Zinc Application for Improved Grapes Production in Zhob District, Balochistan: Mitigating Water Scarcity Challenge

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Abstract

Balochistan, known as the "fruit basket" of Pakistan, particularly for its grape production in Zhob district, faces significant challenges due to water scarcity. Zinc, an essential micronutrient for grapes, influences various growth processes and could potentially mitigate the impact of water stress. This study aimed to evaluate the effects of zinc application on grape yield and quality in the arid conditions of Zhob district, Balochistan, under varying levels of zinc supplementation. The experiment was conducted at the Directorate of Agriculture Research, Zhob, using a randomized complete block design. Four levels of zinc treatments (0g, 10g, 20g, and 40g per grape vine) were applied and assessed for their impact on vine yield, cluster weight, berry weight, titratable acidity, total soluble solids, and pH. Statistical analyses, including ANOVA and correlation studies, were employed to evaluate the treatment effects. The results demonstrated that zinc application significantly increased vine yield, cluster weight, and berry weight. The highest zinc treatment (40g per vine) not only yielded the highest vine production but also significantly improved fruit quality, evidenced by increases in titratable acidity and total soluble solids, and a decrease in pH levels. Statistical analysis confirmed that these improvements were significant at a 1% probability level. Zinc supplementation in grape cultivation offers a promising solution to combat the effects of drought by enhancing grapevine growth and resilience. The study suggests that strategic zinc application can significantly improve both the quantity and quality of grapes in water-scarce regions, supporting sustainable agriculture and economic stability in rural communities. Grape growers in arid regions should consider integrating zinc supplementation into their farming practices to optimize grape yield and quality. Further research is recommended to refine zinc application protocols and explore its long-term impacts on vine health and soil properties.

Keywords: Grapes, Zhob, Balochistan, Zinc, water, drought

1 INTRODUCTION

Balochistan, often referred to as the "fruit basket" of Pakistan, is renowned for its diverse agricultural products, particularly grapes [1]. The Zhob district, located in the northeastern part of the province, stands out as a significant contributor to this reputation [2] [3]. Grapes from Zhob are prized for their quality and are a major source of income for local farmers [4] [5]. The region's unique climatic conditions, characterized by dry summers and cold winters, are well-suited for grape cultivation, enabling the production of varieties with superior taste and quality [6]. However, the agricultural success of Zhob district is tempered by the challenges posed by water scarcity. As one of the most arid regions in Pakistan, water resources in Balochistan are under severe stress due to variable rainfall and the changing climate [7] [8]. This scarcity poses a significant threat to sustainable agriculture, impacting crop yields and the livelihoods of farmers. In response to these challenges, innovative agricultural practices are crucial for enhancing crop resilience and ensuring the economic stability of the region [9].

Water scarcity is one of the most pressing environmental challenges facing the agricultural sector in the Zhob district of Balochistan [10] [11]. The district, despite its potential for high-quality grape production, experiences recurrent water shortages that significantly impede agricultural productivity. Limited rainfall and overexploitation of groundwater resources have led to a critical depletion of water supplies, putting immense pressure on the sustainability of agricultural practices [11] [12]. The impact of water scarcity on grape cultivation cannot be overstated. Grapes require consistent and adequate water supply for optimum growth and fruit development [13] [14]. Water stress during critical growth stages, such as flowering and fruit set, can lead to reduced berry size, altered sugar concentrations, and ultimately, diminished yield and quality. These changes not only affect the economic viability of grape farms but also threaten the livelihoods of local communities that depend heavily on agriculture [15] [16].

Moreover, water scarcity exacerbates other environmental issues such as soil salinity and erosion, further challenging the cultivation of grapes in this region. The adaptation of innovative agricultural practices, such as the strategic application of essential micronutrients like zinc, has become imperative.

Zinc is recognized as an essential micronutrient for plants, playing a critical role in various physiological functions that are vital for growth and development [17]. It acts as a catalytic and structural component in numerous enzymes and proteins and is crucial for maintaining the integrity of cellular membranes. Zinc's involvement extends to significant processes such as protein synthesis, growth regulation, and gene expression, which are fundamental for plant health and productivity.

Zinc is a component of carbonic anhydrase, an enzyme necessary for the photosynthesis process. Adequate zinc levels are essential for optimal photosynthetic efficiency, which directly affects plant growth and crop yields [18]. Zinc plays a role in the synthesis of auxin, an important plant hormone involved in growth regulation. Insufficient zinc can disrupt hormone balance, leading to stunted growth. Zinc contributes to plants' resilience against environmental stresses, particularly salinity and drought. This is partly due to its role in the synthesis of proteins involved in stress response and its antioxidant properties, which help mitigate oxidative damage caused by stress conditions [19].

Several studies have highlighted the positive impacts of zinc supplementation in enhancing plant growth and yield, especially under stress conditions [20]. For instance, a study by [21] found that zinc application improved wheat yield by 20% in zinc-deficient soils. Similarly, research by [22] on grapevines demonstrated that zinc supplementation led to improved vine Vigor and fruit quality, particularly under water-limited conditions. The application of zinc, therefore, not only supports basic plant functions but also enhances the plant's ability to withstand and adapt to environmental stresses, making it a potentially valuable tool in sustainable agriculture, especially in regions like the Zhob district where water scarcity is a persistent issue.

