Integrated Nutrient Management and Salicylic acid Improves Grain Yield of Quinoa (*Chenopodium quinoa* Willd.) Subjected to Moisture Deficit Stress

ABSTRACT

Aims: A field study was conducted to quantify the effect of moisture deficit stress at different critical stages of quinoa and different mitigation approaches were adopted in order to alleviate moisture deficit stress.

Study design: The experiment was designed in split plot design comprising of six main plots (water management) and four sub plots (stress mitigation approaches). The treatments in main plots viz., no irrigation at branching (M_1), at ear formation (M_2), flowering (M_3), grain filling (M_4) stages, irrigating at all four stages (M_5) and irrigating as and when required (M_6), and sub plot treatments viz., soil test-based fertilizer recommendation (STBFR) (S_1), STBFR + Salicylic acid spray at 100 ppm (S_2), STBFR + rice straw mulching (S_3) and integrated nutrient management (S_4) were tested.

Place and Duration of Study: The experiment was conducted at the Instructional Farm, Odisha University of Agriculture and Technology, Bhubaneswar during *Rabi* 2021-22.

Methodology: Moisture deficit stress was imposed by withholding irrigation water and not irrigating in the defined period. The treatments in the subplots were imposed as per the schedule.

Results: Optimal results, including significantly taller plants, elevated relative water content, and increased grain yield, were achieved when irrigation was applied on an as-needed basis (M_6). Conversely, the lowest grain yield was observed when moisture deficit stress was imposed during the branching stage of quinoa. This outcome was primarily linked to a more substantial reduction in both relative water content and plant height. Among the various stress mitigation approaches, integrated nutrient management (S_4) emerged as the most effective management practice, followed closely by STBFR + Salicylic acid spray at 100 ppm (S_2).

Conclusion: The result indicated that branching stage is the most critical stage for irrigation in quinoa and integrated nutrient management could be the best approach under moisture deficit stress in quinoa among the other treatments.

Keywords: Quinoa, moisture deficit stress, salicylic acid, integrated nutrient management

1. INTRODUCTION

Quinoa (Chenopodium quinoa Willd.) stands out as a highly nutritious Andean seed crop with remarkable adaptability to diverse and challenging environments. Its nutritional richness, characterized by a well-balanced profile of all nine essential amino acids, has propelled its popularity, particularly in India where it covers 440 hectares with an average yield of 1053 tonnes [1]. However, the growing impact of climate change, marked by unpredictable weather patterns, temperature extremes, and prolonged droughts, poses a significant threat to quinoa cultivation. The variability in weather patterns, a consequence of climate change, can disrupt the delicate balance crucial for optimal crop growth. This imbalance often translates into moisture stress during critical stages of crop development, such as flowering and grain filling. For quinoa, losses due to moisture stress, especially from drought, can be staggering, accounting for 78.2% of yield reduction [2]. Addressing this challenge requires a multifaceted approach to enhance the crop's resilience.

In response to moisture stress, various strategies have been developed. Salicylic acid, a naturally occurring plant hormone, has emerged as a promising tool for enhancing crop tolerance to drought by activating stress-responsive mechanisms. Simultaneously, mulching practices prove effective in minimizing water evaporation from the soil, thereby maintaining consistent moisture levels. Complementing these measures, integrated nutrient management (INM) techniques, involving precise nutrient application at different growth stages, contribute to the crop's ability to withstand moisture stress and thrive. In a concerted effort to combat drought stress and fortify crop resilience, the combined application of Salicylic acid [3], adoption of mulching practices, and the implementation of a tailored integrated nutrient management (INM) strategy presents a holistic approach. This comprehensive strategy not only safeguards quinoa yields but also fosters sustainable agricultural practices in the face of the uncertainties posed by climate change. As we navigate an era marked by environmental challenges, this integrated approach ensures food security and promotes the long-term sustainability of quinoa cultivation.

