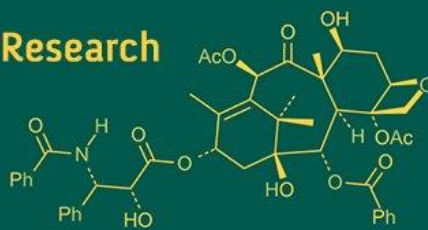


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Seed nano-priming with zinc oxide nanoparticles enhances drought tolerance and reveals SSR-based genetic diversity in basmati rice (*Oryza sativa* L.)

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Abstract

Drought stress severely limits rice productivity by impairing its growth, physiology, and yield. The present study evaluated the effectiveness of seed nano-priming with zinc oxide nanoparticles (ZnO-NPs) in mitigating drought stress in three Basmati rice genotypes, which are Pusa Basmati 1718 (PB-1718), Pusa Basmati 1728 (PB-1728), and Vallabh Basmati 24 (VB-24). Experiments were conducted under the field conditions using a randomized block design with three replications, where drought stress was imposed at the early post-transplanting stage through 5, 10, and 15 days of water withholding. Seed priming with 40 ppm ZnO-NPs significantly improved morphological traits, yield attributes and physio-biochemical parameters under drought stress. ZnO-NP treatment enhanced drought tolerance by maintaining their chlorophyll content, relative water content, and membrane stability, along with that it regulated their proline accumulation and regulated antioxidant enzyme activity. Among all three genotypes, PB-1718 exhibited the highest drought tolerance and yield stability under early-stage drought stress, whereas VB-24 showed comparatively higher sensitivity. Molecular characterization using ten simple sequence repeat (SSR) markers revealed the moderate genetic diversity, with six polymorphic markers effectively differentiating the genotypes. The study demonstrates that ZnO-NP seed priming, combined with genetically tolerant cultivars, offers a promising strategy for improving drought resilience in Basmati rice.

Keywords: Basmati rice, drought stress, ZnO nanoparticles, seed priming, SSR markers, genetic diversity

Introduction

Rice (*Oryza sativa* L.) is the world's most important food crop, serving as the primary staple for approximately 40% of the global population and providing 23% of total caloric intake [1]. Its historical significance spans millennia, with evidence of rice cultivation in India dating back to 1500-1000 B.C. [2]. Rice has played a vital role in sustaining populations in the humid regions of Asia and parts of Western Africa, and its consumption has steadily increased in Europe and North America due to its spread. Currently, more than 120 countries produce rice, with China (148 million metric tons) and India (122 million metric tons) as the leading producers [3]. While rice can be cultivated in diverse agro-climatic environments, from high-altitude regions like Jammu to low-lying delta regions such as Sundarbans, the majority of global production and consumption occurs in Asia. In Southeast Asia, rice accounts for 60% of total food consumption, while it contributes around 35% in East and South Asia. Bangladesh, Cambodia, Indonesia, Laos, Myanmar, Thailand, and Vietnam have the highest per capita rice consumption, ranging from 130 to 180 kg per year [4]. Over the past five decades, global rice production has tripled, rising from 216 to 685 million tonnes, while productivity has more than doubled, from 1.87 to 4.30 tonnes per hectare. China currently leads in global rice production, while India, with the largest rice acreage of 45 million hectares, provides about one-fourth of Asia's total rice production [5]. However, rice production is increasingly threatened by both biotic and abiotic stresses, notably drought. Drought is a major limiting factor in rice cultivation, affecting up to 50% of the global rice crop and resulting in significant economic losses [6]. As global climate change exacerbates water scarcity, it is critical to develop strategies to enhance rice's resilience to drought.

Drought stress affects rice growth, development, metabolism, and physiological states by limiting water content, turgor, and overall plant water balance. It also leads to reduced leaf area, altered nutrient distribution, and diminished gas exchange, impacting photosynthesis and overall plant health [7, 8]. Additionally, drought triggers the production of reactive oxygen species (ROS), which damage cell structures and metabolic processes [9]. In response, plants enhance their antioxidant enzyme activities, store osmolytes such as proline, and activate mechanisms to regulate stomatal closure and water use efficiency [10].