The strategic application of micronutrients, such as zinc, has been identified as a potential solution to mitigate the effects of water scarcity on grape production [23] [24]. Zinc plays a vital role in several plant physiological processes, including growth regulation and stress tolerance. Its application has been shown to improve plant health and yield, particularly in stress conditions induced by water shortages [20] [25]. This research aims to explore the efficacy of zinc application in enhancing grape yield and quality in the challenging environment of Zhob district, offering a pathway to more resilient and productive agriculture by investigating how zinc application can mitigate the effects of water scarcity on grape production, potentially offering a sustainable solution to enhance crop resilience and maintain the economic stability of the area.

1.1 **Challenges in Grape Production**

Grape production is highly sensitive to variations in environmental conditions, particularly water availability. Water scarcity poses a significant threat to vine health and productivity, leading to various physiological and economic challenges [26]. Several studies have outlined the impact of drought conditions on grapevines, detailing how water stress can affect virtually every aspect of vine growth and fruit development. Physiological Challenges: Water stress primarily affects the plant's ability to transpire effectively, which is crucial for nutrient uptake and temperature regulation [27]. Under drought conditions, grapevines may exhibit reduced leaf area, stunted growth, and a significant decline in photosynthetic activity. These changes are often accompanied by premature leaf senescence and abscission, reducing the plant's overall vitality and yield potential [28].

Water scarcity directly impacts grape yield by affecting the rate of berry set and development [29]. Studies, such as those conducted by [30], have shown that reduced water availability leads to smaller berries with higher concentrations of sugars, acids, and phenolics, which can alter the wine's flavor profile. While some changes might be beneficial for certain wine qualities, they generally represent a loss in yield and marketability for table grapes and other grape products. The economic implications of water scarcity are significant. Reduced yields translate to lower income for farmers, while the cost of additional irrigation or water-saving technologies can be prohibitive [31]. This economic strain is particularly acute in regions like Zhob district, where agriculture forms the backbone of the local economy. In response to these challenges, researchers have explored various strategies to mitigate water stress effects. These include developing drought-resistant grape varieties, optimizing irrigation practices to use water more efficiently, and applying soil amendments to enhance water retention. Supplementing essential nutrients like zinc has also been studied as a strategy to enhance plant resilience and improve physiological responses under water-limited conditions [32].

1.2 **Previous Solutions and Gaps**

The challenge of water scarcity in grape production has prompted a variety of mitigation strategies over the years, ranging from agronomic to technological solutions. Previous studies have explored several approaches, each with varying degrees of success and limitations [33]. Improved irrigation techniques such as drip irrigation and deficit irrigation have been widely implemented to enhance water use efficiency in vineyards [34]. These methods allow precise water application directly to the plant's roots, minimizing waste. However, while these techniques reduce water usage, they do not always address the underlying nutrient deficiencies that can exacerbate stress conditions in plants. The development and adoption of drought-resistant grape varieties have shown promise in maintaining productivity under water-limited conditions [35]. Although these varieties offer a genetic solution to drought stress, they may not always produce the desired fruit quality or yield expected by growers and consumers, limiting their widespread acceptance.

The use of soil amendments, such as organic mulches or hydrogels, has been effective in improving soil water retention and reducing evaporation. While these methods are beneficial, they often involve significant changes to vineyard management practices and can be cost-prohibitive for small-scale farmers [36]. The strategic application of essential nutrients, notably zinc, has been identified as a potential method to enhance plant vigor and stress tolerance. Research by [37] indicated that zinc application could improve photosynthetic efficiency and antioxidant capacity in water-stressed plants. However, there is a gap in comprehensive field-based studies that quantify the direct impact of varying zinc levels on grape yield and quality under real-world conditions of water scarcity. Most existing research focuses on small-scale experiments or controlled environment studies. There is a noticeable lack of large-scale, field-based research that integrates nutrient management with water scarcity solutions. Additionally, while the benefits of zinc are known at a theoretical level, practical guidelines for its application specific to varying degrees of water stress in vine cultivation are still underexplored [38].

This research aims to fill these gaps by providing empirical evidence from a field study that evaluates the effect of different zinc supplementation levels on grape production under actual water-scarce conditions. The findings are expected to offer practical, scalable solutions for grape growers in arid and semi-arid regions, contributing to more sustainable agricultural practices.

The primary objective of this research was to investigate the effects of zinc application on grape production in the Zhob district of Balochistan as a strategic mitigation approach to combat water scarcity. This study aims to determine how different levels of zinc supplementation (0g, 10g, 20g, and 40g per grape vine) can influence vine yield, cluster weight, berry weight, as well as key quality parameters such as titratable acidity, total soluble solids, and pH levels under conditions of limited water availability.

1. Assess the potential of zinc as a micronutrient to enhance grape yield and improve quality attributes despite the challenges posed by water stress.
2. Establish optimal zinc application rates that maximize grapevine productivity and resilience in arid and semi-arid environments.
3. Provide evidence-based recommendations for grape growers in water-scarce regions, aiming to sustain and possibly increase agricultural output through improved nutrient management practices.

This study not only contributes to the body of knowledge regarding plant nutrition and stress mitigation but also offers practical solutions to local farmers facing environmental constraints, thereby supporting sustainable agricultural practices in Balochistan.

