary for plant development.

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values below seven are acidic, and values above seven are alkaline.

A *Soil Fertility Index* was developed to integrate the various dimensions of soil fertility (Colque and Muriel, 2024). This index uses key indicators, including pH, organic matter, nitrogen, phosphorus, potassium, and cation exchange capacity. As shown in Figure 1, 80% of the plots were classified as low-fertility, and the remaining 20% were classified as moderately fertile. Figure A.4 presents the results of a principal component analysis, which identified four dominant factors explaining 65.9% of the total variability in soil properties. Organic matter, calcium, cation exchange capacity, sulfur, boron, and sand content were found to be the most influential contributors. Higher-fertility plots were characterized by greater organic matter content, higher calcium levels, higher cation exchange capacity, and lower sand content. In contrast, low-fertility plots exhibited the opposite profile.

Overall, the baseline diagnostic indicates that the soil is experiencing severe stress due to environmental constraints and long-term human pressures. The main limitations, critically low levels of organic matter and nitrogen, high alkalinity, and widespread nutrient imbalances, reduce nutrient availability, water retention, and biological activity. These issues lead to yields well below potential. Although other nutrients are present at adequate levels, their benefits are offset by these major constraints. This diagnostic informs intervention strategies that focus on restoring organic matter and correcting key nutrient deficiencies. These steps are necessary to improve the sustainability and productivity of quinoa cultivation in the southern Altiplano region.

5 Intervention Design

The agronomic intervention evaluated in this paper was developed in response to constraints identified in the baseline soil diagnostics. These included widespread depletion of organic matter and nitrogen, and the structural fragility of soils under certified quinoa production systems in the southern Altiplano region. Drawing on the expertise of Óscar Colque, one of the authors, the intervention was formalized as technical guidance for quinoa producers in the *Guide to Composting for Organic Quinoa Production in the Southern Highlands* (Colque and Feliciano, 2025*b*). This guide is the main reference for compost formulation and application. Instead of being used as a generic input, compost is applied as a locally adapted soil amendment compatible with organic and Fairtrade® standards and feasible within the study area's climatic, logistical, and institutional conditions.

Our compost intervention targets the documented degradation of quinoa soils. Composting effectively replenishes soil organic carbon, improves nitrogen supply, and restores essential soil functions. Properly composted organic amendments deliver nutrients, improve soil structure, enhance moisture retention, increase cation exchange capacity, and promote biological activity. These improvements are vital for crop performance in sandy and alkaline soils under extreme climatic stress.

Compost constitutes an organic fertilizer made from the aerobic decomposition of animal and plant materials by microorganisms under controlled conditions of moisture, temperature, pH, and oxygenation. Once stabilized, compost can be used as a soil amendment or fertilizer to sustainably improve soil fertility. In the specific conditions of the southern Altiplano, compost plays a particularly important role in improving soil structure. Its granular texture promotes aggregate formation, increases cohesion in sandy soils, enhances water retention, and reduces susceptibility to wind erosion. Additionally, compost provides essential nutrients, stimulates beneficial microbial populations, and helps suppress soil-borne pathogens during the thermophilic phase of composting.

The compost formulation in this study follows a standardized protocol using only locally available materials. The main ingredients are camelid and ovine manure, with chopped native straw (*paja brava*), wood chip, and a small amount of ground alfalfa to balance the carbon-to-nitrogen ratio. Activated microorganisms and molasses were added to accelerate decomposition and boost microbial activity. Table 1 specifies quantities to produce about seven metric tons of compost, enough to fertilize one hectare of quinoa at the recommended rate (Colque and Feliciano, 2025*b*). This standardization ensures consistency, replicability, and compatibility with certified production.

Table 1: Details of Inputs, Quantities, and Costs for the Production of 7 Ton of Compost (USD)

Inputs	Unit	Quantity	Unit Cost (USD)	Total Cost (USD)
Camelid and ovine manure	m^3	4	19.15	76.61
Chopped native straw	m^3	3	14.37	43.10
Wood chip	m^3	3	8.62	25.86
Ground alfalfa	kg	7	1.69	11.26
Activated microorganisms	L	3	9.82	28.52
Molasses	L	6	0.40	2.30
			Total	187.66

Note: Exchange rate applied: 1 USD = 6.96 Bs.

The composting process follows sequential stages adapted to the cold, dry conditions of the southern Altiplano. Before piling, the area is prepared and leveled, and microorganisms are activated at least twelve days in advance. Materials are then stacked in alternating layers of manure, sawdust, and straw, each about 10 to 15 centimeters thick. After each layer, the material is moistened with a diluted solution of activated microorganisms. The recommended pile dimensions in the Altiplano are about 1.20 meters high, 1.50 meters wide, and 8 meters long. The pile is covered with black plastic or agrofilm to capture solar radiation, maintain internal temperatures, and prevent moisture loss.

Proper decomposition requires active management of the compost pile. The first turning occurs when the internal temperature reaches about 50°C, usually three weeks after piling. Subsequent turnings are done at fifteen-day intervals until the compost stabilizes. Turning improves aeration, mixes the materials, and speeds up decomposition. At each turning, moisture is checked and adjusted with a simple manual test to keep conditions favorable for microbes. In typical Altiplano conditions, composting takes four to six months, but using activated microorganisms shortens this to three to four months, as shown in Table 2. Compost maturity is judged by color, odor, and texture. Stabilized compost is dark and uniform, has an earthy smell, and contains no recognizable original materials.

Our design also specifies optimal methods for applying compost to quinoa fields. Two methods are compatible with certified production systems. First, in the *planting-hole* method, compost is mixed with moist soil in the planting hole before seeding, followed by light irrigation and a thin layer of soil. Second, in the so-called *jichi* method, compost is distributed around established quinoa plants at a depth of 6 to 7 centimeters and within a radius of about 20 centimeters before the rainy season.

Table 2: Compost Production Schedule and Periods for Different Activities

Activity	May				June				July				August				September		
	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3
Collection of inputs	✓																		
Compost preparation		✓																	
Temperature monitoring			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Moisture monitoring			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Compost irrigation						✓		✓		✓		✓		✓		✓			
Compost turning								✓		✓				✓					
Compost screening												✓							
Mesophilic phase I		✓	✓	✓	✓	✓													
Thermophilic phase							✓	✓	✓										
Mesophilic phase II										✓	✓	✓	✓						
Stabilization phase														✓	✓	✓	✓	✓	
Compost application																			✓

Source: Own elaboration.

In both cases, the compost is covered with soil to reduce nitrogen volatilization, prevent moisture loss, and protect beneficial microorganisms.

Overall, the intervention design turns baseline diagnostic evidence into a specific, technically validated agronomic response. By adhering to composting and application protocols for the southern Altiplano, the intervention aims to restore organic matter and nitrogen, improve soil structure, and enhance the resilience of quinoa production systems. It remains feasible for small-scale producers and fully compatible with organic and Fairtrade® certification requirements. This forms a sound foundation for later stages of agronomic validation and impact evaluation.

6 Validation Plot

An initial evaluation was conducted under controlled yet realistic field conditions using an agronomic *validation plot*, following the intervention design described above. This standard agronomic procedure verifies intervention performance across varying local conditions and application rates. The objective was to assess the response of quinoa to different compost dosages before scaling the intervention to heterogeneous producer plots in the pilot phase described in the next section. This evaluation is an intermediate step between the baseline diagnostic and the on-farm impact assessment. It enables identification of a compost application rate that is both agronomically effective and operationally feasible under conditions representative of those faced by producers in the southern Altiplano, and defines the *optimal* dosage recommended for the pilot intervention.

The validation plot was established in Santiago de Huari[5], Sebastián Pagador Province, Oruro Department, at an altitude of 12,328 feet (3,758 meters) above sea level. This site represents the study region's agroecological conditions, characterized by a cold, dry climate with an average annual temperature of 8.5°C and an average annual precipitation of 392 millimeters. Soil conditions at the site indicated low fertility, with a sandy loam texture, a neutral pH of 7.12, low salinity, a very low organic matter content of 0.32%, and a critically low total nitrogen content of 0.02%. Calcium and magnesium levels were low, potassium levels ranged from low to moderate, and phosphorus levels

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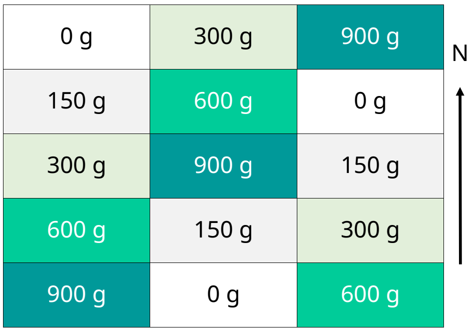
[5] GPS coordinates: 19°00'46.8"S 66°46'31.4"W.

were moderate. These characteristics closely mirror those identified in the baseline soil diagnostic of the seventy-five real plots across the Southern Altiplano, as described in Section 4, and classify the validation plot as having low fertility. This makes the validation plot well-suited to assessing the potential of compost to alleviate structural and nutritional soil constraints.

The validation area covered 800 m^2 and followed a completely randomized design, as shown in Figure 2. One control and four treatment arms were defined based on increasing compost application rates (in grams) per quinoa plant: 0 g (control), 150 g (T1), 300 g (T2), 600 g (T3), and 900 g (T4). The compost applied in all treatment arms was produced locally following the protocol described earlier, based on ovine and camelid manure mixed with straw and sawdust and composted under controlled conditions (see Table 1). Activated microorganisms and molasses were incorporated to accelerate decomposition and enhance microbial activity. Quinoa of the *Toledo royal quinoa* (QRT) variety was sown on October 18, 2023, and harvested on May 5, 2024. Each treatment arm included six replications, with each replication consisting of an experimental unit of twenty-five quinoa plants. Within each unit, ten plants were randomly selected for evaluation, excluding border plants to minimize edge effects.

Figure 2: The Resulting Random Assignment within the Validation Plot



0 g	300 g	900 g
150 g	600 g	0 g
300 g	900 g	150 g
600 g	150 g	300 g
900 g	0 g	600 g

Source: Own elaboration.

Throughout the crop cycle, three outcome variables were systematically monitored for the validation plot: number of quinoa plants per clump, plant height, and grain yield per plant. Plant number and height were measured eight times during the phenological cycle. The first five evaluations occurred at 14-day intervals, then three more at 28-day intervals. Grain yield was measured at harvest by weighing the grain per plant from samples of ten randomly selected plants per treatment. A generalized linear model framework was used for statistical analysis. Differences between treatments were assessed using analysis of variance (ANOVA) and multiple comparison tests, including Duncan's, Fisher's least significant difference, and Tukey's, in line with standard agronomic evaluations.