Nanotechnology has emerged as a promising solution to enhance agricultural sustainability and productivity. Seed priming with zinc oxide nanoparticles (ZnO-NPs) has shown significant potential to improve seed germination, seedling vigor, and overall plant resistance to drought stress [11]. Zinc plays a vital role in improving plant homeostasis, enhancing chlorophyll content, and regulating protein metabolism, thus supporting crops under water-deficit conditions [12, 13]. In rice, ZnO-NPs have shown promising results in alleviating drought-induced stress by improving seed germination and plant vigor.

Understanding genotype-specific responses to drought mitigation strategies is equally critical for effective crop improvement. Variability in drought tolerance among rice genotypes is governed not only by physiological adaptability but also by underlying genetic differences. Molecular characterization using Simple Sequence Repeat (SSR) markers has been widely employed to assess genetic diversity and establish genetic relationships among rice genotypes due to their high polymorphism, co-dominant inheritance, and reproducibility [14]. SSR-based analysis provides reliable insights into genetic distinctness and diversity, which are essential for identifying drought-tolerant genotypes and supporting breeding programs [15]. Integrating morpho-physiological, biochemical, and molecular analyses offers a comprehensive approach to understanding drought tolerance mechanisms in rice.

Therefore, the present study was undertaken to evaluate the effect of zinc oxide nanoparticle (ZnO-NP) seed priming on morpho-physiological and biochemical traits of selected Basmati rice genotypes under drought stress conditions. In addition, the study aimed to assess the genetic diversity and molecular differentiation among these Basmati rice genotypes using Simple Sequence Repeat (SSR) markers.

Materials and Methods

The present study was conducted at the Rainout Shelter and Genomics Laboratory, Department of Agricultural Biotechnology, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, India. Three Basmati rice (*Oryza sativa* L.) genotypes, namely Pusa Basmati 1718 (PB 1718), Pusa Basmati 1728 (PB 1728), and Vallabh Basmati 24 (VB 24), were used as experimental material. Seeds of all genotypes were surface sterilized and soaked in a 40 ppm zinc oxide nanoparticle (ZnO-NP) solution for 24 h prior to sowing, while untreated seeds served as the control. The experiment comprised seven treatments. Treatment T₀ represented the well-watered control. Drought stress treatments T₁, T₂, and T₃ were imposed by withholding irrigation for 5, 10, and 15 days, respectively. To evaluate the effect of ZnO-NP seed priming under drought conditions, primed seeds were subjected to the same durations of water withholding, constituting treatments T₄,

T₅, and T₆, corresponding to ZnO-NP priming combined with 5, 10, and 15 days of drought stress, respectively.

The field experiment was conducted using a Randomized Block Design (RBD) with three replications. Thirty day old seedlings were transplanted into the field, and drought stress was imposed at the active tillering stage by withholding irrigation for the specified durations.

Data were recorded on various morphological and yield-related traits, including flag leaf length, flag leaf width, primary leaf length, primary leaf width, plant height, panicle length, number of productive tillers per plant, days to 50% flowering, days to maturity, grain yield per plant, 1000-grain weight, biological yield per plant, and harvest index. Physiological parameters such as chlorophyll content were measured using a Minolta™ SPAD chlorophyll meter [16], relative water content (RWC) was determined following the method of Turner and Beg [17], and membrane stability index (MSI) was estimated according to Sairam and Srivastava [18]. Biochemical analyses included estimation of total protein content using Lowry method [19], proline content estimated using method of Bates [20], and peroxidase (POD) enzyme activity as described by Curne and Galston [21].

For molecular characterization, genomic DNA was isolated from young leaf tissue using the cetyltrimethylammonium bromide (CTAB) method by Murray and Thompson [22]. Polymerase chain reaction (PCR) amplification was carried out using ten Simple Sequence Repeat (SSR) markers, namely RM-1, RM-16, RM-20, RM-201, RM-206, RM-212, RM-228, RM-252, RM-273, and RM-289 [23]. PCR amplification was performed with an initial denaturation at 94 °C for 4 min, followed by 35 cycles of denaturation at 94 °C for 45 s, annealing at 56-64 °C for 1 min, extension at 72 °C for 2 min, and a final extension at 72 °C for 8 min. Amplified products were resolved on agarose gels, and bands were scored as present [1] or absent [0].