2. MATERIAL AND METHODS

A field experiment was conducted at the Instructional Farm, Odisha University of Agriculture and Technology (OUAT), Bhubaneswar during the *Rabi* season of 2021-2022 to investigate the impact of moisture deficit stress on quinoa. The experiment utilized a split-plot design with six main plots and four subplots, resulting in 24 treatment combinations distributed across three replications. The main plots were assigned as follows: no irrigation at the branching stage (M_1), no irrigation at ear formation (M_2), no irrigation at the flowering stage (M_3), no irrigation during both branching and ear formation (M_4), irrigation at all four stages (M_5), and irrigation as needed (M_6). The subplots encompassed STBFR (S_1), STBFR with Salicylic acid @ 100 ppm (S_2), STBFR with Rice straw mulching @ 5 tonnes ha^{-1} (S_3), and INM (75% N inorganic + 25% N FYM) (S_4).

The experimental site's soil characteristics revealed low organic carbon content (4.9 kg ha^{-1}), low nitrogen levels (248 kg ha^{-1}), medium availability of phosphorus (41.2 kg ha^{-1}), and medium levels of available potassium (263 kg ha^{-1}). The recommended dose of fertilizers (60:30:30 kg of N: P_2O_5: K_2O) was applied to the crop. Moisture deficit stress was induced in the designated treatments (M_1, M_2, M_3, and M_4) by withholding irrigation at the respective stages, followed by subsequent irrigation to alleviate stress. In contrast, scheduled irrigation was provided for M_5 and M_6. The subplot treatments were implemented according to the prescribed schedule.

Measurements of plant height and relative water content were documented at various intervals: 20, 35, 50, and 65 days after sowing (DAS), in addition to the final harvest stage. Plant height in centimetres was determined by measuring from the base to the tip of the upper leaf. Relative water content, expressed as a percentage, was calculated using the formula specified by [4]. The grain yield, measured in kilograms per hectare (kg ha^{-1}), was assessed post-harvest. Subsequently, the collected data underwent statistical analysis using the standard analysis of variance technique for a randomized complete block design, following the recommended approach by [5].

3. RESULT AND DISCUSSION

Table 1 presents the recorded plant heights at various observation points. Notably, there was a substantial difference in plant height across different observation days, attributed to both moisture deficit stress and diverse mitigation strategies. The highest plant height at harvest (120.5 cm) was significantly observed in M_6, indicating its effectiveness among the various water management practices. Conversely, the lowest plant height (67 cm) was noted when irrigation was withheld at the branching stage, a result statistically on par with M_2 (no irrigation at ear formation stage), which averaged at 69.5 cm. Additionally, plants subjected to integrated nutrient management (INM) practices (S_4) exhibited significantly greater height (99.2 cm), comparable to S_2 (STFBR + Salicylic acid spray) with an average height of 95.5 cm. In contrast, the shortest plant height (87.5 cm) was recorded in S_1 (STBFR), standing out as the lowest among all stress mitigation approaches.

Table 1. Effect of different water management and stress mitigation approaches on the plant height (cm) of quinoa

Water management	20 DAS	35 DAS	50 DAS	65 DAS	At harvest
M_1: No irrigation at branching	17.2	34.9	47.2	59.5	67.0
M_2: No irrigation at ear formation	16.7	35.7	49.2	62.3	69.5
M_3: No irrigation at flowering	17.8	41.6	60.5	74.6	83.9
M_4: No irrigation at grain filling	18.4	43.6	78.5	85.9	99.8
M_5: Irrigation at all above four stages	18.3	43.0	81.0	105.0	116.3
M_6: Irrigation as and when required	18.7	44.5	80.5	105.3	120.5
SEm(±)	0.62	1.46	2.57	3.29	1.25
CD (5%)	2.0	4.6	8.1	10.4	3.9
Stress mitigation approaches					
S_1: STBFR	17.3	37.1	60.2	77.9	87.5
S_2: STBFR + Salicylic acid	17.0	40.3	68.1	84.6	95.5