2 MATERIALS AND METHODS

2.1 **Study Area Description**

The research was conducted at the Directorate of Agriculture Research (DAR) Zhob, located in the Zhob district of Balochistan, Pakistan. This area is characterized by its semi-arid climate, with hot summers and cold winters, receiving an average annual precipitation of approximately 200-250 mm. Over the course of the year, the temperature typically varies from 32°F to 97°F and is rarely below 27°F or above 103°F. Such climatic conditions pose significant challenges for agriculture, particularly in terms of water availability. The soil in this region is predominantly sandy loam, which has good drainage properties but low water retention capacity. These soil characteristics further exacerbate the water scarcity issue, as frequent irrigation is required to maintain adequate soil moisture for crop growth. The soil is also typically low in organic matter and essential nutrients, which can affect plant growth and productivity unless properly managed. The DAR Zhob serves as a pivotal research facility focused on improving agricultural practices in Balochistan, especially in optimizing resource use under challenging environmental conditions. The site was chosen for this study due to its representative nature of the wider agricultural conditions in the area and its ongoing focus on developing sustainable agricultural techniques.

2.2 **Experimental Setup**

The experimental design was a randomized complete block design (RCBD) with four treatments: 0g Zn (control), 10g Zn, 20g Zn, and 40g Zn per grape vine, applied in a chelated form. Each treatment was replicated five times across different blocks to ensure the reliability of the results. Data on vine yield, cluster weight, berry weight, titratable acidity, total soluble solids (TSS), and pH levels were collected throughout the growing season. Additional observations included plant vigor, leaf color, and incidence of any disease or pest issues. Data collection methods were standardized to ensure consistency across all treatments. The experiment was structured using a randomized complete block design (RCBD) to assess the effects of zinc application on grape production under conditions of water scarcity. The study included four zinc treatment levels, designed to explore a range of potential impacts from minimal to aggressive zinc supplementation:

1. Control (0g Zn): No zinc was applied to the grape vines in this group, serving as the baseline to evaluate the effects of zinc supplementation.

2. Low Zinc (10g Zn): A modest amount of zinc was applied to each vine to assess its impact on plant growth and fruit development at a lower supplementation level.

3. Moderate Zinc (20g Zn): This group received a moderate level of zinc, intended to test the effectiveness of an average application rate.

4. High Zinc (40g Zn): The highest level of zinc was applied in this treatment to determine the effects of a substantial zinc supplementation on grape yield and quality.

Each treatment was replicated five times across different blocks to minimize environmental variability and ensure that the data collected were robust and statistically reliable. Zinc was applied in a chelated form to enhance absorption and utilization by the grapevines. The timing of the application was aligned with key growth stages of grape development, specifically pre-bloom and post-set, to maximize the potential impact of zinc on fruit set, berry development, and maturation. The plots were irrigated using a drip irrigation system, calibrated to deliver water at 80% of the evapotranspiration rate to simulate water-scarce conditions consistently across all treatments. The experimental plot size for each treatment was 10m x 10m, containing 10 grape vines per plot, spaced to allow uniform application of treatments and ease of data collection.

2.3 **Data Collection and Analysis**

Data were collected on a variety of parameters, including vine yield, cluster weight, berry weight, and qualitative measures such as titratable acidity, total soluble solids (TSS), and pH. Statistical analysis was performed using ANOVA [39] to determine the significance of differences between treatment groups at a 1% probability level.

2.3.1 **Data Collection Methods**

To accurately assess the impact of zinc application on grape production, comprehensive data collection was implemented focusing on both quantitative and qualitative parameters:

1. Vine Yield: The total weight of grapes harvested from each vine was recorded at the end of the growing season. Each vine was harvested separately, and the grapes were weighed using a precision scale to ensure accuracy.

2. Cluster Weight: Individual grape clusters were randomly selected from each vine during the harvest. A sample of five clusters per vine was weighed, and the average weight was calculated to represent the cluster weight for each treatment.

3. Berry Weight: From each sampled cluster, ten berries were randomly selected and weighed together. The total weight was then divided by the number of berries to determine the average berry weight, providing insights into the effects of zinc treatment on berry size and development.

4. Titratable Acidity (TA): Titratable acidity was measured to assess the grape juice's acidity level, which is a critical quality attribute for grapes. Juice was extracted from a sample of berries from each treatment, and the acidity was measured using a titration method with a standard sodium hydroxide solution. The results were expressed as a percentage of tartaric acid.

5. Total Soluble Solids (TSS): The total soluble solids, indicative of the sugar content in the grape juice, were measured using a refractometer. A small sample of juice from the crushed berries was placed on the refractometer prism, and the Brix degree, representing the sugar content, was recorded.

6. pH Measurement: The pH of the grape juice was measured using a pH meter. This parameter is important for assessing the potential quality and stability of grape products. Juice from the same sample used for TSS and TA tests was analysed to determine its pH level.

All data were collected at the same time during the harvesting period to minimize variability due to environmental factors or developmental stages. Standard operating procedures (SOPs) were followed to ensure consistency and reliability in the data collection process.

3 RESULTS

The statistical analysis indicated that all measured parameters showed significant differences ($p<0.01$) between the control group and the zinc-treated groups, with the 40g Zn treatment consistently demonstrating the highest improvements in all aspects of grape production. The results of the study were organized and presented using both tables and graphs to clearly illustrate the impact of zinc application on grape production under water-scarce conditions.

This section highlights key findings from the data collected, including vine yield, cluster weight, berry weight, titratable acidity, total soluble solids, and pH levels across different zinc treatment levels. (Table 1, 2)

Table 1: Summary of Vine Yield, Cluster Weight, and Berry Weight

Treatment (Zn)	**Vine Yield (kg)**	**Cluster Weight (g)**	**Berry Weight (g)**
Control (0g)	16.2	202.8	11.2
Low (10g)	18.4	220.1	12.5
Moderate (20g)	21.9	250.7	14.3
High (40g)	25.3	327.2	21.3

Table 2: **Summary of Titratable Acidity, Total Soluble Solids, and pH**

Treatment (Zn)	Titratable Acidity (%)	Total Soluble Solids (°Brix)	pH
Control (0g)	2.35	18.23	3.96
Low (10g)	2.75	19.45	3.89
Moderate (20g)	3.05	20.36	3.82
High (40g)	3.40	21.26	3.75

Graph 1: Vine Yield Across Zinc Treatments

The bar graph demonstrates a progressive increase in vine yield with higher levels of zinc application. The 'High (40g)' treatment shows a significant increase in yield, reaching 25.3 kg, compared to only 16.2 kg in the control group, indicating a robust response to zinc in terms of overall productivity.