As seen in Figure 3, the number of quinoa plants per clump[6] shows a clear and meaningful response to compost application. Plant numbers per clump declined across all treatments over the cycle, reflecting natural mortality. The control treatment consistently had the highest losses. In contrast, higher compost doses, especially 600 g and 900 g per plant, maintained significantly higher plant densities throughout the cycle. By the final evaluation, the 900 g treatment averaged 14.1 plants

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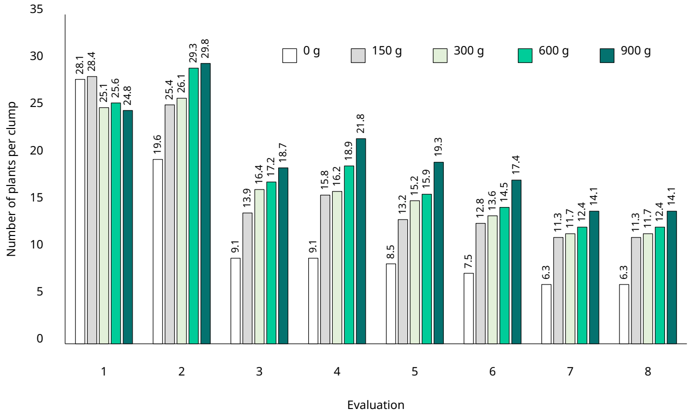
[6] In quinoa production, seeds are sown in clusters, meaning a single clump contains multiple plants. Therefore, agronomic measurements are taken at the clump level rather than per plant.

per hill, the 600 g treatment averaged 12.4 plants, and the control averaged only 6.3 plants. The ANOVA results in Table A.3 in the Appendix confirmed these differences were highly statistically significant, indicating a strong effect of compost dosage on plant survival. These results suggest that compost reduces plant mortality by improving nutrient availability, soil structure, and moisture retention, which reduces competitive stress among plants.

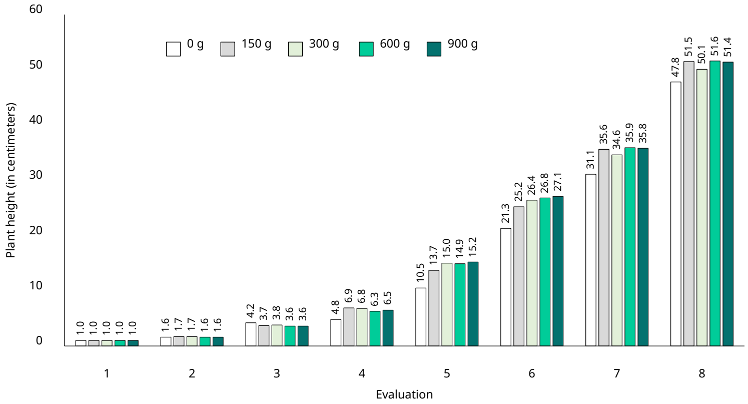
Figure 3: Number of Plants Per Level of Compost from Eight Evaluations Performed



Source: Own elaboration.

Plant height showed a more nuanced response to compost application. As shown in Figure 4, visual inspection of growth trajectories indicates that the 600 g and 900 g treatments consistently achieved greater vegetative development across the eight evaluation rounds, especially from mid-cycle onward. At the final measurement, plants in these treatments reached an average height slightly above 51 cm, while control plants remained below 48 cm. However, ANOVA results (Table A.4 presented in the Appendix) did not detect statistically significant differences in plant height across treatments. This suggests that under the sandy, low-organic-matter conditions of the experimental plot, vertical growth is more strongly constrained by soil moisture dynamics and structural limitations than by nutrient availability. Still, the persistently lower heights observed in the control group are consistent with a positive, though statistically insignificant, effect of compost on vegetative growth.

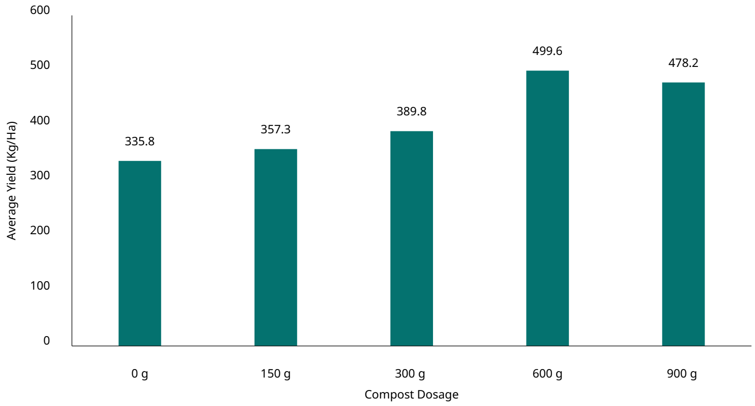
Figure 4: Height of Plants Per Level of Compost from Eight Evaluations Performed



Source: Own elaboration.

Grain yield was the variable most responsive to compost application. The ANOVA results reported in Table A.5 in the Appendix indicate highly significant differences across treatments, with yield clearly associated with compost dosage. Figure 5 shows that the treatment that received 600 g of compost per plant had the highest average yield of approximately 500 kg/ha, which is 48.78% higher than the control. The 900 g treatment closely followed with an average yield of around 480 kg/ha. In contrast, the control treatment yielded the lowest amount, approximately 336 kg/ha. Intermediate application rates of 150 g and 300 g produced only modest yield gains that were not statistically distinguishable from the control. Tukey's multiple-comparison test confirmed that the 600 g treatment was statistically superior to the control and lower-dose treatments, but not significantly different from the 900 g treatment.

Figure 5: Average Yield (Kg/Ha) Per Level of Compost



Source: Own elaboration.

The absence of additional yield gains at the highest application rate indicates a non-linear response to compost. Beyond a certain threshold, further increases in compost may lead to diminishing returns or slight negative effects. These effects may result from nutrient imbalances or excessive organic matter, which reduces nutrient uptake efficiency. This interpretation aligns with prior empirical evidence from similar agroecological contexts. Studies in the Bolivian Altiplano, for example, report yield gains up to compost-equivalent doses of about 600 g per plant, with marginal benefits declining beyond that level (Colque and Feliciano, 2025*b*). Although absolute yield levels in the Huari validation plot remain moderate due to severe baseline soil constraints, the observed improvements are significant in relative terms, indicating increased productivity and yield stability under degraded soil conditions.

The validation plot evaluation shows that applying compost improves key agronomic outcomes in organic quinoa production under southern Altiplano conditions. Compost significantly increased plant survival and grain yield, but the effects on plant height were positive without being statistically conclusive. The 600-g-per-plant dosage was optimal across all indicators, balancing productivity gains with efficient input use. It was selected as the recommended rate for the pilot intervention described in the next section. These results validate the technical rationale of the intervention design and provide a basis for selecting the compost dosage for the subsequent on-farm pilot evaluation.

7 Pilot Intervention

7.1 Evaluation Design

The preceding sections established that soils for certified quinoa in the southern Altiplano face severe fertility constraints, especially low organic matter and nitrogen in sandy, highly alkaline soils (Section 4). They also showed that a locally adapted compost intervention can be implemented in a way compatible with certification (Section 5) and provides clear agronomic gains at an optimal rate of 600 g per clump in a validation plot (Section 6). This section evaluates whether the validated dosage leads to measurable productivity gains under real farming conditions, where climate shocks, varied management histories, and imperfect protocol adherence are part of the production environment. The evaluation design prioritizes validity through randomized selection of plots and maintains external relevance by working with representative certified producer plots.

The evaluation framework first considers the seventy-five Fairtrade®-certified quinoa plots included in the baseline laboratory diagnostic, as detailed in Section 4. From this group, a subset of twenty producer plots was randomly selected to participate in the pilot evaluation, based on statistical power calculations, project budget, and field feasibility.[7] Figure A.5 in the Appendix show the geolocation of the plots selected for the pilot study. Random selection at this stage is essential for representativeness because it prevents overrepresentation of atypical plots, such as those that are unusually fertile, degraded, or well-managed. It also ensures the evaluation sample reflects the distribution of soil conditions and management environments observed in the baseline diagnostic.

Within each selected plot, two subplots of equal area were delineated. One subplot was assigned to receive the compost treatment described in Section 5, while the other served as an untreated control. This design follows a *Fisherian blocking* approach (Pearl and Mackenzie, 2018), in which plots act as blocks and treatments are assigned within them. By assigning treatment at the subplot level, the design enables direct within-plot comparisons between treated and control units. Because both subplots share the same soil profile, microtopography, management history, and local climatic exposure, this design controls for all time-invariant plot-level characteristics. As a result, treatment effects are identified from contrasts within the same plot, substantially reducing variance due to unobserved heterogeneity and strengthening causal interpretation in highly heterogeneous smallholder systems. This paired-subplot design is standard in agronomic experimentation and is particularly well suited to contexts where cross-plot comparisons are prone to bias from unobserved differences in soil quality, wind exposure, and management intensity. Potential interference between subplots was minimized by maintaining physical separation and restricting compost application strictly to the treated area. Agronomists and trained technicians supervised implementation to ensure protocol adherence and to prevent contamination between treatment and control subplots.

The optimal compost dosage for the treated subplots was determined from the validation plot and set at 600 grams per quinoa plant. This dosage balanced agronomic effectiveness and operational feasibility. As previously mentioned, it produced significant yield increases compared to the control

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[7] The initial sampling frame included twenty plots, but only ten were included in the final analysis. The remaining ten did not meet the criteria due to attrition or data quality issues identified during the final reporting stage.

plot and showed no statistically significant benefits at higher doses, avoiding the inefficiencies of over-application (see Figure 5). The application method followed the intervention protocol outlined in Section 5, within the constraints of certified production systems and the agricultural calendar. To ensure accountability and clarity, plot owners provided informed consent and signed a memorandum of understanding specifying the responsibilities of the technical team, operational commitments, and monitoring access throughout the entire crop cycle 2023-2024.

Implementation and monitoring followed a structured supervision model. Each plot was assigned to a technician trained in certified quinoa production and compost management. The technician oversaw the application process, verified protocol compliance, and documented conditions affecting crop development. Throughout the season, producers and technicians recorded significant environmental stressors and plot conditions, including rainfall, frost, wind intensity, and weed pressure. Technicians evaluated management-related conditions that could affect the effectiveness of treatment, such as how often plot owners were present in the field. These variables support the interpretation of heterogeneous outcomes across plots and help characterize the operational context of the intervention. Given baseline evidence of severe soil constraints and the realities of organic management in the region, the design anticipates that treatment effects may vary with climatic stress and compliance.

The primary outcome is the *weight of drain grain produced by each quinoa plant clump*, measured in grams. This is meaningful from an agronomic perspective because it matches the productive unit recognized by quinoa producers. It also reflects productivity at the scale where compost is applied and plants compete for moisture and nutrients. At harvest, the technical team randomly sampled twenty clumps per subplot using a pre-specified field protocol to avoid selection bias and ensure spatial coverage. Each clump was cut, cleaned, dried, and weighed under standardized post-harvest conditions to provide a consistent and comparable measure of productivity. Thus, the dataset is hierarchical: clumps are nested within subplots, which are nested within plots.

Treatment effects are estimated using two complementary regression specifications with standard errors clustered at the plot level. The first model regresses clump-level grain weight on a treatment indicator set to one for clumps in compost subplots and zero for clumps in control subplots. This model uses both within-plot and between-plot variation to estimate an average treatment effect, assuming randomization yields comparable treated and control subplots. The second model builds on the first by adding plot fixed effects, which absorb all unobserved, time-invariant plot characteristics, including baseline soil fertility, microtopography, and persistent management traits. This model identifies the treatment effect from within-plot contrasts. Clustering at the plot level provides valid inference when there is within-plot correlation in outcomes across sampled clumps in both cases.

Formally, the plot fixed-effects specification is given by

$$Y_{icp} \;=\; \alpha_p \;+\; \tau\, T_{cp} \;+\; \varepsilon_{icp},$$

where Y_{icp} denotes the quinoa grain weight (in grams) of clump i located in subplot c of plot p; T_{cp} is a binary indicator equal to one if subplot c in plot p received the compost treatment and zero otherwise; α_p represents plot p fixed-effects that capture all unobserved, time-invariant plot characteristics; and ε_{icp} is an idiosyncratic error term. Under this specification, the parameter τ

identifies the effect of compost application using only within-plot variation between treated and control subplots. Standard errors are clustered at the plot level to allow for arbitrary correlation of outcomes across clumps within the same plot.

