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Variability and Correlation Study of Various Seed Vigour Parameters in Rice (*Oryza sativa* L.) under Elevated Temperature Condition

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ABSTRACT: Seedling vigour is a crucial agronomic trait. High-vigour seeds are synonymous with high-quality seeds, yet in India, the availability of such quality seeds remains a challenge. Quality seeds with superior physiological performance, particularly in terms of seed vigour are vital for achieving higher yields, uniformity of seedling emergence, and greater resilience to adverse climatic conditions. In the present investigation, thirty rice landraces collected from different states of India were examined for eight seed vigour-contributing physiological traits under elevated temperature (ET) conditions *viz.,* germination percentage, speed of germination, shoot length, root length, seedling length, seedling dry weight, seed vigour index I (SVI-I) and seed vigour index II (SVI-II). There was a significant reduction in mean values of various seed vigour-related physiological parameters studied under ET conditions in comparison to the control. Among the genotypes tested under ET conditions, Magura had the highest germination percentage of 75.67%, Karinellu had the highest seed vigour index I of 816.27 and, Adira-2 had the highest SVI-II of 2.902. The study revealed significant genotypic variability among the seedling vigour-related traits studied under ET condition, with the highest heritability observed for the shoot length (99.4%) followed by speed of germination (99.4%), root length (99.3%), seedling length (99.2%), seed vigour index II (98.3%), and seed vigour index I (98.1%). Out of the 30 genotypes, 3 genotypes recorded high seed vigour (SVI-I and SVI-II) values under ET conditions. Concerning every aspect of seed quality studied under ET conditions, a great deal of variation was seen among the genotypes. Among the two principal components (PCs) in principal component analysis, PC1 had an eigen value of 4.018, which accounted for 50.22% of the variation in the population. PC2 had an eigen value of 2.260, contributing 28.24% of the variation in the population. In addition, under ET condition, a significant positive correlation was recorded between seed vigour index I with shoot length (0.814), seedling length (0.791), speed of germination (0.745), seed vigour index II (0.574), seedling dry weight (0.457), and germination (0.422). Moreover, seed vigour index II was found to have a significant positive correlation with seedling dry weight (0.962), speed of germination (0.836), and seed vigour index I (0.574). The superior genotypes identified with high seed vigour under elevated temperature conditions could be used as suitable donor parents in future high-temperature tolerance breeding programs. Variability and correlation estimates revealed a better selection of target traits for improving seed vigour under high-temperature stress conditions.

Keywords: Seed vigour index, Elevated temperature, Germination percentage, Speed of germination, Seedling length, Seedling dry weight, Variability, Correlation, Rice.

INTRODUCTION

Rice, scientifically known as *Oryza sativa* L., is a crucial staple food crop that feeds over half of the global population. It is cultivated across a vast area of 167 million hectares and yields an average production of approximately 782 million tons. According to Fitzgerald *et al*. (2009). It supplies 76% of the calorific intake value for the people of Southeast Asia, which is considered to be the region experiencing the most rapid increase in temperature as stated by the IPCC (2014). Given the projected increase in the global population to reach 10 billion by 2050, the demand for rice is expected to outpace that of other crops (Krishnan *et al*., 2011). As living standards improve, the rice production and consumption market shows a growing preference for high-quality rice. Nevertheless, because of rapid industrialization and the excessive growth of the population, human activities are believed to have resulted in approximately 1.0°C of global warming (IPCC, 2018). Global warming resulting from climate change causes heat stress (HS), which is commonly defined as a temperature increase above a specific threshold for a certain period, leading to irreversible harm to the growth, development, and productivity of agricultural crops (Southworth *et al*., 2000; Zhao *et al*., 2017; Khan *et al*., 2019; Janni *et al*., 2020).

The availability of good-quality seeds is a pre-requisite for increasing agricultural production and improving the social and economic standards of farmers in stressful environments (Chauhan *et al*., 2015; Hunter *et al*., 2017; Pradhan *et al*., 2019a; Vijaylaxmi *et al*., 2022). Vigour is a critical factor in assessing seed quality. It determines the genetic potential, yield, ability of seeds to ensure uniformity in seedling growth, seed germination, field establishment and resistance to unfavourable environmental conditions, thereby directly affecting the productivity of crops (Chowdhury and Singh 2000; Rajjou *et al*., 2012; Ventura *et al*., 2012). Moreover, the presence of high seed vigour is equally important in direct sowing because it enhances the early establishment of crops in the field and produces robust seedlings that can effectively compete against weeds (Yamauchi and Winn 1996; Mahender *et al*., 2015; Anandan *et al*., 2021; Panda *et al*., 2021a; Parul *et al*., 2022). Seed vigour is a complex trait encompassing a combination of morphological, physiological and biochemical characteristics. The physiological parameters that can be observed morphologically include the seed germination percentage, speed of germination, shoot length, root length and seedling dry weight. By adopting new tolerant varieties that have superior physiological qualities, especially in terms of vigour, we can address various issues, such as poor nutritive value, low productivity, and lower quality of agricultural produce. This adoption can also help reduce the cost of production, mitigate the negative environmental effects of farming, improve crop resilience against the adverse impacts of climate change and increase agricultural yields (Daniel, 2017).