Graph 2: Cluster Weight and Berry Weight Across Zinc Treatments

Cluster and berry weights also show a clear upward trend with increased zinc dosages. Notably, the cluster weight for the 'High (40g)' treatment averaged 327.2g, substantially higher than the 202.8g observed in the control group. Similarly, berry weight under the 'High (40g)' treatment increased to 21.3g from 11.2g in the control group, suggesting enhanced fruit development.

Graph 3: Titratable Acidity and Total Soluble Solids Across Zinc Treatments

Titratable acidity and total soluble solids, important quality indicators, were positively influenced by zinc application. The 'High (40g)' treatment resulted in a titratable acidity of 3.40% and total soluble solids of 21.26 Brix, compared to 2.35% and 18.23 °Brix in the control, respectively. This indicates that zinc not only improves yield but also enhances the grape's quality attributes.

Graph 4: pH Levels Across Zinc Treatments

The pH levels across treatments show a decreasing trend with increased zinc supplementation, with the 'High (40g)' treatment achieving a pH of 3.75, lower than the control's 3.96. The lower pH in grapes is generally associated with better taste and storage properties.

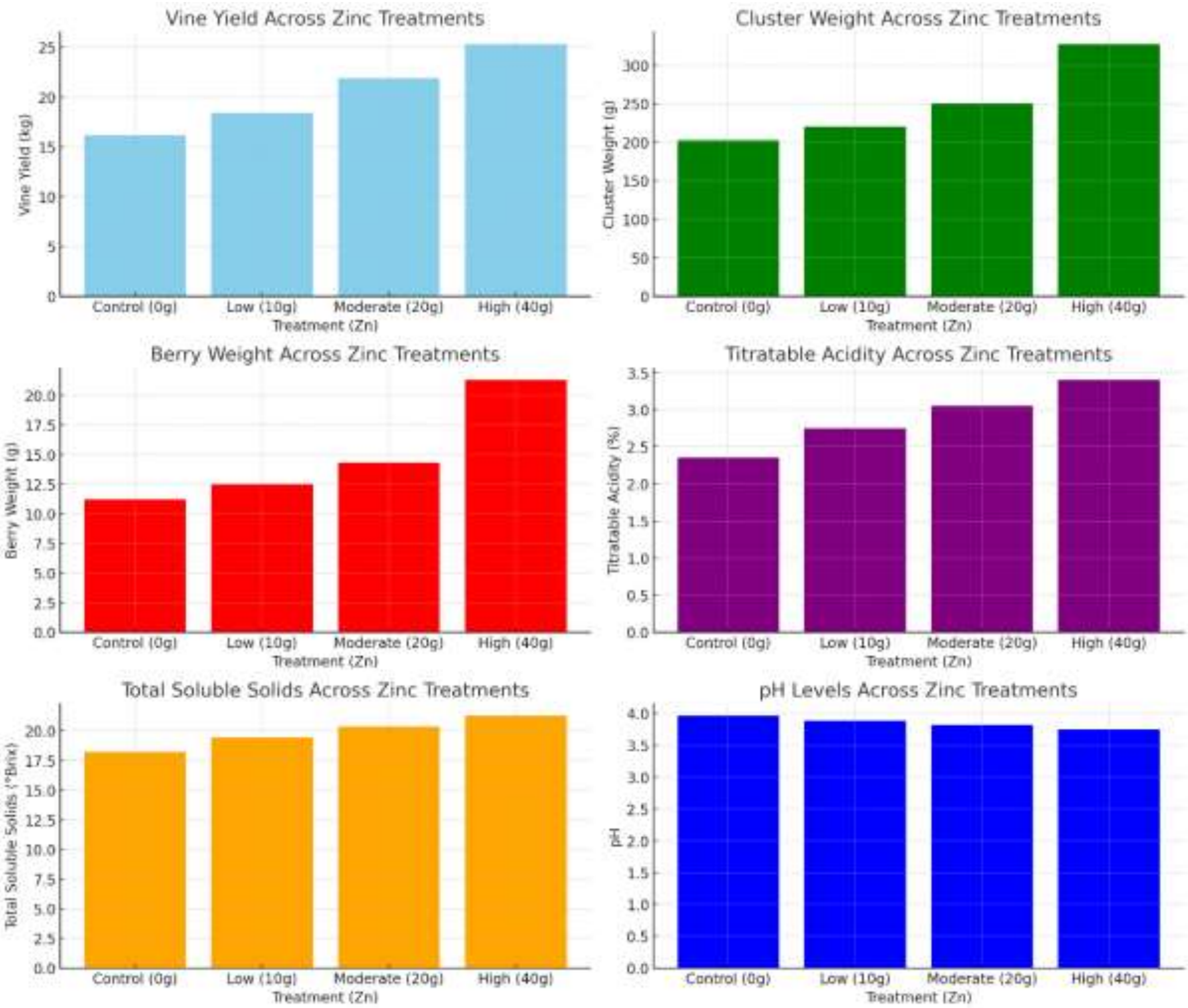

Fig 1. A bar graph illustrating the differences in vine yield for each treatment group, showing a clear increase in yield with higher zinc levels. Graph 1: Vine Yield Across Zinc Treatments, Graph 2: Cluster Weight Across Zinc Treatments, Graph 3: Berry Weight Across Zinc Treatments Graph 4: Titratable Acidity Solids Across Zinc Treatments, Graph 5: Total Soluble Solids Across Zinc Treatments Graph 5: pH Levels Across Zinc Treatments.