S_3: STBFR + Rice straw mulching	17.5	40.0	64.0	78.0	89.1
S_4: INM (75% Inorganic + 25% organic)	19.6	44.9	72.4	87.8	99.2
SEm(±)	0.45	0.80	1.34	1.51	1.78
CD (5%)	1.3	2.3	3.8	4.3	5.1

There were significant variations in plant height among different water management and stress mitigation approaches. Notably, treatment M_6 yielded the tallest plants at harvest, attributed to a continuous and timely water supply. Conversely, plants experiencing water stress (M_1 to M_4) exhibited relatively shorter stature compared to M_6. A substantial reduction in height, measuring 44.3% and 42.3%, was observed in M_1 and M_2, representing moisture deficit stress during the branching and ear formation stages, respectively. This reduction primarily stemmed from the imposition of moisture deficit stress at the early stage of the crop, hindering optimal plant height development. Additionally, the stress-induced reduction in relative water content contributed to these observed height differences. The increased height of plants under M_5 and M_6 was attributed to the continuous and ample moisture supply. These findings align with results reported by another researcher [6].

Diverse stress mitigation approaches exerted an influence on the final plant height. Noticeably, plants subjected to integrated nutrient management (INM) and soil test-based fertilizer recommendation (STBFR) combined with the application of Salicylic acid exhibited significantly taller stature. The increase in plant height was 13.3% and 9.1% in S_4 and S_2, respectively, over S_1 (STBFR). This elevation in plant height could be attributed to the synergistic effects of integrated nutrient management and the application of Salicylic acid in conjunction with STBFR. In the case of INM, the incorporation of farmyard manure (FYM) alongside inorganic fertilizers likely played a role in promoting superior crop growth by enhancing soil physical and chemical characteristics. Similarly, the application of Salicylic acid contributed to increased plant height, acting as a growth regulator, both under controlled irrigation and moisture deficit stress conditions. These findings align with results reported by another researcher [6].

The recorded relative water content (RWC) on various observation days (Table 2) exhibited significant differences attributed to distinct water management practices and stress mitigation approaches. At 20 days after sowing (DAS), the RWC of plants showed no significant variation due to different water management practices. However, by 35 DAS, M_1 (no irrigation at the branching stage) displayed a significantly lower RWC (63.8%), statistically comparable to M_2 (no irrigation at ear formation) with an average RWC of 64.3%. At 50 DAS, a notably lower RWC (66.6%) was recorded in M_3 (no irrigation at the flowering stage), but it was statistically similar to M_1 and M_2. By 65 DAS, the lowest RWC value (71.6%) was observed in M_4 (no irrigation at the grain-filling stage). At harvest, a similar trend persisted, with M_2 recording a significantly higher RWC value (60.5%). Among the different stress mitigation approaches, the INM treatment consistently recorded higher relative water contents on all observation days except 20 and 35 DAS, where STFBR + Salicylic acid spray showed higher RWC values. Conversely, treatment S_1 (STBFR) consistently recorded significantly lower RWC values on all observation days.

Table 2. Effect of different water management and stress mitigation approaches on the relative water content (%) of quinoa

Water management	20 DAS	35 DAS	50 DAS	65 DAS	At harvest
M_1: No irrigation at branching	91.5	63.8	67.1	71.6	58.5
M_2: No irrigation at ear formation	91.9	64.3	67.7	72.0	60.5
M_3: No irrigation at flowering	93.2	94.4	66.6	71.8	55.8
M_4: No irrigation at grain filling	90.5	92.8	92.0	71.6	54.8
M_5: Irrigation at all above four stages	90.7	93.2	92.6	82.5	56.2
M_6: Irrigation as and when required	91.3	93.3	90.3	82.4	57.2
SEm(±)	1.60	1.74	1.20	1.12	0.84
CD (5%)	NS	5.5	3.8	3.5	2.7
Stress mitigation approaches					
S_1: STBFR	90.0	80.6	75.2	69.3	54.0
S_2: STBFR + Salicylic acid	91.8	85.9	82.1	79.6	58.3
S_3: STBFR + Rice straw mulching	91.5	83.3	77.9	72.0	55.6
S_4: INM (75%N inorganic + 25%N FYM)	92.7	84.7	82.4	80.4	60.8
SEm(±)	1.01	1.22	0.89	1.48	1.12

