GGE Biplot Analysis in Thermo Sensitive Genic Male Sterile Lines of Rice (Oryza sativa L.) across Multiple Environments

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ABSTRACT

Introduction

Rice is considered as the staple food in many parts of the world, including developing countries like Asia, Africa and Latin America. Exploitation of heterosis in rice has significantly contributed to meet out the increasing demand for food (Jiang et al.,

Stable performance of Thermo-sensitive Genic Male Sterile lines (TGMS) for pollen and spikelet sterility is critical for hybrid seed production in two –line hybrids of rice. The objective of this study is to investigate nine traits in twenty five TGMS lines across three locations viz., Coimbatore (E1), Aduthurai (E2) and Ambasamudram (E3). GGE biplot method was used to analyse the multi-environment data. There was a significant interaction between genotypes and environments for focused traits viz., pollen and spikelet sterility. Among the two weather parameters studied, temperature was found to be the major determinant for sterility induction besides genotypic background. The TGMS lines viz., TNAU 14S, TNAU 100S, TNAU 101S, TNAU 116S, TNAU 124S, TNAU 135S, TNAU 18S, TNAU 139S, TNAU 143S, TNAU 147S, TNAU 151S, TNAU 45S, TNAU 46S and TNAU 67S were best performing and stable genotypes in terms of pollen and spikelet sterility%. Apart from these traits, TNAU 151S and TNAU 124S were found to be stable and best performing for productive tillers, TNAU 139S for panicle exsertion %, TNAU 45S for angle of glume opening, TNAU 67S for stigma exsertion % and TNAU 46S for stigma exsertion % and panicle length. In the present study, Aduthurai has been identified as a suitable location for production of two line hybrids apart from Coimbatore.
Cytoplasmic male sterile (CMS) system of hybrid seed production is the most widely used system yet it has a major drawback where only 20-30% of rice germplasm can be used as effective restorers among rice varieties (Singh et al., 2011). On the other hand, the thermosensitive genic male sterility system poses no limitation on the genotypes to be used as male parent and can be exploited in tropical countries like India for production of hybrid rice. However to exploit the TGMS system for hybrid seed production, information on suitable location, time of sowing, genotypes and their flowering time and the prevailing temperatures during the critical phase etc. is required so that fertility reversion of the TGMS line does not occur.

In Tamil Nadu, so far the fertile and sterile phases are being exploited only at two locations viz., Gudalur and Coimbatore respectively. It is important to identify new sites for hybrid seed production in commercial ventures; also genotypic differences exist for stable expression of sterility in TGMS lines. Thus, the objective of the present study is to identify suitable locations for two line hybrid seed production and to identify stable genotypes across multiple environments.

**Materials and Methods**

Experiments were conducted in three different locations namely Paddy Breeding Station-Coimbatore (E1), Tamil Nadu Rice Research Institute-Aduthurai (E2) and Rice Research Station-Ambasamudram (E3) during Summer 2018. The details of the location are furnished in Table 1. Twenty five TGMS lines viz., TNAU 14S, TNAU 18S, TNAU 45S, TNAU 46S, TNAU 67S, TNAU 71S TNAU 83S, TNAU 84S, TNAU 86S, TNAU 93S, TNAU 100S, TNAU 101S, TNAU 114S, TNAU 115S, TNAU 116S, TNAU 124S, TNAU 135S, TNAU 136S, TNAU 137S, TNAU 139S, TNAU 142S, TNAU 143S, TNAU 145S, TNAU 147S and TNAU 151S from Paddy Breeding Station, Coimbatore constituted the material of study. The lines were sown on 2nd January, 2018 at all the locations and thirty day old seedlings were transplanted in a spacing of 20 x 20 cm in Randomized Block Design (RBD) with two replications. Data was recorded on nine characters viz., days to 50% flowering, plant height (cm), number of productive tillers per plant, panicle length (cm), panicle exsertion %, angle of glume opening (°), stigma exsertion %, pollen sterility % and spikelet sterility %. (SES, IRRI, 2001).