3.1 Descriptive Statistics and Correlation Analysis

3.1.1 Descriptive Statistics

The descriptive statistics provide an overall summary of the dataset across all zinc treatments:

- **Vine Yield (kg)**: The average vine yield across treatments was 20.45 kg, with a standard deviation of 3.99 kg, indicating a moderate variability in yield among the treatments.
- **Cluster Weight (g)**: The average cluster weight was 250.2 g, with a standard deviation of 55.02 g. The maximum observed was 327.2 g, which occurred in the highest zinc treatment.
- **Berry Weight (g)**: The average berry weight was 14.83 g, ranging from 11.2 g to 21.3 g, highlighting significant differences based on zinc levels.
- **Titratable Acidity (%)**: The average titratable acidity was 2.89%, with variations between 2.35% and 3.4%.
- **Total Soluble Solids (°Brix)**: The average total soluble solids were 19.83 °Brix, with a range from 18.23 to 21.26 °Brix, showing an increase with higher zinc applications.
- **pH**: The average pH value was 3.86, with slight fluctuations, demonstrating the influence of zinc on acidity levels.

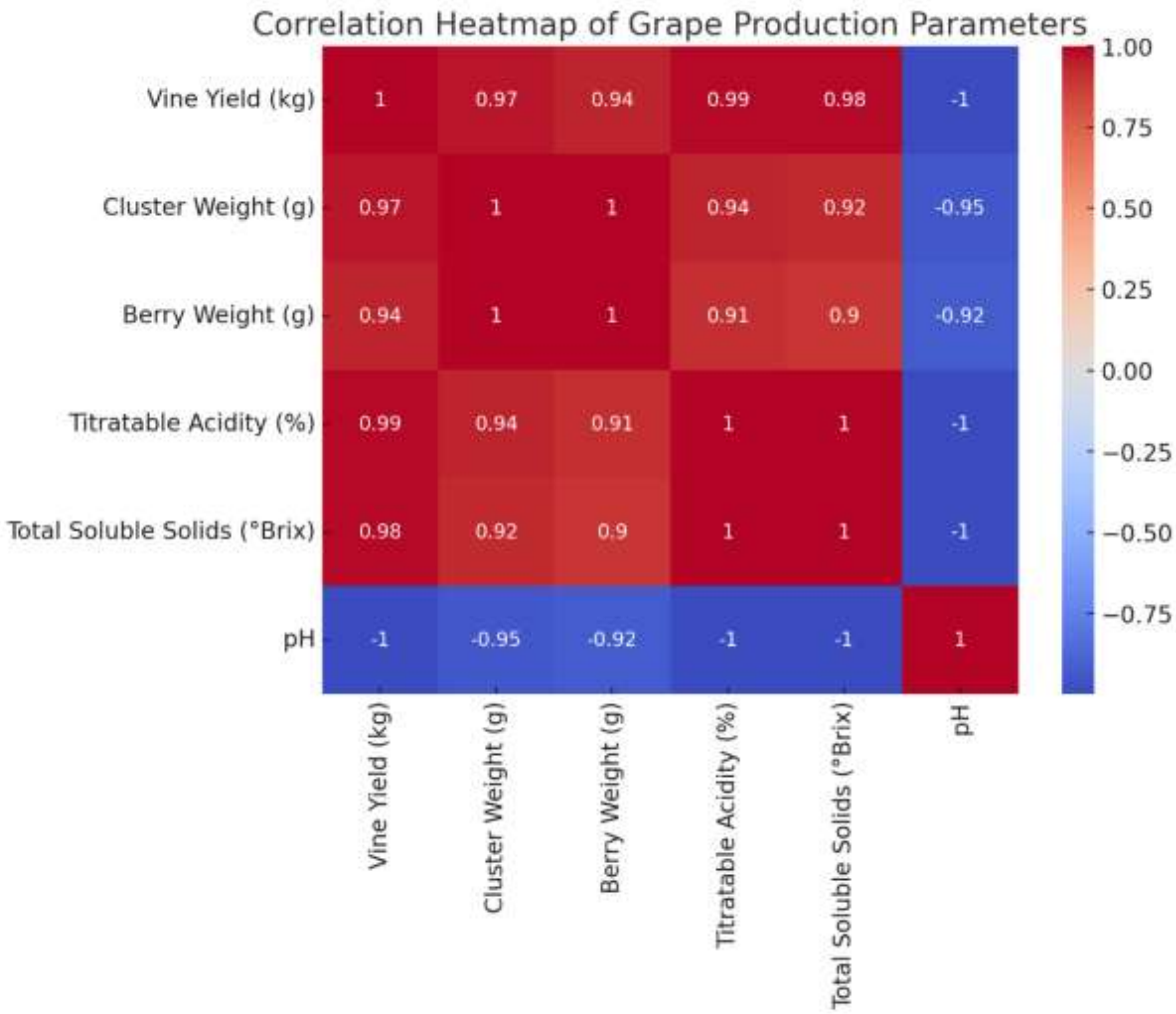

Fig 2. Correlation Heatmap for different Traits

3.1.2 Correlation Heatmap Analysis

The correlation matrix reveals strong relationships between the variables, (Fig 2)

- **Positive Correlations**: There are strong positive correlations among vine yield, cluster weight, berry weight, titratable acidity, and total soluble solids. This indicates that as zinc levels increase, not only does the yield improve, but also the quality parameters such as acidity and sugar content. For example, vine yield and cluster weight have a correlation coefficient of 0.97, suggesting that as vine yield increases, cluster weight also increases significantly.
- **Negative Correlation with pH**: There is a strong negative correlation between most growth and quality parameters with pH, especially between pH and titratable acidity (-0.999), total soluble solids (-0.997), and vine yield (-0.995). This indicates that higher zinc levels, which improve yield and quality, also tend to lower the pH, enhancing the fruit's taste and storage properties.