According to Bita and Geras (2013), heat stress can have a negative impact on plant growth, productivity, yield, and seed quality owing to various morphological, physiological, biochemical, and molecular alterations. Elevated temperatures have a negative impact on almost every stage of rice growth, that is from emergence to ripening and harvesting. Typically, the reproductive stage of many crop species is more susceptible to heat stress than the vegetative stage. However, heat stress during the germination stage in rice reduces seed germination potential, slows germination rates, stunts seedling growth, delays seedling establishment, reduces overall vigour, and causes seedling mortality, all of which affect the yield (Fahad *et al*., 2017; Liu *et al*., 2019).

Rice, a prominent cereal crop, is vulnerable to both extremes of temperature *i.e.,* low and high temperature stresses. Rice cultivation thrives best within the temperature range of 25–35°C. Deviations from this optimal temperature range, either lower or higher, have a detrimental effect on the growth, physiology, and yield of the crop. Elevated critical temperatures above 35°C negatively affect the seed germination potential in rice (Satake and Yoshida 1978; Lloh *et al*., 2014; Borriboon *et al*., 2018; Sari *et al*., 2022). Moreover, it causes a reduction in mean shoot length (Lloh *et al*., 2014), disruption of root growth and development (Sehgal *et al*., 2017), delayed mean germination time (Flores and Briones 2001), lower seed germination rate (Tilebeni *et al*., 2012; Solangi *et al*., 2015), decrease in seedling dry weight (Essemine *et al*., 2007) and lower seedling vigour (Wahid *et al*., 2007; Fahad *et al*., 2017). Breeding climate resilient crop varieties with improved seed quality in terms of seed vigour under elevated temperature conditions is required to perform better under unfavourable environmental conditions.

In this study, thirty different rice germplasm varieties were examined to evaluate their variability and investigate the correlation between various physiological traits such as seed germination percentage, speed of germination, shoot length, root length, seedling length, seedling dry weight, seed vigour index I, and seed vigour index II under elevated temperature conditions. The primary objective was to identify superior genotypes with high seed vigour under elevated temperature conditions so that they could be used as suitable donor parents in future high temperature tolerance breeding programs, and to evaluate the variability and correlation between various seed vigour-related physiological traits under elevated temperature conditions.

MATERIALS AND METHODS

In the current study, thirty different rice genotypes obtained from eight distinct states, including Assam, MP, Kerala, Karnataka, Tamil Nadu, Jeypore, Odisha, and Manipur have been preserved and collected from the gene bank of the ICAR-National Rice Research Institute (ICAR-NRRI), Cuttack. The landraces from Odisha have been gathered from the Jeypore tract of Odisha, which is recognized as the secondary centre of origin for rice, and is reported to exhibit broad diversity in the genetic constitution of the landraces. All germplasms were cultivated during the *Kharif* season of 2021 in the experimental field of ICAR-NRRI, Cuttack, Odisha, India. Freshly harvested seeds were used to estimate several seed vigour parameters under both control and elevated temperature conditions after treatment with dormancy-breaking chemical, that is, 2% KNO_3 solution.

A. Germination (%)

The seed germination test was conducted according to the method outlined by ISTA (1999), using the top of paper method of germination. Three replicates of 100 seeds each were arranged in a Petri plate and placed for the germination test. The seeds were subjected to standard germination tests under control conditions, specifically at a temperature of 30°C for 14 days. Additionally, they were tested under stress conditions, specifically at an elevated temperature of 42°C, for 14 days. At the end of the 14th day, the number of normal seedlings (seedlings showing normal root and shoot development) was counted and the mean was expressed as the germination percentage. The final germination percentage and other seedling vigour-related physiological traits were recorded on the 14th day in both elevated temperature treated and untreated seeds.

Germination percentage was calculated by the following formula

$$\text{Germination \%} = \frac{\text{Number of normal seedlings}}{\text{Total number of seeds}} \times 100$$

B. Speed of germination

The speed of germination was calculated using the following formula (Maguire, 1962).

$$\text{Speed of germination} = \sum \left(\frac{n_i}{d_i}\right)$$

Where,

n_i= Number of seeds germinating on the day 'd_i^{th}'

d_i = Number of days after putting seeds for germination.

C. Shoot length, root length and seedling length (cm)

A total number of ten normal seedlings were randomly selected from each replication on the 14th day. The measurements of root length, shoot length, and seedling length were taken, and the average value was expressed as centimeters per seedling.

D. Seedling dry weight (g)

The ten number of normal seedlings chosen for measuring the seedling length from each replication were also utilized for measuring the seedling dry weight. After the cotyledons were removed, ten seedlings were dried in an oven at 70°C for a duration of 48 hours. The dry weight of the seedlings was then measured, and expressed in grams per seedling (Kleyer *et al*., 2008).

E. Seed vigour

Based on the observation data of mean seedling length and mean seedling dry weight, the seed vigour index (SVI-I and SVI-II) was calculated to evaluate the seed vigour (Abdul-Baki and Anderson 1973).

SVI-I = Seed germination (%) × Mean seedling length (cm)

SVI-II = Seed germination (%) × Mean seedling dry weight (g)

The analysis of variance (ANOVA), coefficient of variation (CV %), mean, and range were estimated using Crop Stat software 7.0. By examining Pearson's correlation coefficients, which were derived from the mean values of the 30 genotypes, a correlation matrix heat map was generated to determine the relationships between the different physiological traits. In this experiment, the mean estimates of the eight physiological traits were categorized into three groups: low, medium, and high value containing germplasm lines.