The credibility of this design relies on standard, transparent assumptions commonly adopted in randomized agronomic evaluations. All assumptions were explicitly addressed. First, allocating compost to one subplot within each selected plot ensures exogeneity because plots were randomly selected, avoiding the bias of choosing more productive plots or more “motivated” producers. Second, it is assumed that interference between subplots is negligible, so outcomes in the control subplot are not materially affected by compost applied to the treated subplot. This is supported by the physical separation of subplots required during implementation. Third, trained agronomists conducted outcome measurements using uniform, standardized procedures across treatment states, including pre-established randomized sampling protocols and consistent weighing methods. Under these conditions, the evaluation design yields valid estimates of the effect of compost application on quinoa productivity in certified producer plots and remains interpretable in settings with extreme environmental stress and heterogeneous management practices.

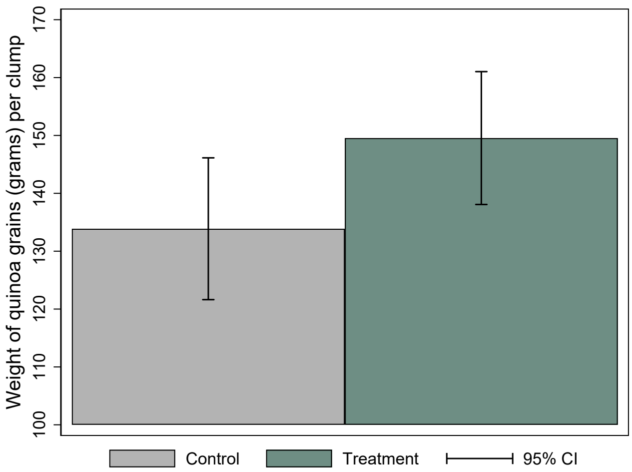
7.1.1 Overall Treatment Effects

We begin our analysis by examining the average effect of compost application on quinoa productivity across all pilot plots. These estimates are based on ten plots encompassing 400 quinoa clumps evaluated across treated and control subplots. This overall analysis captures the intervention’s performance under real farming conditions by integrating the full range of climatic stress, soil heterogeneity, and management practices represented in the pilot design. Subsequent subsections examine how this average effect varies with environmental conditions and implementation quality.

Figure 6 shows the average dried grain weight per quinoa clump for the treated and control subplots. The figure shows a clear upward shift in average grain weight for compost-treated clumps compared to the control group. This difference is both economically meaningful and agronomically relevant, indicating that the compost intervention improves productivity at the plant-clump level. The reported 95% confidence intervals, constructed using plot-level clustered standard errors in accordance with the evaluation design, partially overlap but are consistent with a positive average treatment effect. This evidence closely aligns with the agronomic rationale developed in Section 5 and the validation-plot results that motivated selecting the 600-g-per-plant dosage in Section 6.

Table 3 formalizes these comparisons using the regression framework described in subsection 7.1. Columns (1) and (2) report estimates for the full pilot sample. In this baseline specification, compost application increases grain weight per clump by 15.670 grams, with plot-clustered standard errors of 7.935 and statistical significance at the 10% level. The estimated coefficient is consistent across specifications with and without plot fixed effects, reflecting the paired subplot design. Once treatment is assigned within plots, identification relies on within-plot contrasts. Including fixed effects mainly improves precision rather than changing the point estimate. Relative to the control group mean of 133.88 grams, this estimate corresponds to an average productivity gain of about 11.7%.

Figure 6: Average Grain Weight per Clump by Treatment Status



Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per quinoa plant clump, pooled across all sampled clumps. Whiskers display 95% confidence intervals with standard errors clustered at the plot level, consistent with the randomized within-plot design.

Table 3: Estimated Treatment Effect on Grain Weight per Clump (grams)

	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	15.670*	15.670*	20.860**	20.860**	27.393***	27.393***
	(7.935)	(7.935)	(5.786)	(5.786)	(5.812)	(5.812)
Observations	400	400	200	200	280	280
R2	0.008	0.439	0.021	0.465	0.029	0.499
Average Dep. Var.	133.880	133.880	118.170	118.170	124.014	124.014
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

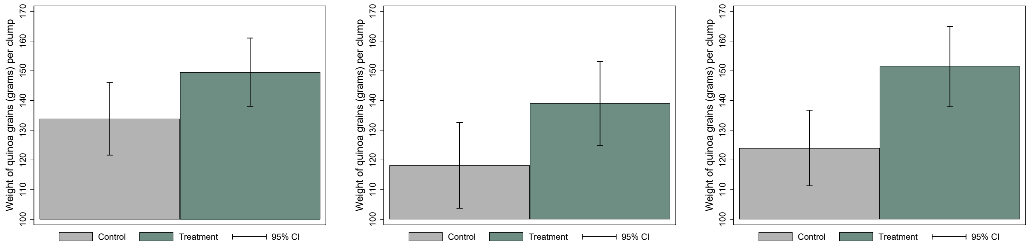
Source: Own elaboration based on pilot evaluation data.

Note: The dependent variable is dried grain weight (grams) per quinoa plant clump. Columns (1)–(2) use the full pilot sample; columns (3)–(4) restrict to plots meeting predefined information and measurement standards; columns (5)–(6) restrict to plots with comparatively high protocol compliance as assessed by the technical team. Even-numbered columns include plot fixed effects, identifying the effect from within-plot contrasts between treated and control subplots. Standard errors clustered at the plot level are reported in parentheses. The control-group mean (constant term) is reported to facilitate percentage interpretation. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Figure 7 and the remaining columns of Table 3 expand the analysis by examining subsamples defined by implementation and measurement quality. Panel (a) shows the full-sample comparison. Panels (b) and (c) focus on plots that met predefined information standards and plots with high protocol compliance. Although agronomists supervised all grain weight measurements, accurate estimation required strict adherence to post-harvest procedures, including uniform drying, cleaning, and weighing of grains. Effective implementation of the intervention also depended on consistent compliance with compost application protocols throughout the agricultural cycle. In practice, some variation in adherence emerged. To account for this, the technical team systematically evaluated each plot based on the quality of the final data collected (*information standards*) and the extent to which the intervention protocol was followed throughout the quinoa harvest cycle (*protocol compliance*).

These sample restrictions are informative about how operational conditions shape outcomes. Consistent with the visual patterns in Figure 7, the estimated treatment effect in Table 3 increases across these subsamples. Under the information-standards restriction (columns 3–4), the estimated effect rises to 20.860 grams ($p < 0.05$), relative to a control mean of 118.170 grams. Under the protocol-compliance restriction (columns 5–6), the estimated effect increases to 27.393 grams ($p < 0.01$), a 22.1% increase over the control mean of 124.014 grams. These results suggest that productivity gains from compost application are robust and amplified when implementation and monitoring protocols are strictly followed.

Figure 7: Average Grain Weight per Clump by Treatment Status and Implementation Quality



(a) Full sample (b) Information standards (c) Protocol compliance

Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per clump by treatment status. Panel (a) includes all pilot plots. Panel (b) restricts the sample to plots that met predefined information and measurement standards based on the technical team's comparative assessment. Panel (c) restricts the sample to plots classified by the agronomic team as exhibiting comparatively high compliance with the intervention protocol and monitoring requirements. 95% confidence intervals are computed with standard errors clustered at the plot level.

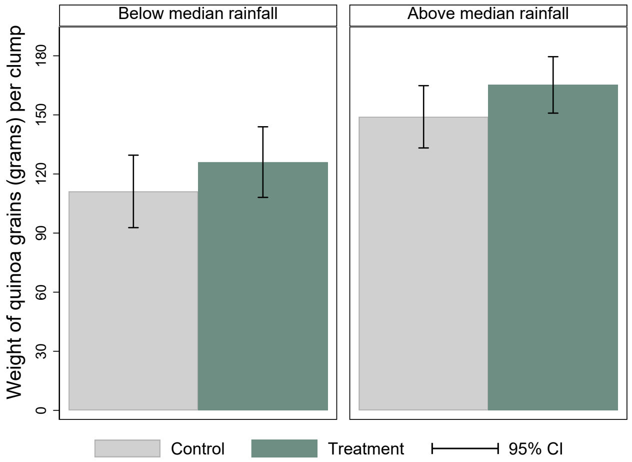
Taken together, these results show the positive average impact of compost application on quinoa grain weight per clump in certified producer plots. The stability of the point estimates across fixed-effects and non-fixed-effects specifications supports the design's internal validity. The systematic amplification of effects under stricter implementation conditions highlights the importance of execution quality. These results provide an empirical baseline for subsequent heterogeneity analyses, which examine how climatic stressors and management practices affect the intervention's effectiveness.

7.1.2 Heterogeneous Effects by Rainfall Intensity

Having established a positive average effect of compost application on quinoa grain weight, we now examine whether this effect varies systematically with rainfall intensity. Rainfall is a critical source of exogenous variation in the southern Altiplano, where precipitation is scarce, unevenly distributed, and often concentrated in short periods (see Section 2). Because compost affects soil water retention and nutrient availability, its productivity impacts may differ depending on whether moisture constraints are binding. This subsection therefore investigates treatment-effect heterogeneity by rainfall intensity, using the agronomic rainfall classification recorded by the technical team during the crop cycle.

Figure 8 shows the average grain weight per clump by treatment status, for plots with rainfall intensity below and above the median. In both regimes, compost-treated subplots had higher average grain weights than control subplots, indicating the intervention improves productivity in both drier and wetter conditions. The size of the difference varies across regimes. Under below-median rainfall, treated clumps show a moderate increase over the control group. Under above-median rainfall, both groups have higher grain weights, and the treatment-control gap appears wider. The reported confidence intervals partially overlap but remain consistent with positive treatment effects across rainfall conditions.

Figure 8: Average Grain Weight per Clump by Treatment Status and Rainfall Intensity



Source: Own elaboration based on pilot evaluation data.

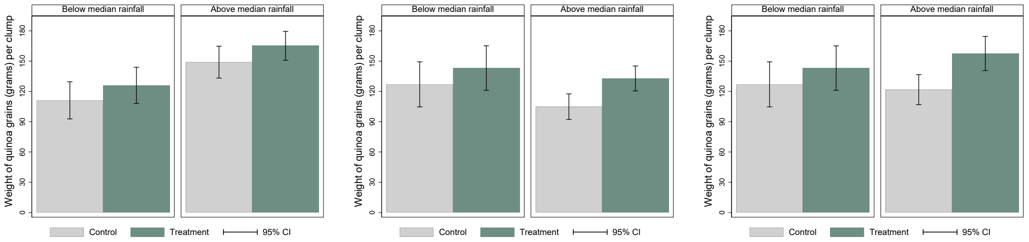
Note: Bars report average dried grain weight (grams) per quinoa plant clump by treatment status, separately for plots with rainfall intensity below and above the median of rainfall. Whiskers display 95% confidence intervals computed using standard errors clustered at the plot level.

Figure 9 illustrates this comparison by disaggregating the sample by rainfall intensity and implementation quality. Panel (a) shows the full-sample pattern, with positive treatment effects under both rainfall regimes. Panels (b) and (c) restrict the sample to plots meeting information standards and to plots with high protocol compliance. In these subsamples, treatment effects are larger and more distinct from the control group, especially under above-median rainfall. These results suggest that favorable moisture conditions amplify the benefits of compost application when the intervention is rigorously implemented and monitored.