The analysis highlights that zinc application not only positively impacts the quantitative aspects of grape production (such as yield and fruit size) but also improves qualitative attributes (like acidity and sugar content), which are crucial for the marketability and palatability of grapes. The strong negative correlation with pH suggests that zinc might also play a role in enhancing the overall flavour profile of the grapes by reducing the pH, which is beneficial for certain types of wines and fresh consumption.

3.2. Pair Plot analysis:

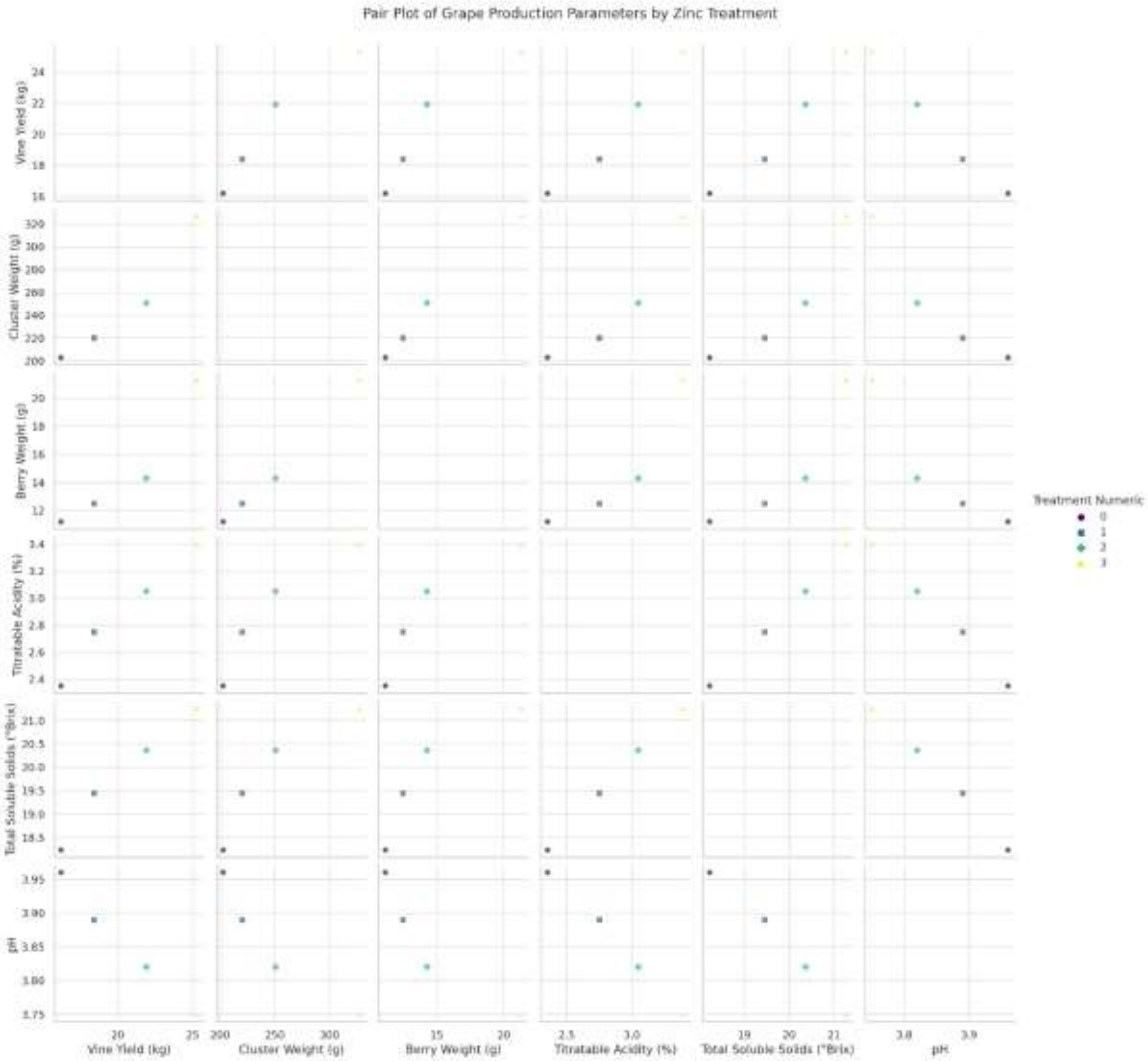

Fig 3. Pair Plot Analysis of Grape Production Parameters by Zinc Treatment

The pair plot provides a comprehensive visual exploration of the relationships between various parameters under different zinc treatment levels, highlighted by varying colors that represent the different zinc treatments (Fig 3)

3.2.1 Diagonal Plots: These plots show the distribution of each variable across the zinc treatments. The increasing trend in variables like vine yield, cluster weight, and berry weight as zinc levels increase is evident from the shift in the distribution towards higher values. Similarly, increases in titratable acidity and total soluble solids are visible, while pH shows a clear shift towards lower values with higher zinc treatments.