RESULTS AND DISCUSSION

Among the 30 landraces, five germplasms studied under ET conditions namely, Kartiksal was observed with the highest speed of germination (8.610); Magura with the highest germination (75.67%); Manavari with the longest shoot length (4.69 cm); Karinellu with the longest root length (6.21 cm), seedling length (10.84 cm), and seed vigour index I (816.27); Adira-2 had the highest seedling dry weight (0.039 g) and highest SVI-II (2.902). Karinellu and Adira-2 germplasms showed better results for more than two physiological traits under ET conditions. Whereas Jayapadma was observed with the lowest germination (41.00%), seedling length (5.31 cm), seedling dry weight (0.015 g), SVI-I (217.94), and SVI-II (0.602); Bilipandya with the lowest speed of germination (1.937), shoot length (1.58 cm); Tulasi was observed with the lowest root length (3.34 cm).

Similarly, under control conditions, the four germplasms namely, Magura was observed with the highest germination (98.04%), highest speed of germination (18.014), longest root length (15.97 cm), seedling length (28.38 cm), seed vigour index I (2782.34); Manavari with the longest shoot length (13.26 cm); Chitapa with the highest seedling dry weight (0.080 g); Karinellu was observed with the highest SVI-II (7.731). The germplasm, Magura showed better results for more than two physiological traits under control conditions. In contrast, Kabokphou had the lowest germination (87.00%), speed of germination (11.881), shoot length (8.60 cm), root length (7.31 cm), seedling length (15.91 cm), SVI-I (1383.84), and SVI-II (4.422). Chinamal showed the lowest value for the seedling dry weight (0.048 g). Apart from Kabokphou, Jayapadma also showed the lowest SVI-I (1522.84) and SVI-II (4.422), followed by Bilipandya (SVI-I: 1525.57) and (SVI-II: 4.583).

There was a considerable reduction in the mean values of various seed vigour-related physiological traits estimated under elevated temperature conditions compared to the control (Table 1 & 2). Under control conditions, the germination percentage ranged from 87.00% (Kabokphou) to 98.04% (Magura). However, under elevated temperature conditions, it decreased ranging from 41.00% (Jayapadma) to 75.67% (Magura). The speed of germination varied from 11.881 (Kabokphou) to 18.014 (Magura) in the control, and from 1.937 (Bilipandya) to 8.610 (Kartiksal) under ET condition. Shoot length in the control ranged between 8.60 cm (Kabokphou) and 13.26 cm (Manavari), but after ET treatment, it reduced and ranged between 1.58 cm (Bilipandya) and 4.69 cm (Manavari). Root length ranged from 7.31 cm (Kabokphou) to 15.97 cm (Magura) in the control, and from 3.34 cm (Tulasi) to 6.21 cm (Karinellu) in ET-treated seeds. Seedling length in the control ranged between 15.91 cm (Kabokphou) and 28.38 cm (Magura) and decreased and ranged between 5.31 cm (Jayapadma) to 10.84 cm (Karinellu) after ET treatment. Seedling dry weight ranged from 0.048 g (Chinamal) to 0.080 g (Chitapa) in the control, and from 0.015 g (Jayapadma) to 0.039 g (Adira-2) under ET conditions. The seed vigour index I varied from 1383.84 (Kabokphou) to 2782.34 (Magura) in the control, and from 217.94 (Jayapadma) to 816.27 (Karinellu) under ET conditions. The Seed vigour index II ranged from 4.422 (Kabokphou) to 7.731 (Karinellu) in the control, and from 0.602 (Jayapadma) to 2.902 (Karinellu) under ET conditions.

Statistical analysis revealed substantial variation among the genotypes for all the parameters evaluated under both ET and control conditions. The physiological traits examined under both ET and control conditions also exhibited a wide range of variability (Table 1 & 2). According to Tejaswi (2012), there was significant variation in the seedling vigour index across the different genotypes. The variability analysis included landraces collected from different states where prior studies have identified significant genetic diversity in rice (Latha *et al*., 2013; Pandit *et al*., 2017; Pandit *et al*., 2020; Sahoo *et al*., 2020; Vanlalsanga and Singh 2019; Bastia *et al*., 2022). There was a reduction in mean germination and various seed vigour-related physiological traits due to the effect of elevated temperature over control values. However, the superior germplasm lines identified under ET conditions may serve as potential donors for the improvement of germination percentage and vigour for high temperature tolerance breeding programs. Multiple studies have indicated that elevated temperature treatment leads to a decrease in germination and various physiological parameters related to seed vigour in rice (Deng *et al*., 2011; Lloh *et al*., 2014; Solangi *et al*., 2015; Borriboon *et al*., 2018; Sari *et al*., 2022) and wheat (Essemine *et al*., 2007).