Data was subjected to GxE biplot analysis for detection of GE interaction using Plant Breeding Tools software version 1.3 (PB Tools, 2013).

**Results and Discussion**

The genotype and environment always go hand in hand for a plant breeder to reduce the disparity in selection of superior/ideal genotypes during cultivar development. As most of the traits have quantitative inheritance, understanding their Genotype x Environment Interaction (GEI) will be helpful in making decisions for deployment of genotype(s) in specific/wider environments (Ebdon and Gauch, 2002, Kang et al., 2004). Thus GE is both an opportunity and challenge for the plant breeders.

There are many standard univariate and multivariate methods to evaluate the G x E viz., joint linear regression, singular value decomposition, Additive Main effects Multiplicative Interaction (AMMI) (Kang, 2002). The gap between quantification of GE and matching genotypes with environments was partially bridged by biplot analysis methodology of Gabriel (1971). Later Yan et al., (2000) devised a comprehensive graphical method in which genotype and genotype
environment interaction are simultaneously considered for appropriate genotype in test environment evaluation, popularly termed as ‘GGE biplot’ method. This visual method is simple but informative even for researchers with limited training in statistics and computer applications (Yan and Tinker, 2006).

GGE biplot shows the first two principal components (PC1 and PC2) which are obtained by decomposition of singular values of multi-location trials data for a particular trait. It enables the identification of stable genotypes in different environments and also comparison of their yield performances in different environments, identification of so-called ‘ideal’ genotype, as well as ‘mega-environments’ (Mitrovic et al., 2012). It is also a useful tool for identifying locations with optimized cultivar performance and for making better use of limited resources available for the testing program (Khalil et al., 2011).

In our study, the foremost criterion for a TGMS line to be exploited for hybrid seed production is its stability in expression of pollen and spikelet sterility during the critical stage. Thus, the variance analysis for the two focused traits (Table 2) revealed significant interaction between genotypes and environments and thus, the need to identify suitable genotypes vs. locations.

**Mean performance and stability of genotypes**

The mean data across three locations for nine traits is given in Table 3a and Table 3b. The flowering period for the TGMS lines was from 1st April to 26th April at Coimbatore, 14th March to 24th April at Aduthurai and 11th March to 5th April at Ambasamudram respectively. The maximum, minimum temperature and relative humidity recorded during the flowering was 30.9°C, 20.4°C and 87.6% at Coimbatore, 34.1°C, 22.9°C and 95% at Aduthurai and 34.5°C, 23.5°C and 25.9% at Ambasamudram. It has been pointed out by Liu *et al.*, (1997) that fertility varies with different genetic background and the primary factor which alters the fertility in TGMS lines is the temperature whereas relative humidity is one of the secondary factors. At Coimbatore, the maximum and minimum temperatures were lower than that at other locations. Hence six genotypes viz., G5, G6, G14, G16, G24 and G25 showed fertile pollen grains but were 100% sterile at other two locations. The lines G2 and G23 are to be rejected because they did not conform to TGMS line behavior. One genotype G10 expressed only 41.5 per cent pollen sterility at Ambasamudram while it was 100 per cent sterile at other locations. Reduction in sterility may be due to decrease in RH (25.9% only as against 87.6 % and 95% at other two locations) as it causes a reduction in the spikelet temperature than the corresponding atmospheric/ air temperature (Weerakoon *et al.*, 2008).

The ranking of 25 genotypes based on their mean and stability of performance and relative to an ideal genotype across three environments is presented in Figure 1. Genotypes with high mean performance (except flowering and plant height) and stability are the desirable ones in stability analysis. Genotypes present in the concentric area were stable genotypes compared to those laid outside (Yan and Hunt, 2002). Accordingly, in our study, the following genotypes (Table 4) were identified as stable for each trait.