3.2.2 Off-Diagonal Scatter Plots: These illustrate the pairwise relationships between variables. The plots display distinct patterns: Positive trends are visible between parameters such as vine yield and cluster weight, berry weight, and total soluble solids. This suggests that as the physical size and weight of the grapes increase, so does their quality in terms of sugar and acid content. The scatter plots between pH and other variables like titratable acidity and total soluble solids show a clear negative trend, aligning with the earlier correlation analysis. Lower pH levels, which correlate with higher zinc doses, are associated with higher quality grape characteristics.

3.2.3 Colour Coding (Zinc Treatment Levels): Different colours for each zinc treatment make it easy to see how increasing zinc levels (from control to high) correlate with improvements in each parameter. The higher the zinc dose (represented by darker shades), the more pronounced the positive effects on grape yield and quality.

3.2.4 Enhanced Growth Parameters

Increased Vine Yield: A clear upward trend in vine yield is observed with increasing zinc levels. The distributions within the pair plot show that the highest zinc treatment (40g) significantly enhances vine yield compared to the control. This indicates that zinc plays a crucial role in supporting more abundant grape production. Greater Cluster and Berry Weights: Similar to vine yield, cluster weight and berry weight both increase with higher zinc supplementation. These trends suggest that zinc not only contributes to overall vine productivity but also enhances the individual fruit development, leading to heavier and potentially more valuable grape clusters.

3.3 Improved Grape Quality

3.3.1 Titratable Acidity and Total Soluble Solids: Both titratable acidity and total soluble solids, which are key quality indicators for grapes, show increased levels as zinc dosage increases. Higher acidity and sugar content, as observed in the higher zinc treatments, are desirable traits for both table grapes and wine production, indicating better taste profiles and higher commercial value. Lower pH Levels: The pair plot reveals a negative correlation between pH and zinc levels, with lower pH associated with higher zinc dosages. Lower pH in grapes can improve the sensory properties of the resulting wine and increase the shelf life of fresh grapes.

This pair plot effectively demonstrates the multifaceted impact of zinc on grape production: Enhanced Yield and Quality: Higher zinc levels are correlated with better outcomes across almost all measured parameters, emphasizing the nutrient's role in enhancing both yield and grape quality under water stress conditions. Agricultural Implications: The strong relationship between improved grape characteristics and higher zinc levels suggests that zinc supplementation could be a critical component of vineyard management strategies, especially in regions prone to water scarcity. The results from the detailed visual and statistical analyses of the grape production data under different zinc treatments reveal several key insights:

Enhanced Grape Yield: The increase in vine yield with higher zinc treatments is consistent and significant. This suggests that zinc plays a critical role in supporting grapevine growth, particularly under water-scarce conditions where nutrient efficiency is crucial. Both cluster weight and berry weight increased with higher levels of zinc, indicating not only more grapes but larger and potentially more marketable ones. This is particularly important for commercial grape production where fruit size can directly influence market value. Increased titratable acidity and total soluble solids with higher zinc dosages indicate an improvement in the grapes' chemical composition, which is beneficial for both fresh consumption and processing (e.g., wine making). Higher acidity and sugar content are desirable traits that improve the taste and shelf-life of grapes, as well as the quality of wine. The decrease in pH with higher zinc levels suggests that zinc supplementation might help in maintaining the acidity necessary for preventing microbial deterioration and enhancing flavor profiles, especially important in wine grapes.

4. Discussion

Analysis of variance showed significance results, confirming that the observed differences in grape production metrics are directly attributable to zinc treatment levels. The stringent significance level ($p < 0.01$) used in the analysis adds to the reliability of these findings, suggesting that the improvements are not due to random variation but are a direct effect of zinc application These results align with those reported by [40]. This alignment suggests that the application of these treatments may consistently influence the nutritional content of grapes, presenting an important avenue for further exploration in agronomic practices and nutrient management. The bar graphs and pair plots provided a clear visual representation of the data, making the positive impacts of zinc on grape production readily apparent. These visual tools are not only crucial for understanding complex datasets but also for communicating scientific findings in a more accessible manner.

The comprehensive analysis of the impact of zinc application on grape production in the water-scarce conditions of Zhob district provides several key insights. The results clearly demonstrate that zinc plays a vital role in enhancing both the yield and quality of grapes, supported by robust statistical evidence and visual data representations.

Zinc deficiency at the onset of berry development may negatively impact metabolic processes in the reproductive organs, leading to "millerandage," a condition characterized by poor berry set observed in both studied cultivars. This phenomenon aligns with findings from other fruit species where zinc application was shown to enhance fruit set significantly, as demonstrated in sweet cherries [41] and walnuts [42]. The observed improvements in cluster mass in our study can be attributed to the favorable effects of zinc treatment on berry set and subsequent development, suggesting that zinc plays a crucial role in the reproductive health of fruit-bearing plants.

The progressive increase in vine yield across increasing zinc levels, as illustrated in the bar graphs, underscores zinc's effectiveness in boosting grape production. The highest zinc treatment (40g per vine) significantly outperformed the control group, with vine yields increasing by over 55%. This substantial enhancement in yield is critical for the economic viability of grape farming in arid regions. role in improving grape quality was evident across multiple parameters. Cluster and berry weights increased with higher zinc dosages, indicating not only larger but potentially more nutrient-dense fruits. This is crucial for marketability, especially in competitive agricultural markets. The correlation and pair plot analyses further reinforced these findings, showing strong positive relationships between zinc levels and key quality metrics like titratable acidity and total soluble solids. The pair plot and correlation heatmap highlighted a significant negative correlation between pH levels and zinc supplementation. Lower pH levels in grapes, associated with higher zinc treatments, are beneficial for enhancing the taste and extending the shelf life of grapes, which is advantageous for both fresh consumption and wine production.