A. Estimation of Genetic Parameters

The GCV percentage of various genotypes studied under ET conditions varied from 13.67% to 31.52% (Table 1). Among the traits, GCV % was the highest for seed vigour index II (31.52%), speed of germination (27.99%), shoot length (26.72%), seed vigour index I (22.20%), seedling length (15.00%), germination (14.99%), seedling dry weight (14.10%), and root length (13.67%). The highest GCV was found for Seed vigour index II and the lowest was recorded for root length. The PCV range of all the traits studied under ET conditions varied from 13.72% to 31.79% (Table 1). Among the traits, PCV % recorded for seed vigour II was the highest (31.79%), followed by speed of germination (28.04%), shoot length (26.81%), seed vigour index I (22.41%), seedling dry weight (16.87%), germination (15.16%), seedling length (15.07%), and root length (13.72%). The highest PCV was found for seed vigour index II and the lowest was recorded for root length. The heritability of all traits studied under ET conditions was more than 90% (Table 1). The highest heritability was observed for shoot length (99.4%), speed of germination (99.4%), root length (99.3%), seedling length (99.2%), seed vigour index II (98.3%), followed by seed vigour index I (98.1%), and the lowest was for germination (97.4%) and seedling dry weight (90.1%). The genetic advance for all the characters studied under ET conditions varied from 28.060 to 64.390 (Table 1). The highest GA was recorded for seed vigour index II (64.390), followed by speed of germination (57.590), shoot length (54.860), seedling dry weight (40.270), seedling length (30.780), germination (30.440). One trait showed genetic advance less than 30, *viz.,* root length (28.060).

Similarly, the GCV percentage of the various genotypes studied under control conditions varied from 2.921% to 18.709% (Table 2). Among the traits, GCV % was highest for root length (18.709%), SVI-II (17.322%), SVI-I (16.254), seedling length (13.917%), shoot length (11.749%), speed of germination (9.252%), seedling dry weight (8.570%), and germination (2.921%). The PCV range of all traits studied under the control conditions varied from 4.123% to 18.878% (Table 2). Among the traits, PCV % for root length (18.878%), seed vigour index II (17.855%), seed vigour index I (16.465%), seedling dry weight (15.102%), seedling length (14.142%), shoot length (12.125%), speed of germination (9.512%) followed by germination

(4.123%). The heritability of all traits studied under the control conditions varied from 50.20% to 97.5% (Table 2). The highest heritability was observed for root length (98.20%), seed vigour index I (97.50%), seedling length (96.90%), speed of germination (94.60%), seed vigour index II (94.10%), shoot length (93.90%), seedling dry weight (79.80%), and germination (50.20%). The genetic advance for all the characters studied under control conditions varied from 4.264 to 38.194 (Table 2). The highest GA was recorded for root length (38.194), seed vigour index II (34.617), seed vigour index I (33.056), seedling dry weight (31.217), seedling length (28.215), shoot length (23.452), speed of germination (18.541), and germination (4.264).

The identification of high PCV (phenotypic coefficient of variation) and GCV (genotypic coefficient of variation) for seed vigour-related physiological traits studied under both ET and control conditions might be valuable in breeding programs aimed at improving seedling vigour in high temperature stress environments. The success of most crop improvement programs largely depends on the genetic variability, heritability, and genetic advance of desired traits. Breeders can use the degree and type of genetic variability to establish selection criteria for character selection and breeding plans for improvement (Yadav *et al*., 2021; Manivelan *et al*., 2022). Since heritability does not always indicate genetic gain, heritability coupled with genetic advance is more effective for the selection of seed vigour traits in rice. Numerous studies have documented high GCV, PCV, and genetic advances in different rice traits (Agrama *et al*., 2007; Zhao *et al*., 2011; Huang *et al*., 2012; Zhang *et al*., 2012; Zhao *et al*., 2013; Huang *et al*., 2015; Kumar *et al*., 2015; Pan *et al*., 2015; Anandan *et al*., 2016; Pradhan *et al*., 2016; Pandit *et al*., 2017; Swamy *et al*., 2017; Pradhan *et al*., 2019). Rice crop has a great genetic and phenotypic diversity which enhances its adaptability as a species as reported by McNally *et al*. (2009). In addition, Shenoy *et al*. (1990) reported high variability for first count in seed germination test in rice varieties. These findings indicate that seed vigour is a complex physiological parameter that is affected by both genetic and environmental factors, with significant variability observed in different seed vigour indices. Specifically, seed vigour exhibited the highest genotypic and phenotypic coefficient of variance, suggesting that genetic factors have a greater influence on the overall variation of this trait than environmental factors. Furthermore, Zhao *et al*. (2021) revealed that seed vigour is under strong genetic control and influenced by multiple genes.

B. Correlation Analysis

The association or correlation between traits is crucial for determining whether the selection for one characteristic might affect the selection for another. Table 3 and 4 presents the simple correlation coefficients calculated from the aggregated data. Using correlation coefficients computed across 30 rice genotypes for eight seedling vigour parameters examined under both ET and control conditions, we discovered that most vigour-related traits were significantly correlated. There was the presence of a significant correlation between some traits under elevated temperature conditions (Table 3, Fig. 1). Germination % showed a significant and positive correlation with the speed of germination (0.470), shoot length (0.467), and seed vigour index I (0.422). A Significant positive correlation was observed for seed vigour Index I with shoot length (0.814), seedling length (0.791), speed of germination (0.745), seed vigour index II (0.574), seedling dry weight (0.457), and germination (0.422). Seed vigour index II was found to have a significant positive correlation with seedling dry weight (0.962), speed of germination (0.836), and seed vigour index I (0.574). Shoot length was significantly positively correlated with seedling length (0.854), seed vigour index I (0.814), germination (0.467), and speed of germination (0.400). There was a significant positive correlation between root length and seedling length (0.695). Speed of germination was found to have a significant positive correlation with seed vigour index II (0.836), seed vigour index I (0.745), seedling dry weight (0.671), germination (0.470), and shoot length (0.400).

