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Research Article

Chia (*Salvia Hispanica L.*)- A Climate Resilient Oilseed for Sustainable Bioenergy & Agricultural System

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Abstract

Rising energy demand and increasing climate variability have intensified interest in multipurpose crops capable of supporting both nutritional and bioresource needs. The present investigation examines drought tolerance, yield stability, and biomass productivity of diverse chia (Salvia hispanica L.) genotypes under graded moisture regimes to evaluate their relevance for sustainable bioenergy pathways. Considerable variation among genotypes was observed in seed yield, harvest index, and physiological resilience under water-limited conditions, with selected lines maintaining comparatively stable productivity despite moisture stress. Yield performance showed close association with traits such as relative water content, chlorophyll stability, root development, and efficient assimilate partitioning, reflecting integrated adaptive responses that enable continued biomass and seed production. Because chia seeds possess substantial oil content and the residual biomass can be utilized for secondary energy conversion, stable productivity under drought enhances its suitability as a climate-resilient bioresource. The identification of tolerant, high-yielding genotypes therefore supports the possibility of integrating chia into sustainable farming and bioenergy-linked production systems, particularly in semi-arid regions. Overall, the study highlights the dual significance of chia as a nutritionally valuable oilseed and a potential contributor to renewable bioresource strategies aligned with climate-smart agriculture and long-term environmental sustainability.

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1. INTRODUCTION

Climate variability and recurrent drought conditions have emerged as major threats to global agricultural sustainability. The increasing demand for renewable bioresources and climate-resilient crops has intensified interest in alternative oilseed crops capable of maintaining productivity under limited water availability. Chia (*Salvia hispanica L.*), a member of the family Lamiaceae, is gaining global recognition as a nutritionally important "superfood" because of its high omega-3 fatty acid content, dietary fibre, proteins, antioxidants and bioactive compounds [1,6]. Besides its nutritional significance, chia possesses considerable potential for biomass generation and renewable bioenergy applications [1,11,12].

In India, chia cultivation has gradually expanded from southern regions to semi-arid zones due to its relatively short duration, lower input requirement and adaptability to moisture stress conditions. However, successful large-scale cultivation requires identification of drought-tolerant genotypes capable of maintaining physiological stability and reproductive efficiency under reduced irrigation [2,3,8]. Moisture stress negatively affects germination, chlorophyll content, relative water content, cell division, pollen fertility and ultimately seed yield [4,5,8]. Therefore, systematic evaluation of physiological, cytological and yield-related traits is necessary for identifying resilient genotypes suitable for sustainable agriculture.

The present investigation was therefore undertaken to evaluate five chia genotypes under graded moisture regimes in order to identify drought-resistant traits associated with yield stability, root plasticity and cellular tolerance under stress conditions.

2. METHODOLOGY

Five chia genotypes (G1, G2, G3, G4, G5) were selected for the present investigation. A pot culture study was conducted using a factorial arrangement in a Completely Randomized Design (CRD). The moisture treatments were maintained at 100, 75, 50, 25 and 0 percent field capacity, representing well-watered control, mild stress, moderate stress, severe stress and extreme stress conditions, respectively [2,3,10]. The experiment was carried out under controlled environmental conditions and each treatment was replicated adequately to ensure statistical reliability.

Physiological and cytological observations were recorded during vegetative and reproductive growth stages. Relative Water Content (RWC), SPAD chlorophyll readings, Mitotic Index (MI), root-shoot ratio and Seed Yield per Plant (SYP) were measured under each moisture treatment [4,5,8]. Cytological analysis was carried out using root tip squash techniques for evaluating mitotic activity and chromosomal abnormalities. Statistical analyses included Analysis of Variance (ANOVA) and correlation studies to determine the significance of genotypic variation and relationships among physiological and yield parameters.

3. OBJECTIVES

- To evaluate drought tolerance among five chia genotypes under different moisture regimes.
- To study the effect of moisture stress on physiological and cytological parameters.
- To assess the relationship among RWC, SPAD value, mitotic index and seed yield per plant.
- To identify drought-tolerant genotypes suitable for semi-arid agricultural systems and sustainable bioenergy production.