CD (5%)	0.03	3.5	2.5	4.2	3.2

The supply of irrigation water significantly influenced the relative water content (RWC) of quinoa leaves across different treatments. Notably, moisture deficit stress at various stages of crop growth led to the loss of turgidity in plant leaves, resulting in a decrease in RWC. The most substantial reduction in RWC occurred when stress was applied during the branching and ear formation stages, as opposed to the flowering and grain-filling stages. This heightened sensitivity of the crop during these early stages was reflected in the notable decrease in RWC of quinoa leaves. The vulnerability of early crop stages to moisture deficit stress is a well-documented phenomenon supported by various researchers [7, 8].

Among the diverse stress mitigation approaches, integrated nutrient management (INM) exhibited elevated relative water content (RWC) values compared to other treatments. The incorporation of both organic (FYM) and inorganic nutrient sources likely contributed to reducing the crop's susceptibility to stress, enhancing its tolerance to a decrease in relative water content. This effect was particularly notable in INM, distinguishing it from other treatments, except for S_2, where Salicylic acid was applied along with Soil Test-Based Fertilizer Recommendation (STBFR) during the crop period. The application of Salicylic acid demonstrated a positive impact on crop RWC under water deficit stress, actively maintaining cellular turgidity by ensuring osmotic balance in plant cells during drought stress. These findings align with similar results reported by various researchers [3, 9,10].

There were significant variations in grain yield across different water management and stress mitigation approaches, as depicted in Figure 1. The treatment involving no irrigation at the branching stage (M_1) yielded the lowest grain output at 589 kg ha^{-1}. In contrast, treatment M_6, characterized by a continuous and timely water supply, achieved a substantially higher grain yield, recording 2631 kg ha^{-1}, surpassing the other water management practices.

When considering various stress mitigation strategies, S_4 (INM) emerged as the most effective, producing a statistically higher grain yield of 1663 kg ha^{-1}. Following closely was S_2 (STFBR + Salicylic acid spray), which also demonstrated a notable improvement in grain yield.

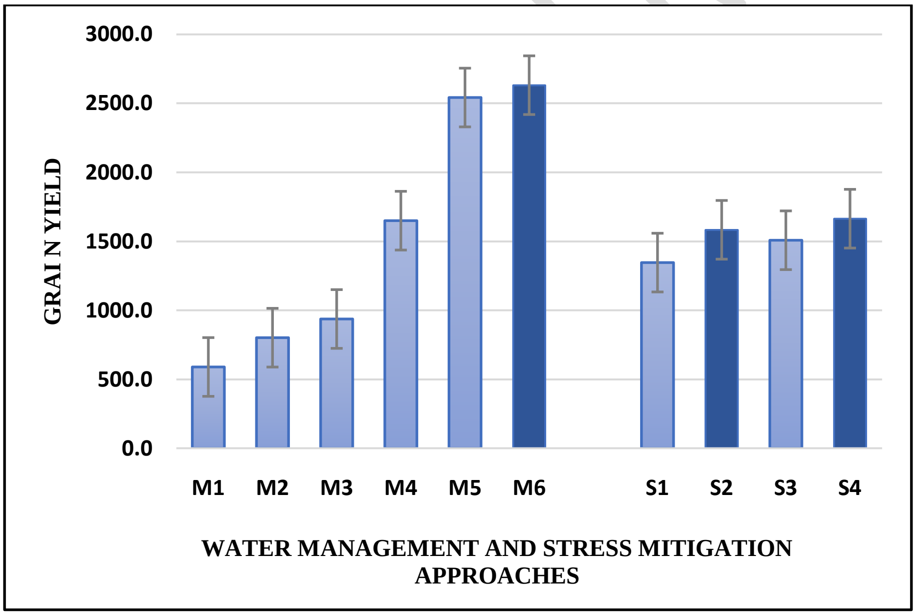

Figure 1. Effect of different water management and stress mitigation approaches on the grain yield (kg ha^{-1}) of quinoa