Statistical analysis of the data was carried out using OPSTAT software. Standard error (SE) and critical difference (CD) at the 5% level of significance were calculated. Percentage reduction due to drought stress was calculated relative to the corresponding control, while percentage recovery under ZnO-NP treatment was calculated relative to the respective drought-stressed treatment using the formula: Percentage change (%) = [(Treatment – Reference)/Reference] × 100.

Results

Morphological Responses

Flag leaf length decreased across all rice genotypes under drought stress, with Vallabh Basmati 24 exhibiting the greatest reduction (37.9%), followed by Pusa Basmati 1728 (36.0%), while Pusa Basmati 1718 showed the least reduction (32.0%). ZnO-NP treatment significantly mitigated drought-induced damage, resulting in an improvement of 16.7% in VB-24, 9.3% in PB-1728, and 4.9% in PB-1718 compared to drought-stressed plants.

Similarly, Flag leaf width declined under drought stress, with reductions of 34.3% in VB-24, 27.7% in PB-1728, and 25.6% in PB-1718. ZnO-NP application alleviated this reduction, leading to a recovery of 6.5% in VB-24, 5.5% in PB-1728, and 4.9% in PB-1718 under drought conditions.

In terms of Primary leaf length, drought stress caused a reduction of 21.8% in PB-1718, 20.3% in PB-1728, and 19.8% in VB-24. ZnO-NP treatment reduced the severity of this decline, resulting in improvements of 6.7%,

5.3%, and 4.5%, respectively, compared to drought-stressed plants. A similar trend was observed for Primary leaf width, where drought stress caused pronounced reductions, particularly in VB-24 (47.6%), followed by PB-1728 (31.9%) and PB-1718 (29.0%). ZnO-NP application significantly alleviated this reduction, with recovery ranging from 7.7% to 15.2%, the highest improvement being observed in VB-24.

Plant height was comparatively less affected by drought stress, though reductions of 9.4% in VB-24, 9.3% in PB-1728, and 8.9% in PB-1718 were recorded. ZnO-NP priming resulted in partial restoration of plant height, with improvements of approximately 2% across all genotypes. Panicle length, however, was severely affected under drought stress, declining by 35.6% in VB-24, 34.5% in PB-1728, and 34.2% in PB-1718. ZnO-NP treatment mitigated this reduction, resulting in a recovery of 5.8-6.3% across the genotypes.

Drought stress substantially reduced the number of Productive tillers per plant, with VB-24 showing the highest reduction (60.0%), followed by PB-1728 (44.4%) and PB-1718 (43.7%). ZnO-NP treatment effectively alleviated this decline, leading to an increase of 30.0% in VB-24, 20.0% in PB-1728, and 16.7% in PB-1718 compared to drought-stressed plants.

Drought stress also accelerated crop phenology. Days to 50% flowering were reduced under drought conditions, with PB-1728 and VB-24 flowering approximately 10 days earlier, while PB-1718 showed relatively less advancement. ZnO-NP priming moderated this effect by delaying flowering by 5-7 days compared to drought-stressed plants. Similarly, Days to maturity were shortened under drought stress by approximately 10-12 days, with ZnO-NP treatment partially restoring normal maturity duration across all genotypes.

Grain yield per plant was markedly reduced under drought stress, with reductions of 38.3% in VB-24, 34.0% in PB-1728, and 31.1% in PB-1718. ZnO-NP treatment significantly mitigated yield loss, resulting in yield improvements of 17.5% in VB-24, 15.1% in PB-1728, and 9.2% in PB-1718 over drought-stressed plants. Additionally, 1000-grain weight declined by 30.5% in PB-1728, 29.5% in VB-24, and 26.4% in PB-1718 under drought stress, while ZnO-NP priming resulted in a recovery of 5.4-6.5% across genotypes.