Khodadad *et al.*, (2011) identified three genotypes viz., G12, G14 and G4 as best based on mean and stability out of the 14 genotypes tested in nine environments. Nassir and Ariyo (2011) identified TOX 3107 as having a combination of stable and average yield when grown in tropical inland swamp. Using
Average Environment Tester coordinate, Akter et al., (2015) identified three rice hybrids viz., BRR110A/BRR110R (G2), IR58025A/BRR110R (G3) and BRRI hybrid dhan1 (G4) to be stable over five environments with high mean. Susanto et al., (2015) reported that G3 (A69-1) was highly stable with high grain yield in all the five environments tested based on mean performance and stability. Two genotypes G3(14S) and G6(166S) were reported as stable across three seasons with high mean performance for yield traits in backcross introgression lines of *Oryza sativa* cv.Swarna/*Oryza nivara* by Divya Balakrishnan et al., (2016)

### GGE biplot polygon view for ideal genotype

The polygon view of a biplot is one of the best way to visualize the interaction patterns between genotypes and environments and to interpret a biplot effectively (Yan and Kang, 2003). In this, some of the genotypes are placed on the crests, while the rest are surrounded by the polygon. Those at the crests of the polygon represent the vertex/id**e**al genotype. As the genotypes placed on the peak had the longest detachment from the biplot origin they were expected to be the most responsive.

The Table 5 represents the ideal genotypes for each environment for each trait extracted from the biplot polygon view. For pollen sterility %, the environment E1 (Coimbatore), E2 (Aduthurai) and E3 (Ambasamudram) fell in three different sectors (Figure 2). The two principal components (PC1 and PC2) accounted for 86.9% of the total variation, of which PC1 explained 66.4% and PC2 explained 20.5%. Genotypes G10, G11 in E1 (Coimbatore), G1, G3, G4, G6, G7, G8, G9, G12, G13, G14, G15, G17, G18, G19, G20 and G21 in E2 (Aduthurai) and G5 in E3 (Ambasamudram) were the vertex genotype and are appropriate for growing in the respective environments.

In case of spikelet sterility %, Environment E1 (Coimbatore), E2 (Aduthurai) and E3 (Ambasamudram) fell in three different sectors (Figure 2). The two principal components (PC1 and PC2) accounted for 96.4% of the total variation, of which PC1 explained 74.3% and PC2 explained 22.1% respectively. The genotype G11 in E1 (Coimbatore), genotypes G1, G3, G4, G6, G7, G8, G9, G12, G13, G14, G15, G17, G18, G19, G20, G21, G22 and G24 in E2 (Aduthurai) and genotype G5 in E3 (Ambasamudram) was the vertex genotype and are appropriate for growing in the respective environments.

Sairekha et al., (2018) identified TNAU 45S (G6), TNUAU 605 (G1) and TNAU 95S (G8) as winning genotypes for pollen and spikelet sterility at Aduthurai (E1), GDR 70S (G2), TNAU 14S (G3) and TNAU 18S (G4) at Ambasamudram (E2) and TNAU 39S (G5) at Coimbatore (E3) environment among eight TGMS lines studied.

One of the important floral traits which effect the outcrossing percentage is male sterility. Apart from male sterility, the outcrossing percentage in female is influenced by several other floral traits which include stigma exsertion and angle of glume opening (Virmani, 1994).

In case of angle of glume opening, environments fell in two different sectors with the genotypes G15 and G19 at the vertex in environment E1 (Coimbatore) and G2 (Aduthurai) while G18 was at the vertex in environment E3 (Ambasamudram). For stigma exsertion, G7 and G20 in environment E1 (Coimbatore), E3 (Ambasamudram) and G10 in environment E2 (Aduthurai) were the vertex genotypes and are appropriate for growing in the respective environments.
Table 1 Agroclimatic zone, Latitude, longitude and weather data of the three locations

| Agroclimatic Zone | Coimbatore        | Aduthurai        | Ambasamudram     |
|-------------------|-------------------|------------------|-------------------|
| Latitude          | Western zone      | Cauvery delta    | High rainfall     |
| Longitude         | 11°1'13.87"N      | 11°00’55”N       | 8°42’33.54”N      |
| Altitude          | 411 m (1,349 ft)  | 25 m (82 ft)     | 66.21 m (217.24 ft) |