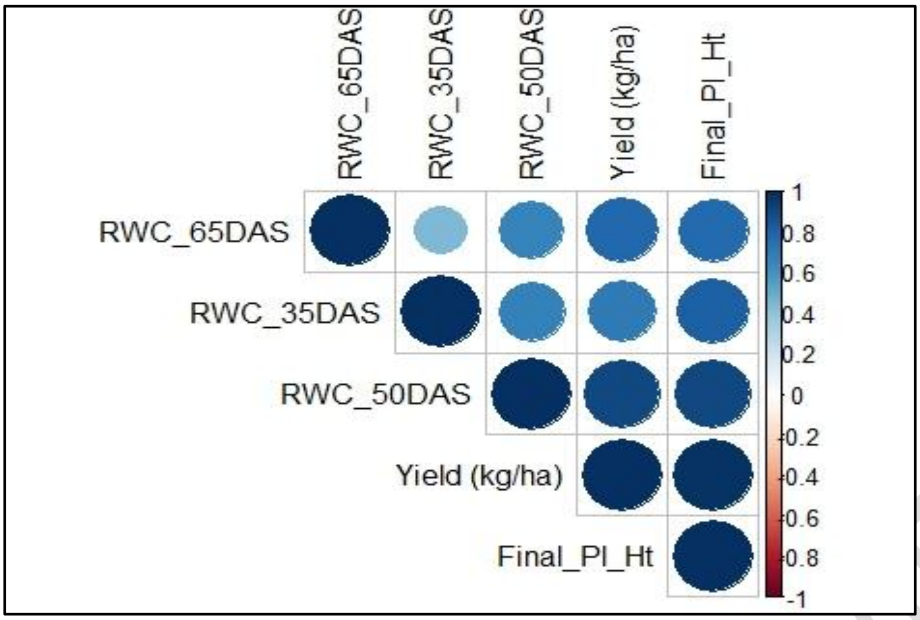

Figure 2. Correlation heat matrix of different traits

Grain yield is intricately linked to growth attributes such as plant height and cellular water content. The imposition of drought stress at various growth stages, including branching, ear formation, flowering, and grain filling stages, resulted in substantial decreases in grain yield (77.6%, 69.5%, 64.3%, and 37.3%, respectively). This decline in grain yield could be attributed to both diminished plant height and reduced cellular turgidity. The early stages of the crop were identified as more vulnerable to drought stress, as the absence of irrigation during this critical phase may have hindered sink formation capacity, ultimately leading to a lower grain yield [11,12]. A positive correlation was observed between grain yield and plant height as well as relative water content at different stages of crop development (see Figure 2). On the other hand, adopting integrated nutrient management (INM) (S_4) and STBFR + Salicylic acid (S_2) during drought stress and irrigated control demonstrated an increment in grain yield by 23.6% and 17.6%, respectively, compared to the fully inorganic nutrient management (S_1). The positive impact of Salicylic acid and INM on crop yield aligns with findings reported by other researchers [13,14].

4. CONCLUSION

Based on the conducted experiment, it is evident that moisture deficit stress has deleterious effects on plant height, relative water content, and grain yield at different growth stages in quinoa, with a more significant impact during the branching and ear formation stages compared to other phases. Among the diverse stress mitigation strategies employed, the combination of integrated nutrient management and the application of Salicylic acid, guided by soil test-based fertilizer recommendations, proved more effective in enhancing yield-influencing parameters compared to the other two treatments. In summary, adopting integrated nutrient management and Salicylic acid application based on soil test recommendations appears to be a more promising approach for mitigating the adverse effects of moisture deficit stress on various aspects of quinoa growth and yield.