Biological yield per plant also decreased significantly under drought stress, with the highest reduction observed in VB-24 (28.8%), followed by PB-1728 (23.7%) and PB-1718 (21.1%). ZnO-NP treatment alleviated these reductions, improving biological yield by 6.7% in PB-1718, 10.7% in PB-1728, and 13.0% in VB-24. Lastly, Harvest index declined under drought stress by 13.3% in VB-24, 13.4% in PB-1728, and 12.8% in PB-1718. ZnO-NP priming reduced the negative impact of drought on harvest index, resulting in a recovery of 2.5-4.1% across the genotypes.

Physio-Biochemical Responses

For physio-biochemical parameters, drought stress significantly reduced Chlorophyll content in all rice genotypes. The reduction in chlorophyll content under drought stress was 36.9% in Vallabh Basmati 24, 34.4% in Pusa Basmati 1728, and 37.2% in Pusa Basmati 1718 compared to their respective controls. ZnO-NP application mitigated this decline, resulting in a recovery

of 2.3-8.7%, with the highest improvement observed in Vallabh Basmati 24 compared to drought-stressed plants.

Total protein content also decreased significantly under drought stress, with reductions of 55.5% in Vallabh Basmati 24, 52.9% in Pusa Basmati 1718, and 53.0% in Pusa Basmati 1728 relative to control plants. ZnO-NP treatments lessened the reduction in protein content, leading to an improvement of 30.9% in VB-24, 23.9% in PB-1728, and 23.9% in PB-1718 over drought-stressed plants.

The Membrane stability index (MSI) declined under drought stress, with reductions of 27.3% in Vallabh Basmati 24, 26.6% in Pusa Basmati 1728, and 30.0% in Pusa Basmati 1718 compared to control conditions. ZnO-NP application resulted in less pronounced declines in MSI, improving membrane stability by 8.4-9.0% across the genotypes under drought stress.

Relative water content (RWC) was also adversely affected by drought stress, showing reductions of 25.3% in Vallabh Basmati 24, 23.6% in Pusa Basmati 1728, and 20.5% in Pusa Basmati 1718. ZnO-NP treatments mitigated the reduction in RWC, resulting in recovery values ranging from 4.4% to 8.8%, with the greatest improvement observed in Vallabh Basmati 24.

In contrast to other parameters, Proline content increased under drought stress, indicating osmotic adjustment. The Vallabh Basmati 24 proline content increased by (96.8%), followed by Pusa Basmati 1728 (108.9%), while Pusa Basmati 1718 increased by (109.8%) compared to their respective controls. ZnO-NP treatments resulted in comparatively lower proline accumulation, indicating reduced stress severity under nanoparticle application.

Similarly, Peroxidase (POD) enzyme activity increased markedly under drought stress, with increases of 63.7% in Vallabh Basmati 24, 49.8% in Pusa Basmati 1718, and 50.0% in Pusa Basmati 1728 relative to control plants. ZnO-NP application moderated this increase, resulting in a reduction of 6.6-10.0% in POD activity compared to drought-stressed plants, suggesting improved oxidative stress management.

Molecular Characterization

A total of ten SSR markers were employed to assess genetic diversity among three Basmati rice genotypes (PB-1718, PB-1728, and VB-24). All markers produced clear and reproducible amplification patterns. The amplified fragments ranged approximately from 100 to 200 bp, as estimated using a 100 bp DNA ladder.

Out of the ten SSR markers analyzed, six markers (60%) were polymorphic, while four markers (RM-1, RM-212, RM-228, and RM-252) were monomorphic across all genotypes. Polymorphic markers, including RM-16, RM-20, RM-201, RM-206, RM-273, and RM-289, effectively differentiated the genotypes based on the presence or absence of alleles. Marker RM-273 showed variation in allele size, indicating multiple allelic forms among the genotypes.

The Polymorphism Information Content (PIC) values ranged from 0.00 for monomorphic markers to moderate values (~0.40-0.45) for polymorphic markers, indicating a moderate level of marker informativeness and their effectiveness in detecting genetic variation among the studied genotypes.

Cluster analysis based on SSR data using the UPGMA method grouped the genotypes into distinct clusters,

revealing clear genetic relationships. PB-1718 and PB-1728 clustered closely, indicating higher genetic similarity, whereas VB-24 formed a separate cluster, reflecting greater genetic divergence.