Table 4 provides regression-based estimates that formalize these patterns within the evaluation framework described in Section 7.1. Panel A reports results for plots with rainfall intensity below the median. In this regime, applying compost increases grain weight per clump by about 14.9 grams in the full sample, significant at the 5% level. The estimated effect remains stable across specifications with and without plot fixed effects and increases modestly in the information standards and protocol compliance subsamples. These results suggest that compost enhances productivity under relatively dry conditions, consistent with its role in improving soil moisture retention and nutrient availability.

Panel B reports results for plots with rainfall intensity above the median. In this subsample, estimated treatment effects are larger, though generally less statistically significant than in the full sample. The only exception is protocol compliance. This pattern reflects greater variability in outcomes under wetter conditions and may also align with nonlinear yield responses to higher rainfall, as documented by Aliaga and Caballero (2024). Restricting the analysis to plots with high protocol compliance yields

Figure 9: Average Grain Weight per Clump by Treatment Status, Implementation Quality, and Rainfall Intensity



(a) Full sample (b) Information standards (c) Protocol compliance

Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per clump by treatment status and rainfall intensity. Panel (a) includes all pilot plots. Panel (b) restricts the sample to plots meeting predefined information and measurement standards. Panel (c) restricts the sample to plots exhibiting comparatively high compliance with the intervention protocol. 95% confidence intervals are computed with plot-clustered standard errors.

an estimated treatment effect that is both large and statistically significant, reaching about 35.8 grams per clump, a substantial proportional increase relative to the control group mean. The contrast between Panels A and B shows that higher rainfall alone does not guarantee larger treatment effects. Favorable moisture conditions must interact with effective implementation to translate compost application into productivity gains.

Taken together, these results suggest that rainfall intensity is important for compost effectiveness. Compost improves quinoa productivity in both drier and wetter conditions. Under above-median rainfall, treatment effects are larger but also more variable. This matches the greater yield dispersion and nonlinear yield responses to rainfall expected in quinoa (Aliaga and Caballero, 2024). In plots with high protocol compliance, the treatment effect under higher rainfall becomes large and statistically significant, reaching about 35.8 grams per clump, a substantial proportional increase over the control group mean. The contrast between Panels A and B shows that higher rainfall alone does not guarantee stronger treatment effects. Favorable moisture conditions must combine with effective implementation and management discipline for compost application to increase productivity in smallholder quinoa systems.

7.1.3 Heterogeneous Effects by Frost Intensity

Next, we examine whether the effectiveness of compost application varies systematically with frost intensity. Frost is one of the most significant climate-related constraints on quinoa production in the southern Altiplano, as described in Section 2. Extreme diurnal temperature fluctuations and frequent freezing events can damage plant tissue, disrupt grain filling, and reduce yields. Compost may indirectly mitigate some of these stresses by improving soil structure, enhancing root development, and stabilizing moisture and nutrient availability. Therefore, this subsection evaluates heterogeneity in treatment effects by frost intensity recorded by the technical team throughout the crop cycle.

Figure 10 shows the average grain weight per clump by treatment status for plots with frost intensity

Table 4: Heterogeneous Effects on Grain Weight per Clump by Rainfall Intensity

Panel A: Rainfall intensity below the median

	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	14.887**	14.887**	16.133**	16.133**	16.133**	16.133**
	(2.760)	(2.760)	(3.484)	(3.484)	(3.484)	(3.484)
Observations	160	160	120	120	120	120
R2	0.008	0.532	0.009	0.494	0.009	0.494
Average Dep. Var.	111.150	111.150	127.017	127.017	127.017	127.017
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Panel B: Rainfall intensity above the median

	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	16.192	16.192	27.950	27.950	35.838**	35.837**
	(13.640)	(13.640)	(14.693)	(14.693)	(7.527)	(7.527)
Observations	240	240	80	80	160	160
R2	0.009	0.333	0.110	0.242	0.058	0.510
Average Dep. Var.	149.033	149.033	104.900	104.900	121.763	121.763
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Source: Own elaboration based on pilot evaluation data.

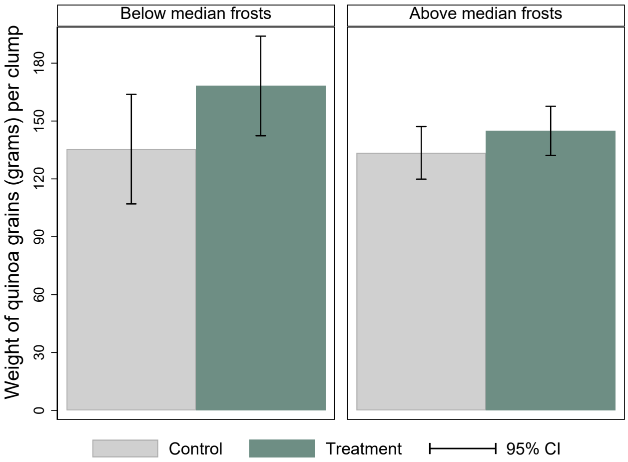
Note: The dependent variable is dried grain weight (grams) per quinoa plant clump. Panel A reports results for plots with rainfall intensity below the median; Panel B reports results for plots with rainfall intensity above the median, based on rainfall recorded by the technical team. Columns (1)–(2) use the full pilot sample; columns (3)–(4) restrict to plots meeting predefined information standards; columns (5)–(6) restrict to plots with comparatively high protocol compliance. Even-numbered columns include plot fixed effects. Standard errors clustered at the plot level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

below and above the median. In both regimes, compost-treated subplots outperformed controls, indicating the intervention improves productivity even with substantial frost. The magnitude of the difference varies across regimes. Under below-median frost intensity, the difference is large and visually pronounced. Under above-median frost intensity, the gap is smaller but still positive. Confidence intervals are wider under lower frost intensity, reflecting greater dispersion in outcomes. The overall pattern remains consistent with a positive treatment effect.

Figure 11 expands this comparison by disaggregating results by frost intensity and implementation quality. Panel (a) shows that compost application increases grain weight under both frost regimes, with a stronger effect in plots with fewer frost events. Panels (b) and (c) restrict the sample to plots meeting information standards and those with high protocol compliance. In these subsamples, treatment effects remain large and distinct from the control group under below-median frost intensity. Under above-median frost intensity, treatment effects are smaller but become more pronounced and statistically clearer in protocol-compliant plots. This visual evidence suggests that effective implementation partially offsets productivity losses from harsher frost conditions.

Table 5 formalizes these patterns using the regression framework described in Section 7.1. Panel A

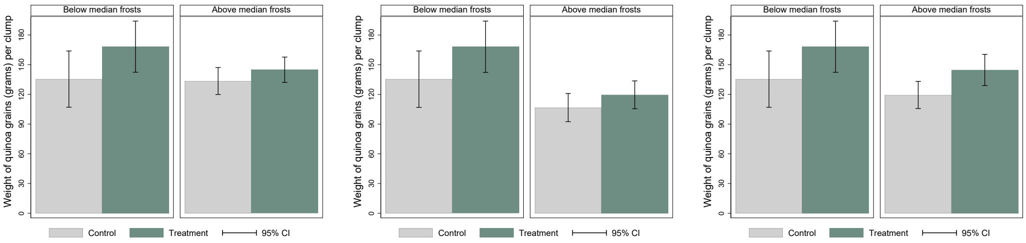
Figure 10: Average Grain Weight per Clump by Treatment Status and Frost Intensity



Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per quinoa plant clump by treatment status, separately for plots with frost intensity below and above the median of frosts. Whiskers display 95% confidence intervals computed using standard errors clustered at the plot level.

Figure 11: Average Grain Weight per Clump by Treatment Status, Implementation Quality, and Frost Intensity



(a) Full sample (b) Information standards (c) Protocol compliance

Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per clump by treatment status and frost intensity. Panel (a) includes all pilot plots. Panel (b) restricts the sample to plots meeting predefined information and measurement standards. Panel (c) restricts the sample to plots exhibiting comparatively high compliance with the intervention protocol. 95% confidence intervals are computed with plot-clustered standard errors.

reports the results for plots with frost intensity below the median. In this regime, applying compost increases grain weight per clump by about 32.8 grams for treated units across all specifications. The estimated effect is large and stable but not statistically significant, and it does not change when plot fixed effects are included. Although this is a substantial productivity gain compared to the mean of 135.4 grams in the control group, it remains statistically insignificant. This suggest that quinoa yields are highly responsive to soil improvements in the presence of moderate frost stress.

Panel B reports the results for plots with frost intensity above the median. In these more stressful conditions, the estimated treatment effects are smaller and more heterogeneous. In the full sample, the point estimate is positive but not statistically significant. When attention is restricted to plots that meet information standards, the treatment effect becomes statistically significant at about 12.9 grams. The largest and most robust effects appear in protocol-compliant plots, where compost application increases grain weight by approximately 25.3 grams, significant at the 5% level. These results suggest that severe frost exposure reduces average treatment effects, but careful implementation and monitoring can preserve much of the productivity gains from compost application.

Table 5: Heterogeneous Effects on Grain Weight per Clump by Frost Intensity

Panel A: Frost intensity below the median	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	32.750	32.750	32.750	32.750	32.750	32.750
	(9.863)	(9.863)	(9.863)	(9.863)	(9.863)	(9.863)
Observations	80	80	80	80	80	80
R2	0.035	0.336	0.035	0.336	0.035	0.336
Average Dep. Var.	135.425	135.425	135.425	135.425	135.425	135.425
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Panel B: Frost intensity above the median	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	11.400	11.400	12.933***	12.933***	25.250**	25.250**
	(9.206)	(9.206)	(0.685)	(0.685)	(7.572)	(7.572)
Observations	320	320	120	120	200	200
R2	0.005	0.468	0.014	0.588	0.028	0.577
Average Dep. Var.	133.494	133.494	106.667	106.667	119.450	119.450
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Source: Own elaboration based on pilot evaluation data.

Note: The dependent variable is dried grain weight (grams) per quinoa plant clump. Panel A reports results for plots with frost intensity below the median; Panel B reports results for plots with frost intensity above the median, based on frosts recorded by the technical team. Columns (1)–(2) use the full pilot sample; columns (3)–(4) restrict to plots meeting predefined information standards; columns (5)–(6) restrict to plots with comparatively high protocol compliance. Even-numbered columns include plot fixed effects. Standard errors clustered at the plot level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

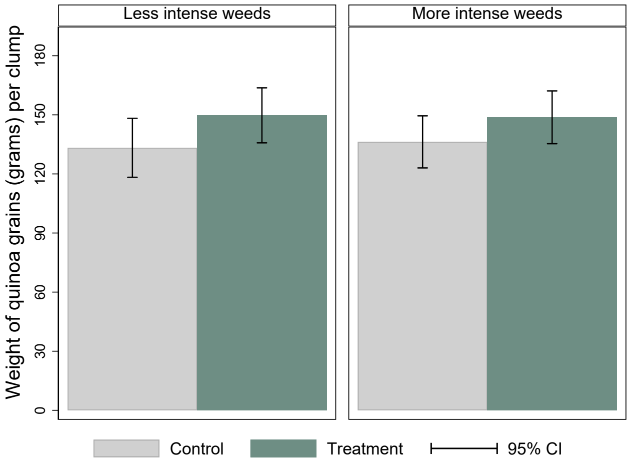
Overall, these results suggest that frost intensity is a key moderator of compost effectiveness. Compost yields the greatest productivity gains under lower frost exposure, when plant growth and grain filling are less affected by temperature fluctuations. Under higher frost intensity, average treatment effects are smaller and more variable but remain statistically significant when the intervention is carefully implemented. These findings highlight that while compost application alone cannot fully offset extreme climatic stress, effective management and protocol compliance can substantially mitigate frost-related yield losses in certified quinoa systems.