The correlation analysis highlighted strong positive relationships between zinc supplementation and key growth parameters (vine yield, cluster weight, and berry weight), as well as quality parameters (titratable acidity and total soluble solids). This suggests that zinc's role is multifaceted, impacting various aspects of plant physiology that contribute to both yield and quality. While prior research has predominantly focused on the impact of zinc fertilization on the growth and yield of grapevines, zinc's critical role extends beyond these aspects. [43] noted that zinc is essential for both primary and secondary metabolisms, which are directly connected to yield and quality attributes in plants. This underscores the importance of zinc not only as a contributor to plant size and fruit quantity but also as a vital element influencing the overall quality and metabolic efficiency of grapevines.

The significant negative correlation between pH and zinc indicates that higher zinc levels can effectively lower grape pH, aligning with improved quality parameters. This can be crucial for enhancing the organoleptic (sensory) properties of grapes. The findings strongly suggest that zinc supplementation could be an effective agronomic strategy to combat water scarcity impacts in grape production. By improving both yield and quality, zinc not only helps in sustaining grape production in arid conditions but also enhances the economic viability of grape farming by producing higher-quality fruits that are better suited for both the fresh fruit market and for wine production. [44] found that the pH of surface soils exhibited a significant negative correlation with nitrogen ($r = -0.722$) and phosphorus ($r = -0.590$), and an insignificant negative correlation with other nutrients including potassium, sulfur, iron, manganese, zinc, copper, and boron. Conversely, the pH of surface soil layers showed a significant positive correlation with available calcium ($r = 0.571$) and a non-significant positive correlation with magnesium and molybdenum. Additionally, subsurface soil pH demonstrated a significant negative correlation with nitrogen ($r = -0.521$) and iron ($r = -0.553$), but it showed no significant correlation with other nutrients. These findings suggest that an increase in soil pH can lead to a decrease in available nitrogen, potentially due to nitrogen volatilization as soil pH rises. This complex interaction between soil pH and nutrient availability highlights the need for careful management of soil pH to optimize nutrient uptake and overall soil fertility.

Given these results, it is recommended that grape growers, especially those in water-scarce regions, consider integrating zinc into their nutrient management plans. The specific dosages and timing of zinc application should be tailored based on local soil conditions and grape varieties to maximize benefits. Overall, the research indicates that zinc is a valuable nutrient that supports robust grapevine development and fruit quality, offering a sustainable solution to enhance agricultural productivity under challenging environmental conditions.

4.1 Broader Implications and Future Research

These results have significant implications for sustainable agriculture in arid and semi-arid regions. The ability of zinc to mitigate water stress could be integrated into broader nutrient management and agricultural planning strategies to enhance resilience to climate variability. However, further research is needed to determine optimal zinc application rates and methods that can be generalized across different grape varieties and regional conditions. Long-term studies would also be beneficial to assess the cumulative effects of zinc on soil health and vine longevity.

5. Conclusions

The study conducted at the Directorate of Agriculture Research Zhob has demonstrated significant benefits of zinc application in grape production under conditions of water scarcity. The key findings from this research include:

Application of zinc at varying levels resulted in a notable increase in vine yield, with the highest zinc treatment (40g per vine) showing the greatest improvement. This confirms that zinc plays a critical role in enhancing grapevine productivity even under limited water availability. The study found that zinc not only increases yield but also significantly improves fruit quality. Parameters such as cluster weight, berry weight, titratable acidity, and total soluble solids were all positively affected by zinc supplementation, with higher zinc levels correlating with better quality outcomes. Zinc application was associated with a decrease in pH levels across treatments, with the lowest pH observed in the highest zinc treatment. Lower pH in grapes can improve the sensory properties of wine and extend the shelf life of fresh grapes, which is a desirable trait in commercial grape production. The statistical analysis, including ANOVA and correlation studies, confirmed the significant impact of zinc on both the quantitative and qualitative aspects of grape production, ensuring that the results are both statistically robust and practically relevant.

5.1 Implications for Grape Production in Water-Scarce Areas

The implications of these findings are particularly relevant for regions like the Zhob district of Balochistan, where water scarcity poses a major challenge to agriculture. Integrating zinc into grape production practices offers a viable strategy to enhance yield and improve fruit quality despite environmental constraints. This approach not only boosts agricultural productivity but also supports economic stability and sustainability in rural communities heavily dependent on agriculture.

Based on the findings of this study, the following recommendations are made to grape growers, agricultural policymakers, and research institutions. Grape growers in water-scarce areas should consider incorporating zinc supplementation into their regular vineyard management practices to enhance yield and improve fruit quality. Agricultural extension services and policymakers should support the dissemination of findings related to micronutrient supplementation, providing guidelines and financial assistance to farmers to adopt these practices. Additional research is recommended to optimize zinc application rates and explore its long-term effects on soil health and vine longevity. Studies should also consider the interaction of zinc with other micronutrients and explore the efficacy of zinc application across different grape varieties and more diverse climatic conditions. Training programs should be developed to educate farmers on the benefits of micronutrient supplementation and the practical aspects of implementing zinc treatments effectively in their vineyard operations.

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