4. RESULTS AND DISCUSSION

A progressive reduction in physiological and reproductive performance was observed with increasing moisture stress. Relative Water Content and SPAD chlorophyll values declined substantially under severe drought conditions, indicating disruption of photosynthetic activity and cellular hydration [4,5]. Reduction in chlorophyll stability under low moisture conditions directly affected biomass accumulation and reproductive efficiency [4,8].

Mitotic index also decreased under increasing stress intensity, demonstrating suppression of cellular division in root meristematic tissues [8,10]. Simultaneously, chromosomal abnormalities increased considerably under severe and extreme moisture stress [8]. These observations confirm that moisture deficit exerts significant genotoxic and physiological effects on chia plants. Genotypic variability was clearly observed among the five genotypes. G3 exhibited superior adaptive responses under moderate and severe stress conditions due to improved root plasticity, better chlorophyll retention and greater cellular stability [2,3,8]. The genotype maintained comparatively stable yield performance despite declining soil moisture, indicating efficient assimilate partitioning and drought adaptation mechanisms.

Table 1. Mitotic Index, Chromosomal Aberrations and Seed Yield per Plant under Different Moisture Levels

Genotype	Moisture (%)	Mitotic Index	Chromosomal Aberrations	Yield/Plant (g)
G1	100	78.4	1	22.5
G1	75	75.9	2	20.8
G1	50	71.5	4	18.2
G1	25	65.2	6	15.0
G1	0	60.8	9	10.5
G2	100	80.1	1	23.2
G2	75	77.3	2	21.5
G2	50	74.0	3	19.6
G2	25	68.8	5	17.2
G2	0	62.5	7	12.8
G3	100	76.9	2	21.4
G3	75	72.5	4	19.1
G3	50	67.3	6	15.7

G3	25	60.2	9	11.5
G3	0	55.6	12	8.3
G4	100	82.0	0	24.0
G4	75	79.5	1	22.6
G4	50	77.0	2	20.9
G4	25	72.8	4	18.4
G4	0	68.5	5	14.7
G5	100	75.3	3	20.5
G5	75	70.8	5	17.9
G5	50	64.5	8	14.6
G5	25	58.2	11	9.8
G5	0	51.0	15	6.5

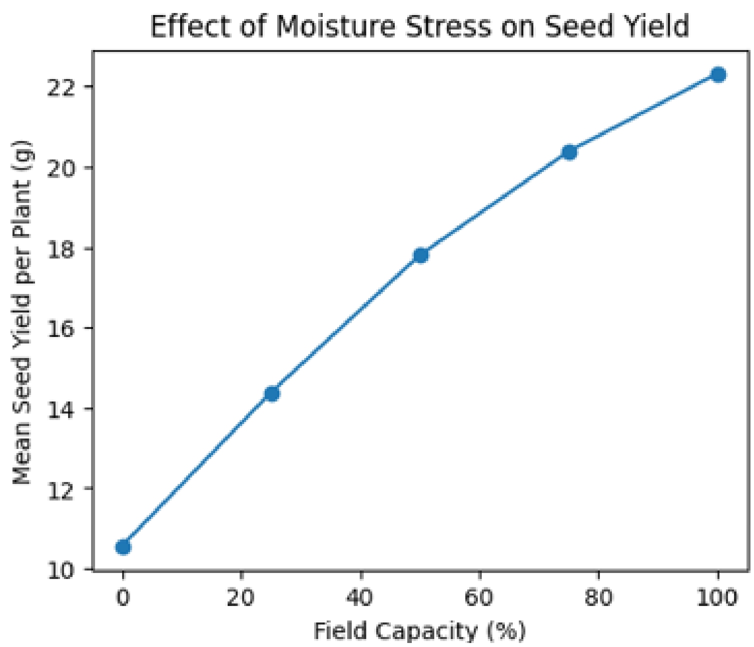

Figure 1. Effect of progressive moisture stress on mean seed yield per plant in chia genotypes

The results further suggest that chia can serve as a sustainable dual-purpose crop due to its combined nutritional and biomass potential [1,6,11,12]. Its adaptability under semi-arid conditions makes it suitable for future climate smart agricultural systems and renewable bioresource strategies [1,7,11].