7.1.4 Heterogeneous Effects by Weed Intensity

Our next step is to examine whether the effectiveness of compost varies with weed intensity. Weed pressure poses a significant challenge to certified organic quinoa systems in the southern Altiplano because chemical herbicides are prohibited by certification standards, and manual control is costly and labor-intensive. High weed intensity increases competition for moisture and nutrients, which may reduce the productivity gains from soil amendments. Compost could affect this interaction by improving crop vigor and competitiveness, or by indirectly stimulating weed growth if management is inadequate. This subsection evaluates the heterogeneity of treatment effects by weed intensity as recorded by the technical team during the pilot intervention.

Figure 12 shows the average grain weight per clump by treatment status for plots with weed intensity below and above the median weed presence level. In both cases, subplots treated with compost have higher average grain weight than control subplots, indicating the intervention improves productivity regardless of weed pressure. However, the difference between treatments and controls is more pronounced under lower weed intensity. Under higher weed pressure, the difference narrows and the confidence intervals overlap substantially, suggesting reduced and more variable treatment effects.

Figure 12: Average Grain Weight per Clump by Treatment Status and Weed Intensity



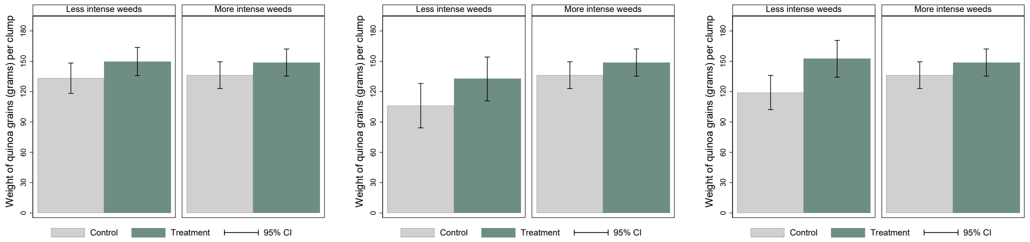
Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per quinoa plant clump by treatment status, separately for plots with weed intensity below and above the median of weed-pressure. Whiskers display 95% confidence intervals computed using standard errors clustered at the plot level.

Figure 13 breaks down these patterns by implementation quality. Panel (a) compares the full sample, where compost application increases grain weight under both weed regimes, with larger gains under lower weed pressure. Panels (b) and (c) restrict the sample to plots meeting predefined information standards and to plots with high protocol compliance. In these subsamples, treatment effects become larger and more precisely estimated under low weed intensity. Under high weed intensity, treatment effects remain positive but show little variation across implementation-quality subsamples. This suggests strong weed pressure limits how much improved soil conditions increase yields.

Table 6 formalizes the visual patterns using the regression framework. Panel A reports results for plots with weed intensity below the median. In this regime, the estimated treatment effect is positive across all specifications and increases with implementation quality. In the full sample, compost application increases grain weight by about 16.5 grams, though the estimate is imprecise. Restricting the sample to plots that meet information standards raises the effect to 26.45 grams (significant at the 10% level). The largest effects are in protocol-compliant plots, where compost

Figure 13: Average Grain Weight per Clump by Treatment Status, Implementation Quality, and Weed Intensity



(a) Full sample (b) Information standards (c) Protocol compliance

Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per clump by treatment status and weed intensity. Panel (a) includes all pilot plots. Panel (b) restricts the sample to plots meeting predefined information and measurement standards. Panel (c) restricts the sample to plots exhibiting comparatively high compliance with the intervention protocol. 95% confidence intervals are computed with plot-clustered standard errors.

application increases grain weight by about 33.36 grams, statistically significant at the 1% level. Compared to the control group mean of 119.11 grams, this is a substantial productivity gain.

Panel B reports results for plots with weed intensity above the median. In these conditions, the treatment effects are smaller but stable across specifications and implementation-quality subsamples. Compost application increases grain weight by about 12.48 grams in all models, with strong statistical significance due to lower variance. However, unlike in the low-weed regime, higher implementation quality does not substantially amplify the treatment effects under intense weed pressure. This pattern may suggests that when weed competition is severe, gains from improved soil fertility are offset by resource competition, which limits the potential for further productivity improvements through compost alone.

Altogether, these results suggest that weed intensity is a critical factor in compost effectiveness. Compost yields the greatest productivity gains when weed pressure is low, especially when the intervention is well implemented and monitored. Even with strong protocol compliance, compost remains beneficial under high weed intensity but yields smaller and less responsive gains. These findings suggest that improving soil fertility and managing weeds are complementary, not interchangeable, practices in certified and organic quinoa systems. Therefore, if the producer does not adequately control weeds, the productivity gains from compost are limited.

7.1.5 Heterogeneous Effects by Wind Intensity

Subsequently, we examine whether the effectiveness of compost application varies with wind intensity. Wind is a significant yet frequently overlooked climatic stressor in the southern Altiplano region. Strong, persistent winds increase evapotranspiration, accelerate soil moisture loss, promote erosion in sandy soils, and damage quinoa plants physically during sensitive phenological stages. Historically, the effects of wind were partially mitigated by natural barriers formed by native vegetation and pasture systems. However, the expansion of quinoa cultivation and the associated removal of

Table 6: Heterogeneous Effects on Grain Weight per Clump by Weed Intensity

Panel A: Weed intensity below the median

	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	16.469	16.469	26.450*	26.450*	33.360***	33.360***
	(10.039)	(10.039)	(8.504)	(8.504)	(6.296)	(6.296)
Observations	320	320	120	120	200	200
R2	0.008	0.459	0.024	0.519	0.034	0.541
Average Dep. Var.	133.281	133.281	106.100	106.100	119.110	119.110
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Panel B: Weed intensity above the median

	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	12.475**	12.475**	12.475**	12.475**	12.475**	12.475**
	(0.881)	(0.881)	(0.881)	(0.881)	(0.881)	(0.881)
Observations	80	80	80	80	80	80
R2	0.021	0.060	0.021	0.060	0.021	0.060
Average Dep. Var.	136.275	136.275	136.275	136.275	136.275	136.275
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Source: Own elaboration based on pilot evaluation data.

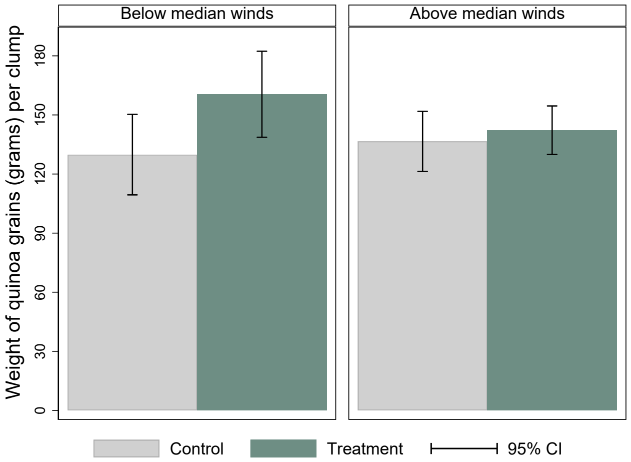
Note: The dependent variable is dried grain weight (grams) per quinoa plant clump. Panel A reports results for plots with weed intensity below the median; Panel B reports results for plots with weed intensity above the median, based on an agronomic weed-pressure recorded by the technical team. Columns (1)–(2) use the full pilot sample; columns (3)–(4) restrict to plots meeting predefined information standards; columns (5)–(6) restrict to plots with comparatively high protocol compliance. Even-numbered columns include plot fixed effects. Standard errors clustered at the plot level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

vegetative cover have increased wind exposure in many production areas. This subsection evaluates whether wind intensity conditions affect the realized productivity gains from compost application.

Figure 14 shows the average grain weight per clump by treatment status for plots with wind intensity below or above the median, as recorded by the technical team. At below-median wind intensity, the grain weight of compost-treated subplots increases substantially and is clearly visible compared to control subplots. The difference is substantial and statistically significant, with limited overlap in confidence intervals. In contrast, under above-median wind intensity, the average grain weight is lower overall, and the difference between the treated and control subplots is smaller. While the treatment effect remains positive, the overlap of the confidence intervals indicates greater variability and a weaker average effect under high wind exposure.

Figure 15 further breaks down these patterns by implementation quality. Panel (a) shows the full sample, in which compost application yields significant productivity increases under low wind intensity and smaller increases under high wind exposure. Panels (b) and (c) narrow the focus to plots that meet predefined information standards and have high protocol compliance. In these subsamples, the effects of the treatment remain large under below-median wind intensity. Above median wind

Figure 14: Average Grain Weight per Clump by Treatment Status and Wind Intensity

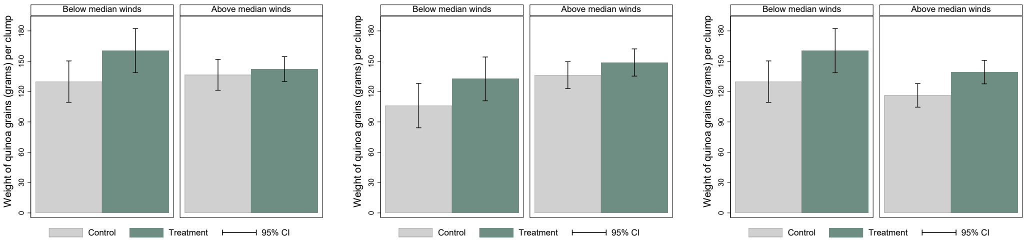


Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per quinoa plant clump by treatment status, separately for plots with wind intensity below and above the median of wind intensity. Whiskers display 95% confidence intervals computed using standard errors clustered at the plot level.

intensity, however, treatment effects only become clear when protocol compliance is high. This suggests that careful implementation can partially offset wind-related stress but cannot fully restore the intervention's potential.

Figure 15: Average Grain Weight per Clump by Treatment Status, Implementation Quality, and Wind Intensity



(a) Full sample (b) Information standards (c) Protocol compliance

Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per clump by treatment status and wind intensity. Panel (a) includes all pilot plots. Panel (b) restricts the sample to plots meeting predefined information and measurement standards. Panel (c) restricts the sample to plots exhibiting comparatively high compliance with the intervention protocol. 95% confidence intervals are computed with plot-clustered standard errors.

Table 7 formalizes these patterns using the regression framework described in Section 7.1. Panel A reports results for plots with wind intensity below the median. In this regime, applying compost increases grain weight per clump by about 30.7 grams in the full sample, statistically significant at the 5% level. The estimated effect remains substantial and consistent across specifications with and without plot fixed effects and under information-standard and protocol-compliance restrictions. Compared to a control mean of 129.9 grams, this is a substantial proportional gain.

Panel B reports results for plots with wind intensity above the median. In this more exposed regime, treatment effects are smaller and more sensitive to implementation quality. In the full sample, the estimated effect is positive but not statistically significant. Restricting the sample to plots that meet information standards yields a statistically significant effect of about 12.5 grams. The largest effects appear in protocol-compliant plots, where compost application increases grain weight by about 23.1 grams. However, estimates are less precise than under low-wind conditions. These results suggest that high wind exposure significantly decreases the average effectiveness of compost, even when soil fertility improves.