REFERENCES

1. Srinivasa Rao K. Sarikotha panta quinoa, Sakhi News, 10 on 11.08.2015.
2. Telahigue DC, Yahia LB, Aljane F, Belhouchett K, Toumi L. Grain yield, biomass productivity and water use efficiency in quinoa (*Chenopodium quinoa* Willd.) under drought stress. J of Scientific Agric. 2017;1:222-32.
3. Najafabadi MY, Ehsanzadeh P. Salicylic acid effects on osmoregulation and seed yield in drought-stressed sesame. Agron. J. 2017;109(4): 1414-22. https://doi.org/10.2134/agronj2016.11.0655
4. Gomez KA and Gomez AA. Statistical procedures for agricultural research Vol. 2nd Ed. New Delhi, India: Wiley India Pvt Ltd. 2010.

5. Saddiq MS, Wang X, Iqbal S, Hafeez MB, Khan S, Raza A, Iqbal J, Maqbool MM, Fiaz S, Qazi MA, Bakhsh A. Effect of water stress on grain yield and physiological characters of quinoa genotypes. Agron. 2021;11(10):1934. https://doi.org/10.3390/agronomy11101934
6. Sun Y, Liu F, Bendevis M, Shabala S, Jacobsen SE. Sensitivity of two quinoa (*Chenopodium quinoa* Willd.) varieties to progressive drought stress. J. Agron. Crop Sci. 2014;200(1):12-23. https://doi.org/10.1111/jac.12042
7. Patnaik GP, Monisha V, Thavaprakaash N, Djanaguiraman M, Sachin S, Vikram K, Girwani T, Jeeva M, Monicaa M, Patnaik L, Behera B. Selenium Application Improves Drought Tolerance during Reproductive Phase of Rice. Sustainability. 2023; 15(3):2730. https://doi.org/10.3390/su15032730
8. Singh B, Usha K. Salicylic acid induced physiological and biochemical changes in wheat seedlings under water stress. Plant Growth Regul. 2003;39:137-41. https://doi.org/10.1023/A:1022556103536
9. Bandurska H, Stroi ski A. The effect of salicylic acid on barley response to water deficit. Acta Physiologiae Plantarum. 2005;27:379-86. https://doi.org/10.1007/s11738-005-0015-5
10. Salama AM, Seleem E, Abd El Salam R, Ghoniem A. Response of quinoa plant grown under drought stress to foliar application with salicylic acid, paclobutrazol and algae extract. J. Agric. Sci. 2021;3(2):87-104. https://doi.org/10.21608/sjas.2021.81529.1118
11. Patnaik GP, Thavaprakaash N, Djanaguiraman M. Effect of Period of Soil Moisture Stress at Panicle Initiation and Flowering Stages on Nutrient Uptake and Post-Harvest Soil Nutrient Status in Rice. Madras Agric. J. 2020 11;107(7-9):1-6. https://doi.org/10.29321/MAJ.2020.000377
12. Sachin S, Thavaprakaash N, Djanaguiraman M, Patnaik GP. Effect of induced moisture stress at critical stages on physiological traits and yield of rice (*Oryza sativa* L.). J. Agromet. 2023 25;25(2):268-73. https://doi.org/10.54386/jam.v25i2.2043
13. Patnaik, G.P., N. Thavaprakaash, M. Djanaguiraman. (2021). Effect of moisture stress at critical stages on growth and relative water content of rice (*Oryza sativa*). In Extended Summaries: 5th International Agronomy Congress, 2, 1037-1038.
14. Yang A, Akhtar SS, Amjad M, Iqbal S, Jacobsen SE. Growth and physiological responses of quinoa to drought and temperature stress. J. Agron. Crop Sci. 2016;202(6):445-53. https://doi.org/10.1111/jac.12167