There were also significant correlations between seedling vigour-related physiological traits studied under the control conditions (Table 4, Fig. 2). Germination % showed a significant and positive correlation with the speed of germination (0.924), seed vigour index I (0.790), shoot length (0.715), seedling length (0.693), and root length (0.579). A significant positive correlation was observed for seed vigour Index I with seedling length (0.989), root length (0.924), shoot length (0.865), speed of germination (0.846), and germination (0.790). The seed vigour index II was found to have a significant positive correlation with seedling dry weight (0.980). Shoot length was significantly positively correlated with seedling length (0.856), speed of germination (0.750), and root length (0.643). There was a significant positive correlation for seedling length with SVI-I (0.989), root length (0.947), shoot length (0.856), and speed of germination (0.784). The speed of germination had a significant positive correlation with germination (0.924), seed vigour index I (0.846), seedling length (0.784), shoot length (0.750), and root length (0.693).

Seedling vigour is a critical trait for successful crop establishment in direct seeded rice. Seedling vigour, along with its associated traits, is inherited quantitatively (Wing *et al*., 1995; Panda *et al*., 2021b). Strong vigour is a characteristic of higher seed quality (Chowdhury and Singh 2000). The presence of strong and significant correlations between several physiological traits and seed vigour in both ET and control conditions could be useful for a more effective selection of seed vigour traits in rice and simultaneous improvement of both traits. The presence of correlations between various seed vigour-related physiological parameters has been documented in previous studies by Cui *et al*. (2002); Sahoo *et al*. (2020); Sanghamitra *et al*. (2021); Barik *et al*. (2022). In addition, several correlation studies with different phenotypic traits in rice have been conducted by researchers, such as Farooq *et al*. (2006); Namuco *et al*. (2009); Rajjou *et al*. (2012); Mithra *et al*. (2018); Panda *et al*. (2021a); Anandan *et al*. (2022).

C. Frequency distribution

The genotypes were categorized into three phenotypic groups *i.e.,* high, moderate and low groups based on the mean data of thirty genotypes for the eight seed vigour-related physiological parameters investigated under both elevated temperature and control conditions (Fig. 3 & 4). Out of the 30 genotypes examined for seed vigour traits under elevated temperature conditions (Fig. 3), four germplasms exhibited high vigour, twenty-three had medium vigour, and three germplasms had low seed vigour index I. Similarly, eleven germplasms exhibited high vigour, sixteen with medium vigour, and three germplasms with poor seed vigour index II. However, according to the mean values of thirty different genotypes for seed vigour traits investigated under control conditions (Fig. 4), five germplasms exhibited high vigour, twenty-two had medium vigour, and three germplasms had low seed vigour index I. Similarly, thirteen germplasms recorded high vigour, fifteen germplasms showed medium vigour and only two germplasms had poor seed vigour index II. Similar results for different physiological parameters linked to seed vigour were reported by Sujay (2007).

D. Genotype by trait biplot analysis of different seed vigour-related physiological quality traits

The genotype by trait biplot analysis of the panel population estimated from 30 genotypes was constructed for eight physiological traits under elevated temperature conditions (Table 5, Fig. 5). Among the 8 principal components, PC1 had an eigen value of 4.018, which accounted for 50.229% of the variation in the population. PC2 had an eigen value of 2.260, contributing 28.244% of the variation in the population (Table 5). Among the eight parameters in PC1, SVI-I had the largest contribution in variation (21.778), followed by germination (16.940), shoot length (15.275), SVI-II (14.708), seedling dry weight (11.981), seedling length (10.713), and speed of germination (8.063). In PC2, the highest recorded value was for root length (29.239), followed by seedling length (24.383), seed vigour index II (14.554), seedling dry weight (13.962), shoot length (7.768), germination (7.121), and seed vigour index I (2.942). Fig. 5 displays the results of the PCA analysis using the first two principal components (PC) for traits studied under ET conditions. The scatter plot reveals that the top right corner (1st quadrant) and the bottom right corner (2nd quadrant) contain landraces with high values for the physiological traits under study. The landraces showing intermediate estimates were retained in the bottom left corner (3rd quadrant), whereas the majority of genotypes with low value were placed in the top left quadrant (4th quadrant). However, the genotypes exhibiting the highest variation are located at the extreme end or are identified as outliers in each quadrant.

Furthermore, a Principal Component Analysis (PCA) was conducted on the panel population to analyse the traits studied under control conditions (Table 6 and Fig. 6). Among the 8 principal components, PC1 had an eigen value greater than 1, namely 5.028, which accounted for 62.851% of the variation in the population. PC2 had an eigen value of 2.006, contributing 25.080% of the variation in the population (Table 6). Among the eight traits in PC1, SVI-I had the largest contribution of variation (19.467), followed by seedling length (18.467), speed of germination (16.485), shoot length (15.467), root length (15.268), and germination (14.542). In PC2, the seed vigour index II had the highest value of 49.388, followed by seedling dry weight (49.042). Fig. 6 shows the results of the PCA analysis using the first two principal components (PC) for traits studied under the control conditions. The scatter plot revealed that the top right corner (1st quadrant) contained landraces exhibiting high values for the physiological parameters under study, while the bottom right corner of the 2nd quadrant accommodated the landraces with high to moderate values. Most landraces with poor estimations were located in the bottom left corner (3rd quadrant), while the top left quadrant (4th quadrant) contained the majority of genotypes with moderate to low estimates for the physiological traits. The variation in performance of different genotypes during the vigour test studied under both ET and control conditions suggested that genotypes with low vigour will lose their viability faster than the genotypes with high vigour when stored in the same conditions. This conclusion is supported by studies conducted by Mahadevappa and Nandisha (1987); Black and Halmer (2006); Richman *et al*. (2006); ISTA (2007). Specifically, seeds with high vigour produce robust and uniform stands, which provide young seedlings enhanced resistance to adverse environmental conditions. Conversely, seeds with low vigour produce weak seedlings that are susceptible to environmental stresses (IRRI, 2009).