Table 7: Heterogeneous Effects on Grain Weight per Clump by Wind Intensity

Panel A: Winds intensity below the median

	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	30.650**	30.650**	26.450*	26.450*	30.650**	30.650**
	(7.337)	(7.337)	(8.504)	(8.504)	(7.337)	(7.337)
Observations	160	160	120	120	160	160
R2	0.025	0.531	0.024	0.519	0.025	0.531
Average Dep. Var.	129.850	129.850	106.100	106.100	129.850	129.850
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Panel B: Winds intensity above the median

	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	5.683	5.683	12.475**	12.475**	23.050	23.050
	(10.847)	(10.847)	(0.881)	(0.881)	(10.632)	(10.632)
Observations	240	240	80	80	120	120
R2	0.001	0.352	0.021	0.060	0.060	0.280
Average Dep. Var.	136.567	136.567	136.275	136.275	116.233	116.233
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Source: Own elaboration based on pilot evaluation data.

Note: The dependent variable is dried grain weight (grams) per quinoa plant clump. Panel A reports results for plots with wind intensity below the median; Panel B reports results for plots with wind intensity above the median, based on wind-exposure recorded by the technical team. Columns (1)–(2) use the full pilot sample; columns (3)–(4) restrict to plots meeting predefined information standards; columns (5)–(6) restrict to plots with comparatively high protocol compliance. Even-numbered columns include plot fixed effects. Standard errors clustered at the plot level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

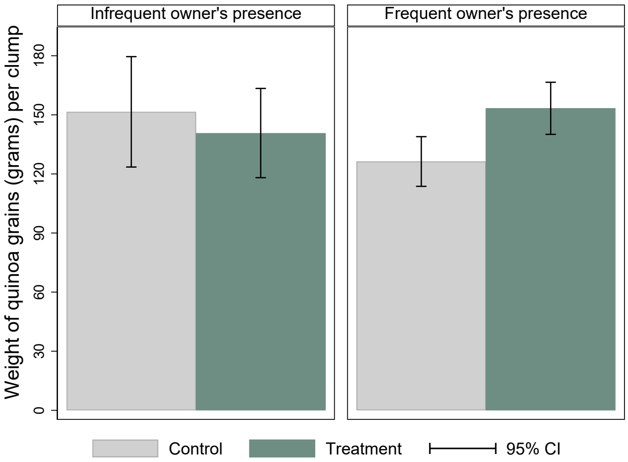
Altogether, these results demonstrate that wind intensity is a critical moderator of compost effectiveness. Compost application yields the greatest productivity gains under low wind exposure, where improvements in soil structure and moisture retention are fully translated into plant growth and grain filling. However, under high wind intensity, conditions that are becoming more common due to the removal of natural wind barriers in the region, the potential benefits of compost are reduced due to enhanced evapotranspiration, physical stress, and soil moisture loss. Although careful implementation and monitoring can partially restore the treatment effect, wind exposure creates a structural constraint that soil fertility improvements alone cannot fully overcome. These findings highlight the importance of complementing soil organic matter restoration with landscape-level management strategies, including wind protection, to maximize productivity gains in certified quinoa systems.

7.1.6 Heterogeneous Effects by Plot Owner Presence

Finally, we examine whether the effectiveness of compost application varies depending on whether or not the plot owner is present during the cycle. In the southern Altiplano, seasonal and permanent migration has led many quinoa plots to be managed intermittently or delegated to third parties, often with limited supervision (Jimenez and Romero, 2022). The presence of a plot owner affects the timing and accuracy of agronomic practices, such as applying compost, controlling weeds, and monitoring the plot. Therefore, the intensity of management may affect the extent to which soil fertility interventions increase productivity.

Figure 16 shows the average grain weight per clump by treatment status for plots with infrequent and frequent owner presence. This presence is defined relative to the median of the records of producer presence collected by the technical team during their periodic visits. In plots with infrequent owner presence, average grain weight is similar between treated and control subplots, with confidence intervals substantially overlapping. In contrast, where owners are frequently present, average grain weight in compost-treated subplots is visibly higher than in control subplots, and the two groups are clearly separated. This evidence suggests that active on-site management is key to turning compost application into yield gains.

Figure 16: Average Grain Weight per Clump by Treatment Status and Plot Owner Presence

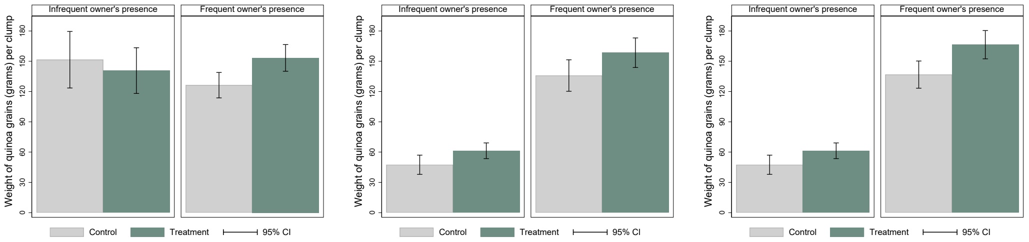


Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per quinoa plant clump by treatment status, separately for plots with plot owner presence below and above the median. Whiskers display 95% confidence intervals computed using standard errors clustered at the plot level.

Figure 17 further disaggregates these patterns by implementation quality. Panel (a) shows the full sample, where treatment effects are modest with infrequent plot owner presence but much larger with frequent presence. Panels (b) and (c) restrict the sample to plots meeting information standards and plots with high protocol compliance. In these subsamples, treatment effects are more pronounced and precisely estimated under frequent plot owner presence. Even with high measurement quality, improvements from compost remain limited with infrequent presence, highlighting the central role of active management in reinforcing intervention impacts.

Figure 17: Average Grain Weight per Clump by Treatment Status, Implementation Quality, and Plot Owner Presence



(a) Full sample (b) Information standards (c) Protocol compliance

Source: Own elaboration based on pilot evaluation data.

Note: Bars report average dried grain weight (grams) per clump by treatment status and plot owner presence. Panel (a) includes all pilot plots. Panel (b) restricts the sample to plots meeting predefined information and measurement standards. Panel (c) restricts the sample to plots exhibiting comparatively high compliance with the intervention protocol. 95% confidence intervals are computed with plot-clustered standard errors.

Table 8 formalizes these patterns using the regression framework described in Section 7.1. All specifications use a subsample of plots with frequent plot owner presence, where treatment effects are expected to be most informative. In the full sample, applying compost increases grain weight per clump by about 27.0 grams, statistically significant at the 1% level. This estimate remains consistent with or without plot fixed effects, reflecting the randomized within-plot design. Restricting the sample to plots that meet predefined information standards yields a slightly smaller but still statistically significant treatment effect of about 22.6 grams. The largest effects appear in plots with high protocol compliance, where compost application increases grain weight by about 29.7 grams, significant at the 1% level. Compared to the control group means, these effects represent substantial proportional gains and reinforce the importance of management intensity and implementation quality.

Table 8: Heterogeneous Effects on Grain Weight per Clump by Plot Owner Presence

	Overall		Information Standards		Protocol Compliance	
	(1) Weight	(2) Weight	(3) Weight	(4) Weight	(5) Weight	(6) Weight
Treatment	27.007***	27.007***	22.613*	22.612*	29.650***	29.650***
	(5.973)	(5.973)	(7.121)	(7.121)	(6.336)	(6.336)
Observations	280	280	160	160	240	240
R2	0.029	0.461	0.027	0.281	0.037	0.392
Average Dep. Var.	126.314	126.314	135.850	135.850	136.775	136.775
Plot Fixed Effects	No	Yes	No	Yes	No	Yes

Source: Own elaboration based on pilot evaluation data.

Note: The dependent variable is dried grain weight (grams) per quinoa plant clump. All columns report results for plots with constant plot owner presence. Columns (1)–(2) use the full pilot sample; columns (3)–(4) restrict to plots meeting predefined information standards; columns (5)–(6) restrict to plots with comparatively high protocol compliance. Even-numbered columns include plot fixed effects. Standard errors clustered at the plot level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Taken together, these results suggest that plot owner presence and management intensity are critical for compost effectiveness. Compost application leads to substantial productivity gains when plot owners actively manage plots and follow protocols. In contrast, limited owner presence hinders treatment benefits, even when the intervention is sound. These findings highlight the importance of soil fertility interventions and management practices in smallholder quinoa systems. Without sufficient on-site engagement, the potential benefits of compost application are not fully realized.

7.1.7 Synthesis of Pilot Intervention Results

Overall, the results of the pilot intervention provide a coherent picture of how compost application affects quinoa productivity for smallholders in the southern Altiplano. Across all pilot plots, compost application increased the average weight of grains per clump. This confirms the intervention's agronomic effectiveness under real farming conditions and supports the choice of the 600-gram-per-plant dosage validated in Section 6. The stability of point estimates with and without plot fixed effects strengthens the validity of the evaluation design. Additionally, treatment effects increase systematically when the analysis is restricted to plots that meet predefined information standards, especially those with high protocol compliance. This pattern suggests that execution and measurement discipline are central determinants of realized impacts, not merely operational details.

Heterogeneity analysis shows that treatment effects are influenced by climatic stressors and management constraints. Rainfall intensity shapes the magnitude and dispersion of treatment effects. Compost improves productivity under both below- and above-median rainfall, but the benefits are larger and more variable under wetter conditions, especially when protocol compliance is high. Similarly, frost intensity moderates effectiveness: compost yields larger gains under lower frost exposure. Under higher frost intensity, average effects decrease but become clearer statistically significant when implementation quality is high. These results are consistent with a setting where compost improves soil functioning, especially moisture retention and nutrient availability, but cannot fully neutralize extreme climatic stress. Realized gains depend on whether these soil improvements coincide with environmental conditions that allow plants to convert them into grain filling.

Weed pressure is a major agronomic constraint that limits the ability to convert improved soil conditions into increased yields. Compost yields the greatest productivity increases when weed intensity is low, and these gains are amplified under strong protocol compliance. Under high weed intensity, the effects of treatment remain positive, albeit smaller, and are comparatively insensitive to improvements in implementation quality. These findings imply that, in certified quinoa systems, soil fertility restoration and weed management are complements rather than substitutes: when weeds intensify competition for moisture and nutrients, part of the intervention's potential is absorbed by the competitive environment rather than expressed in grain production.

Evidence on wind intensity provides an important qualification that enhances the interpretation of climatic heterogeneity. Wind exposure is a background stressor and a way broader land use can reduce the potential of soil fertility interventions. In plots with wind intensity below the median, compost yields substantial and statistically significant estimated gains. This shows that improved soil structure and moisture retention can increase productivity when wind-driven moisture loss and physical stress are limited. In contrast, under wind intensities above the median, average treatment effects weaken and become more sensitive to implementation quality. They are detectable only under stricter information standards and the highest level of protocol compliance. This pattern supports the idea that removing natural wind barriers in the study area increased exposure, reducing the benefits of compost through enhanced evapotranspiration, faster soil drying, erosion risks in sandy soils, and direct plant stress. While wind does not negate the agronomic value of compost, it lowers the ceiling of what compost can deliver when landscape protection is weakened.

Finally, the presence and management intensity of a plot's owner are central to whether agronomic improvements lead to higher productivity. Compost application is most effective in plots where owners are frequently present. This reflects stronger monitoring, better timing of complementary practices, and higher adherence to protocols. In plots where owners are rarely present, differences between treated and control subplots remain limited, even when measurement quality is high. This reinforces a key insight from the pilot: soil amendments are necessary but not sufficient. Their impact depends on sustained on-site engagement and managerial capacity, both currently influenced by migration and labor constraints in the southern Altiplano.