Overall, the SSR-based molecular analysis revealed moderate yet distinct genetic diversity among the three Basmati rice genotypes. This genetic differentiation corresponds well with the observed variation in drought tolerance at the morphological and physio-biochemical levels, supporting the genotype-specific responses to drought stress and ZnO-NP seed priming.

Discussion

Seed nano-priming with ZnO nanoparticles significantly enhanced drought tolerance in Basmati rice by partially mitigating drought-induced reductions in morphological, physiological, and yield-related traits. Under drought stress, all genotypes exhibited pronounced declines in leaf dimensions, plant height, panicle length, and grain yield; however, ZnO-NP application resulted in a consistent and measurable recovery of these traits. Similar improvements in growth and yield under ZnO-NP application have been reported earlier, highlighting the role of zinc in stress mitigation and plant development [24, 25, 26]. This improvement indicates enhanced water retention, better maintenance of photosynthetic capacity, and increased stabilization of cellular membranes under stress conditions. The higher chlorophyll content, relative water content, and membrane stability index observed in ZnO-NP-treated plants suggest that zinc-mediated regulation of cellular homeostasis and antioxidant defense mechanisms played a critical role in reducing drought-induced damage, thereby supporting improved growth and yield performance [27, 28].

The moderated accumulation of proline in ZnO-NP treated plants further indicates a more efficient and regulated stress-response mechanism compared to untreated drought-stressed plants. While drought stress alone induced a sharp increase in proline content particularly in Vallabh Basmati 24 ZnO-NP priming limited excessive proline accumulation, suggesting improved osmotic adjustment and reduced stress

severity. Similar observations have been reported where lower proline accumulation under stress-mitigating treatments was associated with improved stress tolerance rather than stress injury [29, 30]. Similarly, peroxidase activity increased under drought stress as part of the antioxidant defense response; however, comparatively lower enzyme activity in ZnO-NP-treated plants reflects a reduced oxidative burden, indicating effective mitigation of stress-induced reactive oxygen species [31].

Although Vallabh Basmati 24 has been reported as drought tolerant in earlier studies, its comparatively higher sensitivity observed in the present investigation can be attributed to the timing of stress imposition. In this study, drought stress was imposed at the early post-transplanting (active tillering) stage, a phase critically associated with root establishment and tiller initiation. Drought tolerance in rice is well known to be growth-stage specific, and tolerance expressed at reproductive or terminal stages does not necessarily confer resistance during early vegetative stress [32, 33]. The greater susceptibility of VB-24 under early-stage drought conditions suggests that its tolerance mechanisms may be more effective at later developmental stages rather than during initial establishment [34].

Molecular characterization using SSR markers revealed moderate but distinct genetic diversity among the three Basmati rice genotypes. Cluster analysis grouped PB-1718 and PB-1728 together, while VB-24 formed a genetically distinct cluster. This molecular differentiation corresponded well with the contrasting drought responses observed at the morphological and physio-biochemical levels. Similar associations between SSR based genetic diversity and drought response patterns have been reported in rice and other cereals [35, 36]. The genetic separation of VB-24 supports the conclusion that the observed differences in drought response and ZnO-NP efficacy are, at least in part, genetically governed rather than solely environmentally induced. The integration of molecular characterization with physiological screening therefore provides a robust framework for identifying stage-specific drought tolerance in rice genotypes [37].

Table 1: Morphological Characteristics of Rice Varieties Under Drought and ZnO-NP Application Treatments

Genotype(Treatment)		Flag Leaf Length (cm)	Flag Leaf Width (cm)	Primary Leaf Length (cm)	Primary Leaf Width (cm)	Plant Height (cm)	Panicle Length (cm)
PB-1718(Control)		33.06	2.73	51.33	1.83	110.78	29.43
PB-1728(Control)		29.63	2.53	46.7	1.66	107.97	28.13
VB-24(Control)		28.03	2.33	43.4	1.26	106.14	27.36
PB-1718(15 day drought)		22.46	2.03	40.13	1.3	100.99	19.36
PB-1728(15 day drought)		18.96	1.83	37.2	1.13	97.97	18.43
VB-24(15 day drought)		17.4	1.53	34.8	0.66	96.17	17.63
PB-1718(15 day drought + ZnO)		23.56	2.13	42.8	1.4	102.93	20.5
PB-1728(15 day drought + ZnO)		20.73	1.93	39.16	1.23	100.04	19.6
VB-24(15 day drought + ZnO)		20.3	1.63	36.36	0.76	98.01	18.66
SE(m)	Variety	0.125	0.011	0.037	0.009	0.075	0.055
	Treatment	0.190	0.016	0.037	0.013	0.115	0.084
	V x T	0.330	0.028	0.099	0.023	0.199	0.146
C.D. at 5%	Variety	0.358	0.03	0.107	0.025	0.215	0.159
	Treatment	0.546	0.046	0.164	0.038	0.329	0.242
	V x T	N/A	N/A	0.284	N/A	N/A	0.42