Table 1: Estimation of variability of different seed vigour indices of 30 rice germplasms studied under elevated temperature condition.

Traits	Range	Mean	SD	$S.E_m$	CV (%)	GCV	PCV	h^2_{bs}	GA
Germination	41.00-75.67	65.470	9.854	1.799	0.150	14.990	15.160	0.974	30.440
Speed of germination	1.937-8.610	6.321	1.771	0.323	0.280	27.990	28.040	0.994	57.590
Shoot length	1.58-4.69	3.290	0.880	0.161	0.267	26.720	26.810	0.994	54.860
Root length	3.34-6.21	4.650	0.638	0.116	0.137	13.670	13.720	0.993	28.060
Seedling length	5.31-10.84	7.940	1.194	0.218	0.150	15.000	15.070	0.992	30.780
Seedling dry weight	0.015-0.039	0.026	0.006	0.002	0.600	14.100	16.870	0.780	40.270
Seed Vigour Index I	217.94-816.27	522.380	116.341	21.241	0.223	22.200	22.410	0.981	45.290
Seed Vigour Index II	0.602-2.902	1.728	0.546	0.100	0.316	31.520	31.790	0.983	64.390

SD- Standard Deviation, $S.E_m$- Standard error of mean, CV- Coefficient of variation, GCV- Genotypic Covariance, PCV- Phenotypic Covariance, h^2_{bs} – Broad sense heritability, GA- Genetic Advance

Table 2: Estimation of variability of different seed vigour indices of 30 rice germplasms studied under control condition.

Traits	Range	Mean	SD	$S.E_m$	CV (%)	GCV	PCV	h^2_{bs}	GA
Germination	87.00-98.04	93.80	3.188	0.582	0.034	2.921	4.123	0.502	4.264
Speed of germination	11.881-18.014	15.970	1.492	0.272	0.093	9.252	9.512	0.946	18.541
Shoot length	8.60-13.26	11.170	1.327	0.242	0.119	11.749	12.125	0.939	23.452
Root length	7.31-15.97	11.340	2.128	0.388	0.188	18.709	18.878	0.982	38.194
Seedling length	15.91-28.38	22.510	3.150	0.575	0.140	13.917	14.142	0.969	28.215
Seedling dry weight	0.048-0.080	0.061	0.011	0.002	0.174	8.570	15.102	0.798	31.217
Seed Vigour Index I	1383.84-2782.34	2117.61	345.692	63.115	0.163	16.254	16.465	0.975	33.056
Seed Vigour Index II	4.422-7.731	5.701	0.998	0.182	0.175	17.322	17.855	0.941	34.617

SD- Standard Deviation, $S.E_m$- Standard error of mean, CV- Coefficient of variation, GCV- Genotypic Covariance, PCV- Phenotypic Covariance, h^2_{bs} – Broad sense heritability, GA- Genetic Advance

Table 3: Correlation matrix of different seed vigour contributing traits among the 30 rice germplasms studied under ET condition.

	Germination	Speed of germination	Shoot length	Root length	Seedling length	Seedling dry weight	Seed Vigour Index I	Seed Vigour Index II
Germination	1	0.470**	0.467**	-0.087	0.298	0.237	0.422*	0.290
Speed of germination	0.470**	1	0.400*	-0.178	0.200	0.671***	0.745***	0.836***
Shoot length	0.467**	0.400*	1	0.219	0.854***	0.274	0.814***	0.293
Root length	-0.087	-0.178	0.219	1	0.695***	-0.217	0.359	-0.223
Seedling length	0.298	0.200	0.854***	0.695***	1	0.086	0.791***	0.097
Seedling dry weight	0.237	0.671***	0.274	-0.217	0.086	1	0.457*	0.962***
Seed Vigour Index I	0.422*	0.745***	0.814***	0.359	0.791***	0.457*	1	0.574***
Seed Vigour Index II	0.290	0.836***	0.293	-0.223	0.097	0.962***	0.574***	1

*** Correlation is significant at 0.001 level (two tailed) ; ** Correlation is significant at 0.01 level (two tailed); * Correlation is significant at 0.05 level (two tailed)

Table 4: Correlation matrix of different seed vigour contributing traits among the 30 rice germplasms studied under control condition.