Correlation Analysis of Physiological and Yield Traits

Correlation analysis revealed strong positive associations among Relative Water Content (RWC), SPAD chlorophyll values, Mitotic Index and Seed Yield per Plant. Higher RWC and chlorophyll stability under moisture stress were closely associated with improved mitotic activity and greater seed productivity. The positive relationship between Mitotic Index and Seed Yield indicates that maintenance of cellular division and chromosomal stability contributes significantly towards drought resilience and reproductive efficiency in chia genotypes. Similarly, genotypes exhibiting higher SPAD values maintained superior photosynthetic activity and assimilate partitioning under stress conditions. These findings collectively demonstrate that physiological and cytological stability are important determinants of drought tolerance and yield sustainability in chia under graded moisture stress environments [4,5,8].

Table 2. Pearson's correlation coefficients among physiological traits and seed yield in chia genotypes under moisture stress

Trait	Correlation with seed yield
Relative Water Content (RWC)	+0.86*
Chlorophyll Content (SPAD)	+0.79*
Root Length	+0.71*
Shoot Biomass	+0.82*
Harvest Index	+0.74*
Root: Shoot Ratio	+0.62*

The correlation analysis presented in Table 2 further confirmed that physiological stability under moisture stress plays a crucial role in sustaining reproductive performance in chia genotypes. Strong positive correlations were observed between the RWC

SPAD chlorophyll values, Mitotic Index and Seed Yield per Plant, suggesting coordinated physiological and cellular responses under drought conditions.

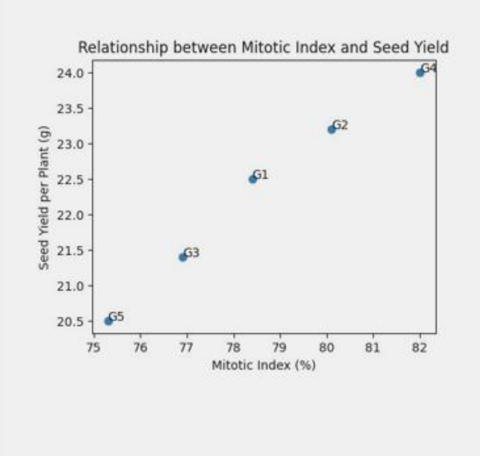

Figure 2. Positive relationship between Mitotic Index and Seed Yield per Plant among chia genotypes under moisture stress

Figure 3. Conceptual framework illustrating the bioenergy and sustainability loop of chia as a climate-resilient dual-purpose crop

The bioenergy and sustainability model presented in Figure 3 further supports the potential of chia as a suitable crop for climate-resilient agriculture and renewable energy applications. Chia seeds can serve as a source of oil for biodiesel production, while the remaining plant biomass and stalk residues may be utilized for lignocellulosic bioethanol and pellet formation. An important advantage observed during the study was the comparatively better performance of tolerant genotypes under limited moisture conditions, particularly G3, which maintained higher physiological stability and biomass production even under stress. The low water requirement and adaptability of chia under semi-arid conditions also indicate its possible role in sustainable farming systems and carbon-conscious agricultural practices. Therefore, the crop may be considered beneficial not only from a nutritional point of view but also for future bioresource and green energy programmes.

5. CONCLUSION

The present investigation demonstrated significant variation among chia genotypes under graded moisture stress conditions. Physiological traits such as Relative Water Content and SPAD chlorophyll values, along with cytological stability measured through Mitotic Index, were strongly associated with yield performance under drought stress. Among the evaluated genotypes, G3 emerged as the most promising candidate for semi-arid agricultural systems in India due to its superior drought adaptability and stable productivity under moisture deficit conditions.

Correlation analysis further demonstrated that maintenance of higher Relative Water Content, chlorophyll stability and mitotic activity significantly contributed towards improved seed yield under moisture stress conditions. The positive relationship among these traits highlights their usefulness as reliable physiological and cytological markers for screening drought-tolerant chia genotypes. The findings obtained from Table 2 and Figure 3 provide additional evidence that integrated physiological resilience and cellular stability are essential for sustaining productivity under limited water availability.

The study established that drought tolerance in chia is associated with high root plasticity, cellular stability and efficient physiological regulation. Chia therefore represents a viable dual-purpose crop with considerable potential for climate-resilient agriculture, sustainable biomass production and future green energy transition programs.

The study therefore supports the integration of chia into future climate smart and bioenergy-oriented agricultural programmes in water-limited regions.

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