Table 2: Yield Characteristics of Rice Varieties under Drought and ZnO-NP Application Treatments

Genotype(Treatment)		Productive tillers per plant	50% Flowering (Days)	Days to Maturity	Grain yield/plant (g)	1000 Grain Weight (g)	Biological yield/plant (g)	Harvest index (%)
PB-1718(Control)		10.66	110.66	150.66	10.12	24.01	20.3	49.87
PB-1718(15 day drought)		6	103.33	140	6.97	17.68	16.02	43.48
PB-1718(15 day drought + ZnO)		7	108.66	148.66	7.61	18.63	17.09	44.56
PB-1728(Control)		9	108.33	148.33	9.05	22.35	18.66	48.5
PB-1728(15 day drought)		5	98.33	138.33	5.97	15.53	14.24	42.01
PB-1728(15 day drought + ZnO)		6	105.33	145.33	6.87	16.54	15.77	43.6
VB-24(Control)		8.33	110	150	8.04	20.62	16.91	47.53
VB-24(15 day drought)		3.33	103.33	140	4.96	14.54	12.04	41.22
VB-24(15 day drought + ZnO)		4.33	106.66	146.66	5.83	15.49	13.6	42.9
SE(m)	Variety	0.065	0.396	0.116	0.11	0.045	0.116	
	Treatment	0.099	0.605	0.177	0.168	0.068	0.178	
	V x T	0.171	1.048	0.306	0.29	0.118	0.308	
	Variety	0.186	1.137	0.332	0.315	0.128	0.334	
	Treatment	0.284	1.736	0.507	0.481	0.196	0.509	
C.D. at 5%								
V x T		N/A	N/A	N/A	N/A	0.339	N/A	

Table 3: Physio-Biochemical Parameters of Rice Varieties under Drought and ZnO-NP Application Treatments

Genotype	Treatment	Chlorophyll (SPAD)	Total Protein (g)	MSI (%)	RWC (%)	Proline (µg)	POD activity
PB-1718	Control	3.12	6.83	79.36	82.31	21.99	116.73
PB-1718	15 day drought	1.96	4.73	55.53	65.36	45.88	196.1
PB-1718	15 day drought + ZnO	2.13	5.86	58.73	69.74	43.93	183.69
PB-1728	Control	3.01	9.63	78.4	79.26	24.2	119.34
PB-1728	15 day drought	1.87	4.53	57.76	60.56	50.58	199.28
PB-1728	15 day drought + ZnO	1.97	5.73	59.73	65.46	47.68	186.19
VB-24	Control	2.92	9.43	75.76	73.91	26.45	122.47
VB-24	15 day drought	1.77	4.2	55.06	58.53	52.05	202.85
VB-24	15 day drought + ZnO	1.81	5.5	60.4	61.1	48.97	189.44
SE(m)	Variety	0.004	0.012	0.54	0.142	0.13	0.152
	Treatment	0.006	0.019	0.824	0.216	0.199	0.233
	V x T	0.011	0.033	1.428	0.375	0.345	0.403
C.D. at 5%	Variety	0.012	0.035	1.548	0.406	0.374	0.437
	Treatment	0.018	0.054	2.365	0.62	0.572	0.668
	V x T	0.032	0.094	N/A	1.074	0.99	N/A

Table 4: SSR marker profile, allele size, polymorphism and PIC values among three Basmati rice genotypes