Therefore, the pilot intervention shows that compost application can increase quinoa productivity in the southern Altiplano. However, its effectiveness varies with environmental exposure and management conditions. Climatic stress, such as rainfall and frost, affects the magnitude and variability of the impacts. Weed pressure and wind exposure influence how much soil fertility improvement is converted into grain weight. Management intensity determines if the intervention is implemented with the discipline needed to achieve its full potential. These findings have direct implications for scaling up the program. Programs promoting compost use should support weed management, monitoring systems, and plot owner engagement. In areas where wind barriers have been removed, these programs should also implement landscape-level wind protection strategies to prevent wind exposure from reducing the productivity gains that organic soil amendments can deliver.

8 Conclusions

This study addressed a central challenge in smallholder quinoa systems in the southern Altiplano of Bolivia: designing, validating, and evaluating soil fertility interventions that are effective and robust despite severe environmental and managerial constraints. Instead of treating impact evaluation as a standalone exercise, this paper used an integrated approach, including baseline diagnosis, agronomic design, standard agronomic validation, and real-world pilot evaluation, to generate scientifically credible and operationally relevant evidence.

The baseline diagnostic revealed an agricultural production system with extreme soil degradation, high exposure to climatic stressors, and inconsistent management practices. In the post-boom years, quinoa productivity is severely limited by low organic matter content, exposure to strong winds after natural barriers were removed, frequent frost, and intense weed pressure under organic certification. Any soil fertility intervention must be evaluated not only for its biological potential but also for how much of that potential can be achieved in actual farming conditions. The diagnostic phase provided the empirical and conceptual foundation for designing the intervention, ensuring the compost formulation and dosage directly target the most significant constraints.

Based on this diagnosis, the design and validation phase determined the agronomic potential of compost application under controlled yet realistic field conditions. The validation plot identified an optimal dosage of 600 grams per quinoa plant clump and documented a 48.78% increase in grain productivity relative to the untreated control. This result is significant because it represents the *upper-bound* of the intervention's potential when soil improvements are not severely constrained by external stressors or implementation failures. Therefore, the validation plot served as necessary proof of concept, confirming that the intervention is biologically sound and capable of generating significant productivity increases.

Then, the pilot intervention moved beyond the controlled setting to test its potential across heterogeneous plots exposed to real climatic variability, weed pressure, wind exposure, and, most importantly, differences in the presence and compliance of plot owners. In these conditions, the estimated average treatment effect stabilized at about 11–12%, a meaningful economic magnitude but much lower than the gain seen in the validation plot. This reduction should not be interpreted as evidence that the intervention is always less effective in real settings. Instead, it highlights the distinction between potential and realized effects. The pilot estimate offers a conservative, policy-relevant *lower bound*, representing the minimum expected productivity gain when compost is applied to typical smallholder plots facing multiple interacting constraints and external stressors.

Heterogeneity analyses clarify why this gap emerges. Rainfall and frost determine how much improved soil conditions contribute to grain filling. Weed pressure diverts nutrients and moisture from the crop. Wind exposure accelerates evapotranspiration and reduces the benefits of restoring organic matter. Limited farmer presence leads to less adherence to protocols and poor timing of complementary practices. These factors do not eliminate the benefits of compost but reduce its effectiveness. When constraints are moderate and implementation quality is high, treatment effects approach a substantial share of validation-plot gains. Where constraints accumulate, realized effects converge toward the lower bound captured by the full-sample pilot estimate.

Methodologically, the study highlights the importance of incorporating impact evaluations into a broader agronomic and diagnostic framework. The randomized within-plot design ensures internal validity, and the *diagnostic-design-validation-pilot* sequence enables structural rather than descriptive interpretation of results. The observed average gains are not an isolated statistic. They result from a transparent process that links biological potential to real-world feasibility. This approach bridges the gap between agronomic trials and policy evaluation by providing a template for assessing interventions in high-risk agroecological environments.

From a policy and scaling perspective, the findings suggest that promoting compost application alone does not maximize its productivity potential. Scaling strategies must address additional constraints, including weed management, farmer engagement, monitoring systems, and, critically in this context, landscape-level wind protection to prevent external stressors from eroding soil fertility gains. The pilot results suggest that compost alone delivers a modest but reliable productivity increase. With these complements, a much larger share of the validated 48.78% potential can be realized. In sum, this study shows that compost application is an effective, scalable soil fertility intervention for quinoa systems in the southern Altiplano when interpreted through the lens of environmental exposure and management capacity. Distinguishing between potential and realized effects is not a weakness of the intervention; it is an essential insight for designing resilient, context-aware agricultural policies. Hence, composting is a short-term solution that should form part of a comprehensive, sustainable strategy for soil regeneration.

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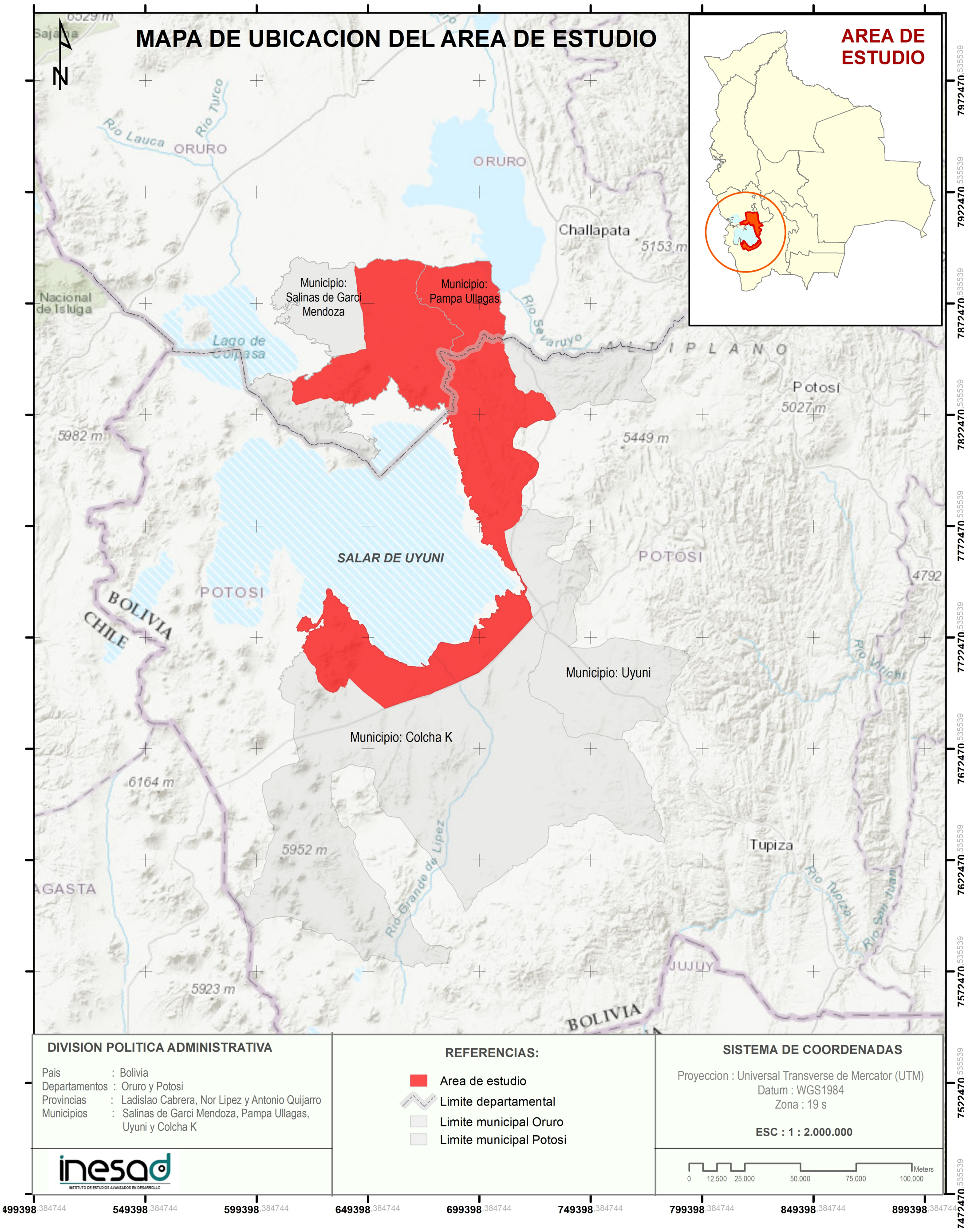
A Appendix

Table A.1: Distribution of Soil Samples by Location

Department	Province	Municipality	Community	No. of Plots
Oruro	Ladislao Cabrera	Salinas de Garci Mendoza	Capura (Cap)	6
			Chalgua (Cha)	10
			Florida (Flo)	13
			Otuyo (Otu)	1
			Rodeo (Rod)	9
			Sigualaca (Sig)	2
			Tolamayu (Tol)	1
		Pampa Aullagas	Bengal Vinto (BVo)	7
	Cercado	Cercado	Santa Ana (SAn)	1
Potosí	Antonio Quijarro	Uyuni	Bella Vista (BVa)	13
			Tuzqui (Tuz)	1
			Vinto (Vin)	1
			Vintuta (Vin)	7
	Nor Lípez	Colcha K	Atulcha (Atu)	2
			Villa Candelaria (VCa)	1
Total	4	5	15	75

Source: Own elaboration based on the soil diagnostic sampling frame.

Figure A.1: Geographic Location of Soil Sampling Plots



Source: Own elaboration based on soil diagnostic data.

Note: The figure shows the geographic distribution of the 75 certified organic quinoa plots sampled between October 2022 and May 2023 across communities in the departments of Oruro and Potosí. Highlighted areas correspond to municipalities included in the soil diagnostic.

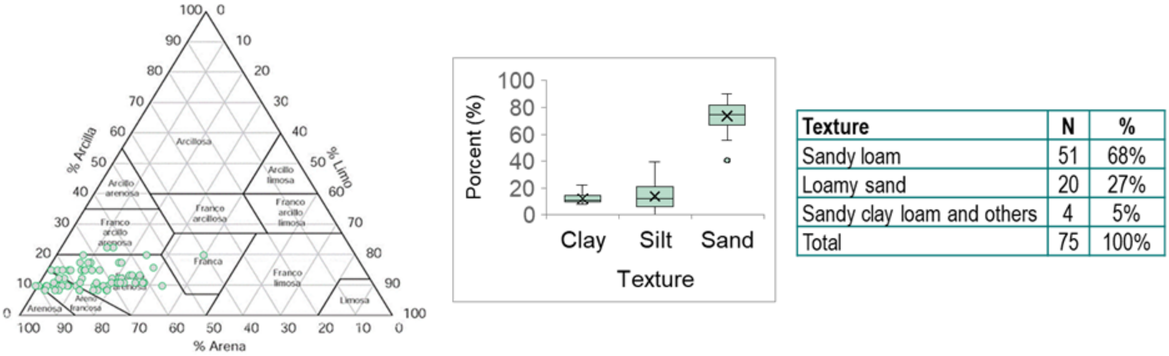
Table A.2: Descriptive Statistics of Soil Variables from Soil Samples

Soil variables	N	Mean	Std. Dev.	Maximum	Minimum	Coeff. of Variation
pH	75	8.55	9.34	7.18	0.54	0.06
Electrical conductivity	75	219.77	2470.00	18.50	438.06	1.99
Clay (%)	75	73.88	90.19	40.57	9.71	0.13
Silt (%)	75	13.99	39.63	0.01	8.67	0.62
Sand (%)	75	12.13	22.30	8.20	3.46	0.29
Organic matter (%)	75	0.47	1.52	0.07	0.25	0.54
Total nitrogen (%)	75	0.03	0.11	0.01	0.01	0.42
C/N ratio	75	7.88	12.57	3.06	1.86	0.24
Sulfur (mg/kg)	75	33.63	737.10	2.00	99.62	2.96
Phosphorus (mg/kg)	75	8.94	92.95	1.47	11.69	1.31
Potassium (cmol/kg)	75	0.90	3.74	0.28	0.59	0.66
Calcium (cmol/kg)	75	15.84	50.50	1.91	11.10	0.70
Magnesium (Mg)	75	1.05	2.54	0.39	0.49	0.47
Sodium (cmol/kg)	75	0.52	8.58	0.03	1.09	2.11
Sodium saturation (%)	75	2.69	25.35	0.19	4.16	1.55
CEC (cmol/kg)	75	19.23	55.91	3.03	11.92	0.62
Iron (mg/kg)	75	5.70	23.84	0.37	5.27	0.92
Manganese (mg/kg)	75	12.88	36.99	0.25	7.54	0.59
Zinc (mg/kg)	75	0.89	7.50	0.07	1.31	1.48
Copper (mg/kg)	75	0.43	5.08	0.11	0.58	1.36
Boron (mg/kg)	75	2.93	11.78	0.28	2.38	0.81
Fertility index	75	1.82	3.00	1.33	0.28	0.15

Source: Own elaboration based on laboratory soil analysis.