	Germination	Speed of germination	Shoot length	Root length	Seedling length	Seedling dry weight	Seed Vigour Index I	Seed Vigour Index II
Germination	1	0.924***	0.715***	0.579***	0.693***	-0.044	0.790***	0.156
Speed of germination	0.924***	1	0.750***	0.693***	0.784***	-0.067	0.846***	0.119
Shoot length	0.715***	0.750***	1	0.643***	0.856***	-0.200	0.865***	-0.055
Root length	0.579***	0.693***	0.643***	1	0.947***	-0.013	0.924***	0.109
Seedling length	0.693***	0.784***	0.856***	0.947***	1	-0.093	0.989***	0.050
Seedling dry weight	-0.044	-0.067	-0.2	-0.013	-0.093	1	-0.082	0.980***
Seed Vigour Index I	0.790***	0.846***	0.865***	0.924***	0.989***	-0.082	1	0.080
Seed Vigour Index II	0.156	0.119	-0.055	0.109	0.050	0.980***	0.080	1

*** Correlation is significant at 0.001 level (two tailed) ; ** Correlation is significant at 0.01 level (two tailed); * Correlation is significant at 0.05 level (two tailed)

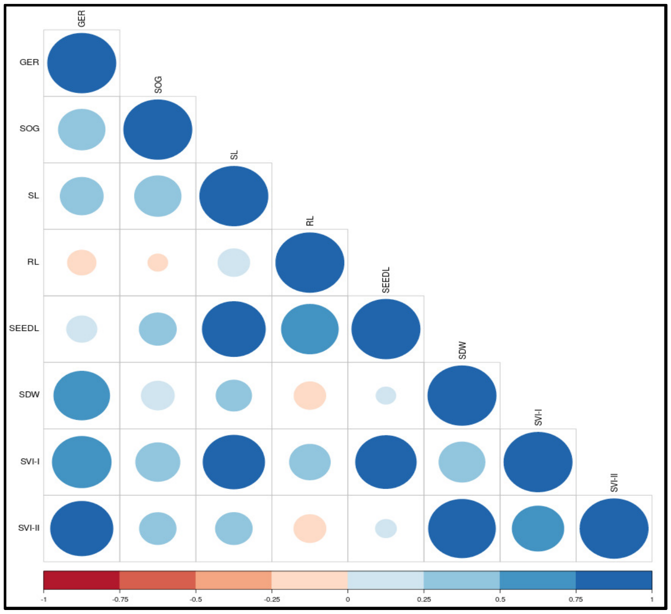

Fig. 1. Heat map showing correlation coefficients of different seed vigour contributing traits among the 30 rice germplasms under elevated temperature condition.

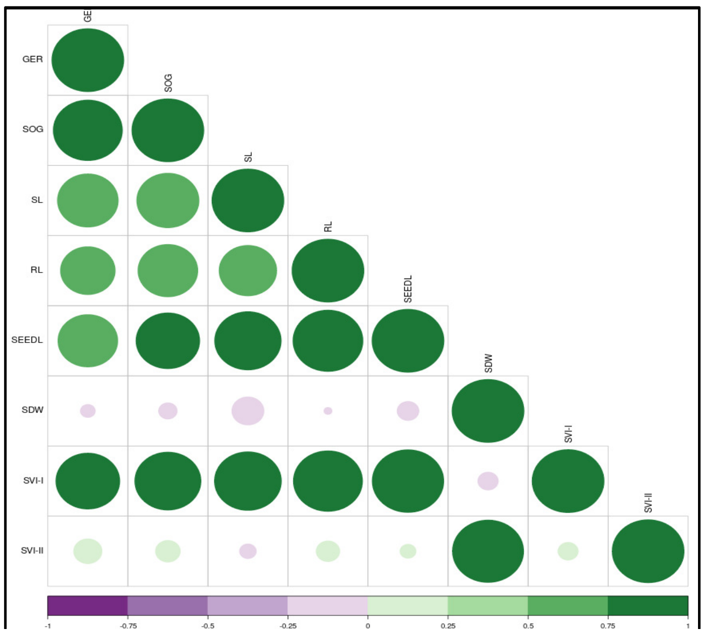

Fig. 2. Heat map showing correlation coefficients of different seed vigour contributing traits among the 30 rice germplasms under control condition.

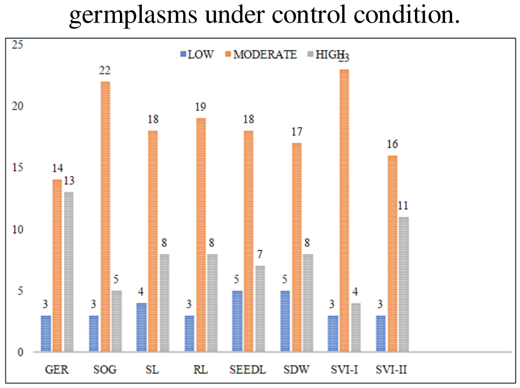

Fig. 3. Frequency distribution of 30 rice germplasm studied under ET condition.

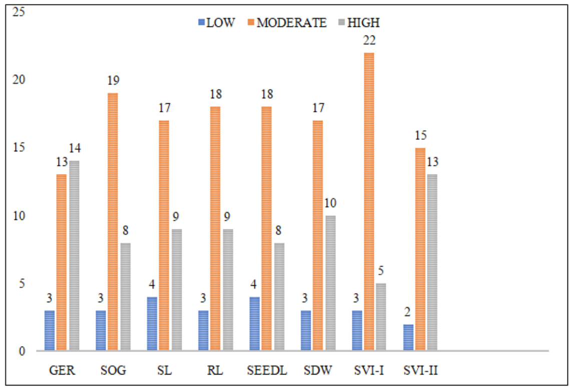

Fig. 4. Frequency distribution of 30 rice germplasm studied under control condition.

Table 5: Eigen value of different principal components and percentage contribution of different seed vigour contributing traits on PCs under ET condition in rice.