S. No.	SSR Marker	Allele size (bp) observed	PB-1718	PB-1728	VB-24	Polymorphism	PIC value
1	RM-1	200	1	1	1	Monomorphic	0
2	RM-16	100	1	0	1	Polymorphic	~0.40-0.45
3	RM-20	200	0	0	1	Polymorphic	~0.40-0.45
4	RM-201	100	0	1	1	Polymorphic	~0.40-0.45
5	RM-206	200	1	1	0	Polymorphic	~0.40-0.45
6	RM-212	200	1	1	1	Monomorphic	0
7	RM-228	100	1	1	1	Monomorphic	0
8	RM-252	100	1	1	1	Monomorphic	0
9	RM-273	100-200	1	0	1	Polymorphic	~0.40-0.45
10	RM-289	100	1	1	0	Polymorphic	~0.40-0.45

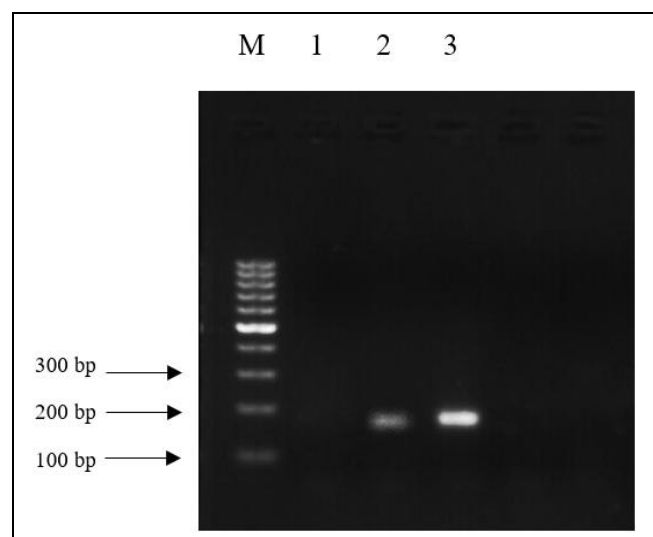


Fig 1: Rice genotypes (PB-1718, PB-1728, VB-24) amplification using primer RM-201

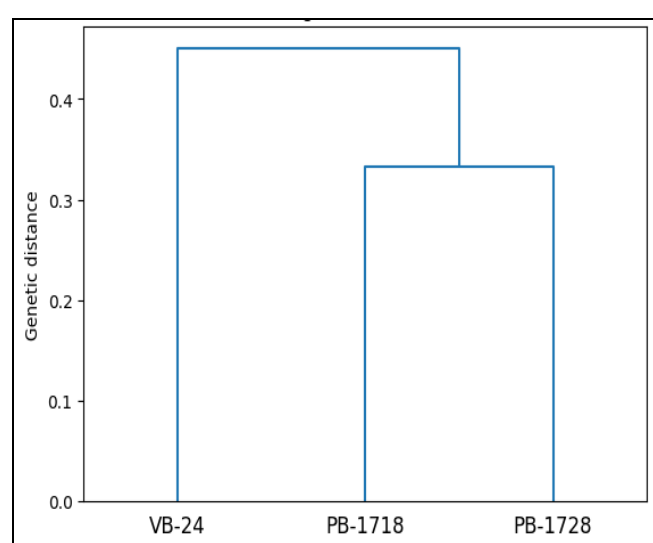


Fig 2: UPGMA Dendrogram based on SSR markers

Conclusions

Seed nano-priming with 40 ppm ZnO-NPs significantly mitigated drought stress effects in Basmati rice by improving physiological stability, enhancing antioxidant defense mechanisms, and partially restoring yield performance under drought conditions. Among the evaluated genotypes, Pusa Basmati 1718 (PB-1718) exhibited the highest level of drought tolerance under early post-transplanting drought stress, whereas Vallabh Basmati 24 (VB-24) showed comparatively higher sensitivity, as evidenced by greater reductions in morphological, physiological, and yield-related traits. The integration of ZnO-NP seed priming with genetically drought-tolerant cultivars represents a promising strategy for sustaining rice productivity under drought-prone environments. However, multi-location field trials and detailed mechanistic studies are required to validate the consistency of genotype-specific and growth-stage-dependent responses and to facilitate large-scale field-level adoption.

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