Note: The table reports descriptive statistics for soil samples collected from certified quinoa plots in the southern Altiplano. The coefficient of variation is defined as the ratio of the standard deviation to the mean.

Figure A.2: Soil Texture Classification of Sampled Plots

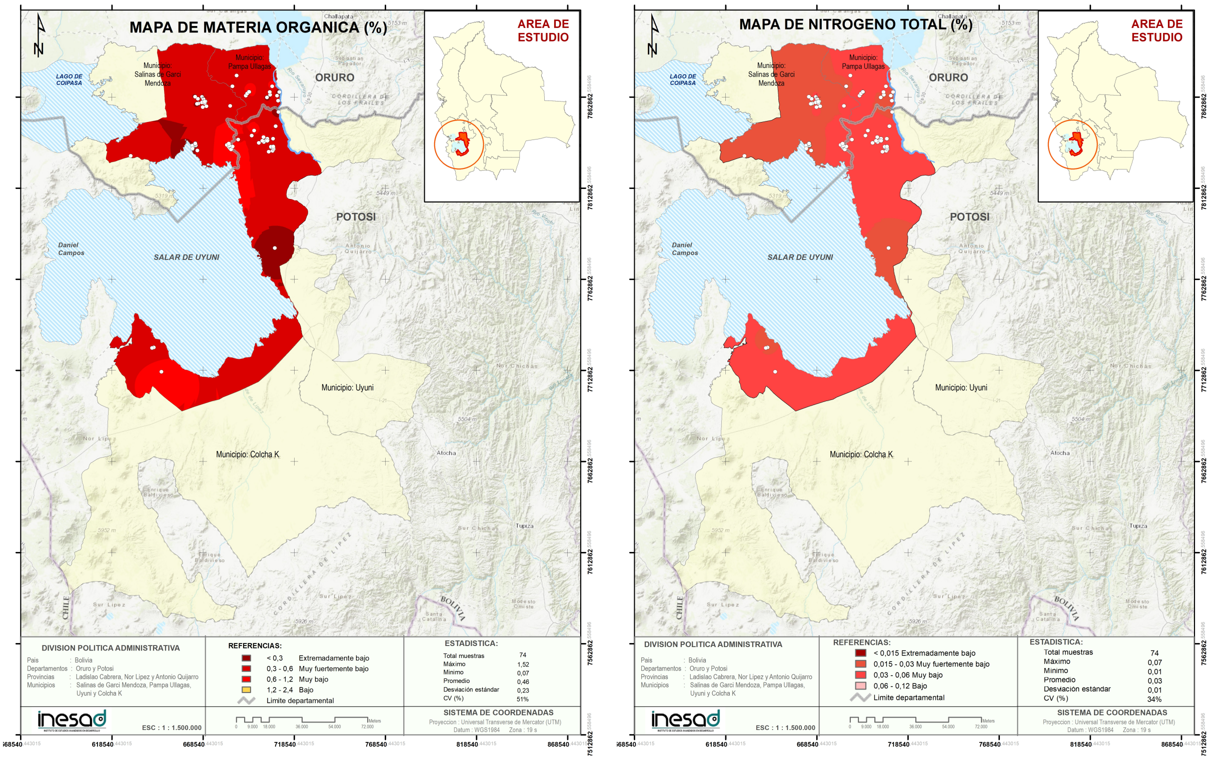


Texture	N	%
Sandy loam	51	68%
Loamy sand	20	27%
Sandy clay loam and others	4	5%
Total	75	100%

Source: Own elaboration based on soil diagnostic data.

Note: The figure summarizes the texture composition of sampled soils, combining the ternary texture diagram (sand–silt–clay), the distribution of texture-related measures, and the corresponding frequency table by texture class.

Figure A.3: Spatial Distribution of Organic Matter and Total Nitrogen in Sampled Plots



(a) Organic matter (%)

(b) Total nitrogen (%)

Source: Own elaboration based on soil diagnostic data.

Note: The figure maps the spatial distribution of organic matter and total nitrogen across sampled certified quinoa plots. Categories reflect the diagnostic classification used in the laboratory analysis.

Table A.3: Analysis of Variance for Number of Plants per Clump

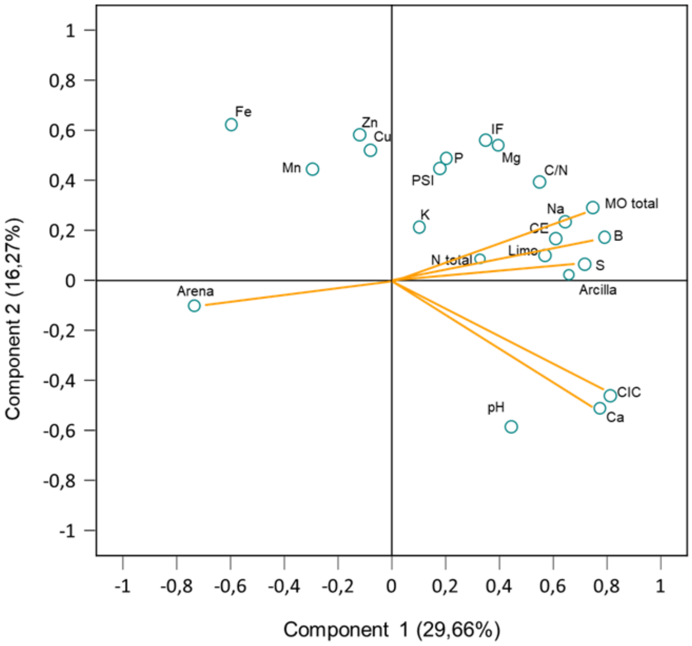
ANOVA Table (Type I Sum of Squares)				
Source of Variation	SS	df	MS	F
Model	981.14	4	245.28	8.45*
Compost level	981.14	4	245.28	8.45*
Error	4092.64	141	29.03	
Total	5073.78	145		

* Significant at $p < 0.05$.

Table A.4: Analysis of Variance for the Effect of Compost on Plant Height

ANOVA Table (Type I Sum of Squares)				
Source of Variation	SS	df	MS	F
Model	291.44	4	72.86	0.47
Compost level	291.44	4	72.86	0.47
Error	22078.24	141	156.58	
Total	22369.68	145		

Figure A.4: Principal Component Analysis of Soil Properties



Source: Own elaboration based on laboratory soil data.

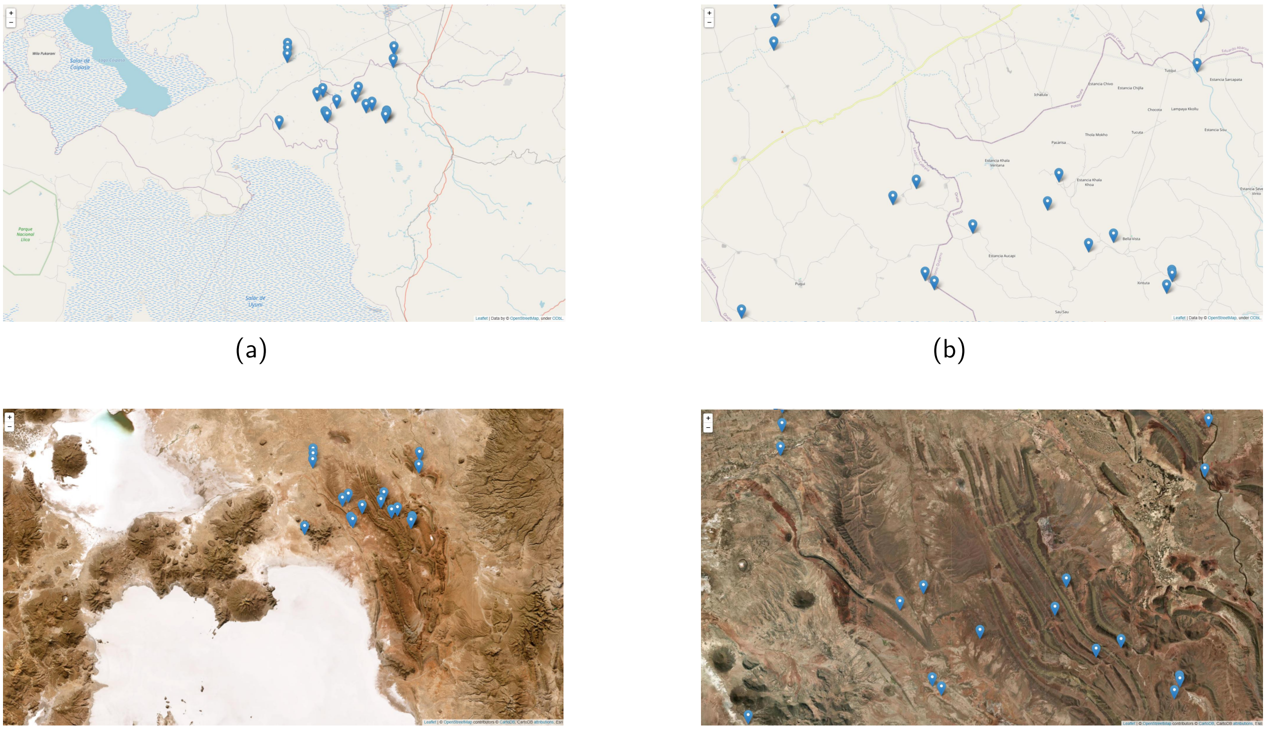
Note: The figure reports the results of a principal component analysis (PCA) applied to standardized soil variables. Points represent individual soil samples projected onto the component space, while vectors indicate the contribution and loading direction of the original soil variables. The first four principal components jointly explain 65.9% of the total variability in soil properties, capturing the dominant dimensions of fertility constraints across certified quinoa plots.

Table A.5: Analysis of Variance for the Effect of Compost on Organic Quinoa Yield

ANOVA Table (Type I Sum of Squares)				
Source of Variation	SS	df	MS	F
Model	606748.47	4	151687.12	5.76*
Compost level	606748.47	4	151687.12	5.76*
Error	3579175.73	136	26317.47	
Total	4185924.20	140		

* Significant at $p < 0.05$.

Figure A.5: Georeferencing of the Pilot Intervention



(a) (b)

(c) (d)

Source: Own elaboration.