Variables	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**
Germination	16.940	7.121	0.011	4.617	38.982	32.124	0.204	0
Speed of germination	8.063	0.030	59.016	23.263	8.951	0.676	0.002	0
Shoot length	15.275	7.768	4.761	35.790	1.101	3.769	1.585	29.951
Root length	0.542	29.239	17.238	33.995	1.519	1.592	0.228	15.647
Seedling length	10.713	24.383	0.369	1.692	2.075	4.686	1.689	54.393
Seedling dry weight	11.981	13.962	10.231	0.099	31.3	2.672	29.754	0.001
Seed Vigour Index I	21.778	2.942	0.765	0.033	13.971	47.61	12.897	0.004
Seed Vigour Index II	14.708	14.554	7.609	0.511	2.101	6.871	53.642	0.003
Principal components	**Eigen value**	**Percentage of variance**						
PC1	4.018	50.23						
PC2	2.260	28.24						

Table 6:Eigen value of different principal components and percentage contribution of different seed vigour traits on PCs under control condition in rice.

Variables	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**
Germination	14.542	0.265	37.134	4.438	37.352	5.614	0.655	0
Speed of germination	16.485	0.088	17.622	8.266	57.265	0.079	0.194	0
Shoot length	15.467	1.016	0.478	68.398	0.652	1.007	2.323	10.658
Root length	15.268	0.181	29.615	16.751	0.190	3.681	6.846	27.467
Seedling length	18.467	0.019	11.454	0.510	0.003	3.887	3.932	61.728
Seedling dry weight	0.175	49.042	0.494	1.270	0.494	28.202	20.258	0.065
Seed Vigour Index I	19.467	0.001	3.003	0.007	3.866	28.758	44.884	0.014
Seed Vigour Index II	0.129	49.388	0.199	0.361	0.177	28.771	20.907	0.068
Principal components	**Eigen value**	**Percentage of variance**						
PC1	5.028	62.85						
PC2	2.006	25.08						

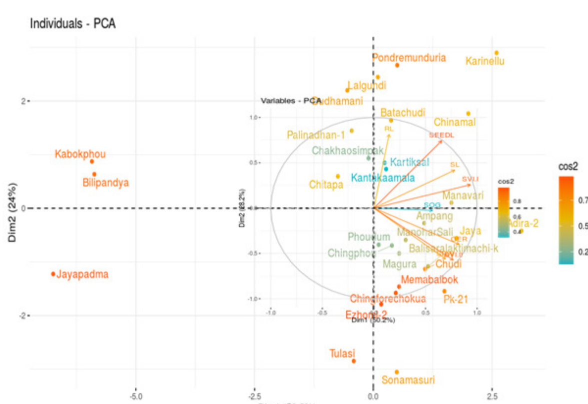

Fig. 5. Genotype by trait bi-plot of different seed vigour traits studied under ET condition in 30 rice germplasm.

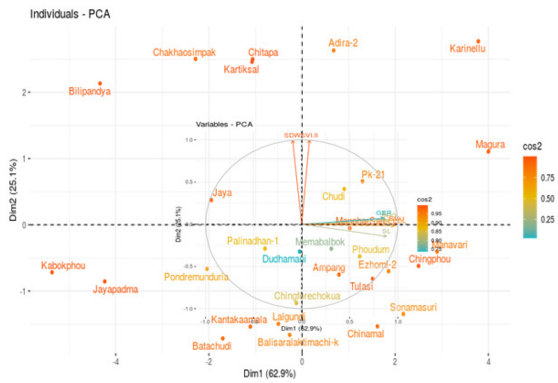

Fig. 6. Genotype by trait bi-plot of different seed vigour traits studied under control condition in 30 rice germplasm.

CONCLUSIONS

The present study mainly examines the variability and correlation of various seed vigour-related physiological traits in thirty rice genotypes collected from diverse states of India, specifically under elevated temperature conditions. There was a significant reduction in mean values of various seed vigour-related physiological parameters studied under ET conditions compared to control. Among the genotypes tested under ET condition, Magura was identified with the highest germination percentage of 75.67%, Karinellu had the highest seed vigour index I of 816.27 while, Adira-2 had the highest SVI-II of 2.902. The study revealed significant genotypic variability among the seedling vigour related traits studied under ET condition, with the highest heritability observed for the shoot length (99.4%) followed by speed of germination (99.4%), root length (99.3%), seedling length (99.2%), seed vigour index II (98.3%), and seed vigour index I (98.1%). From the 30 genotypes, 3 genotypes recorded high seed vigour (SVI-I and SVI-II) under ET conditions. Concerning every aspect of seed quality studied under ET conditions, a great deal of variation was seen among the genotypes. Among the two principal components (PCs) in principal component analysis, PC1 had an eigen value of 4.018, which accounted for 50.23% of the variation in the population. PC2 had an eigen value of 2.260, contributing 28.24% of the variation in the population. In addition, under ET condition a significant positive correlation was recorded for seed vigour Index I with shoot length (0.814), seedling length (0.791), speed of germination (0.745), seed vigour index II (0.574), seedling dry weight (0.457), and germination (0.422). Moreover, seed vigour index II was found to have a significant positive correlation with seedling dry weight (0.962), speed of germination (0.836), and seed vigour index I (0.574).

FUTURE SCOPE

The superior genotypes identified with high seed germination percentage and seed vigour under elevated temperature conditions could be used as a suitable donor parent for resistant variety development in future high-temperature tolerance breeding programs. Variability and correlation estimates could be useful in the selection and improvement of seed vigour-related physiological traits under high-temperature stress conditions.

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