| Month  | Average temperature °C | Max | Min | RH % |
|--------|------------------------|-----|-----|------|
| January|                        | 27.9| 18.0| 88.2 |
|        |                        | 29.1| 19.4| 96.0 |
|        |                        | 31.0| 23.0| 76.7 |
|        |                        | 27.7| 15.2| 85.9 |
|        |                        | 30.8| 20.0| 96.0 |
|        |                        | 33.5| 22.9| 29.7 |
| February|                      | 31.2| 19.0| 86.7 |
|         |                        | 33.8| 22.5| 95.0 |
|         |                        | 35.4| 24.6| 17.2 |
| March  |                        | 32.0| 21.7| 83.9 |
|        |                        | 35.1| 25.4| 92.0 |
|        |                        | 36.5| 26.1| 19.9 |
| April  |                        | 29.5| 21.3| 89.6 |
|        |                        | 35.2| 26.5| 86.0 |
|        |                        | 36.2| 27.1| 48.9 |
| May    |                        | 32.0| 22.7| 88.4 |
|        |                        | 34.6| 25.7| 80.0 |
|        |                        | 34.2| 28.4| 59.0 |

Table 2 Combined analysis of variance over three environments for pollen and spikelet sterility in 25 TGMS lines of rice

| Source                           | Degree of freedom (Df) | Mean Square (MS) Pollen sterility | Spikelet sterility |
|----------------------------------|------------------------|-----------------------------------|--------------------|
| Genotype                         | 24                     | 1137.89**                         | 1992.60**          |
| Environment                      | 2                      | 943.29**                          | 261.89**           |
| Genotype × Environment           | 48                     | 543.96**                          | 632.03**           |
| Error                            | 75                     | 4.94                              | 5.04               |
| Total                            | 149                    |                                   |                    |

** Significant at 1% level of probability
Table 3a Mean performance of twenty TGMS lines in rice across three locations for days to 50% flowering, plant height, productive tillers per plant, panicle length and panicle exsertion

| Genotype code | Genotype  | Days to 50% flowering | Plant height (cm) | Productive tillers per plant | Panicle length (cm) | Panicle exsertion % |
|--------------|-----------|-----------------------|-------------------|-----------------------------|---------------------|---------------------|
|              |           | E1                    | E2                | E3                          | E1                  | E2                  | E3                  | E1                  | E2                  | E3                  |
| G1           | TNAU 14S  | 112.0                 | 107.0             | 94.5                        | 87.4                | 78.5                | 63.2                | 21.8                | 16.3                | 14.1                |
| G2           | TNAU 93S  | 116.0                 | 109.0             | 93.5                        | 84.2                | 80.0                | 79.9                | 15.7                | 8.6                 | 18.7                |
| G3           | TNAU 100S | 112.0                 | 98.0              | 96.5                        | 82.7                | 75.5                | 72.2                | 27.7                | 12.8                | 19.0                |
| G4           | TNAU 101S | 111.5                 | 88.5              | 89.5                        | 79.9                | 73.5                | 81.5                | 22.5                | 11.9                | 21.1                |
| G5           | TNAU 114S | 107.0                 | 110.5             | 87.0                        | 80.6                | 71.4                | 71.8                | 30.9                | 11.0                | 22.4                |
| G6           | TNAU 115S | 103.5                 | 111.5             | 89.5                        | 76.1                | 62.6                | 85.3                | 29.7                | 10.9                | 24.0                |
| G7           | TNAU 116S | 105.0                 | 112.5             | 88.5                        | 75.5                | 69.2                | 86.8                | 29.7                | 9.1                 | 26.7                |
| G8           | TNAU 124S | 102.0                 | 109.0             | 91.5                        | 79.9                | 74.9                | 81.5                | 28.9                | 15.8                | 22.2                |
| G9           | TNAU 135S | 117.5                 | 103.5             | 89.5                        | 92.4                | 82.6                | 82.1                | 22.7                | 11.1                | 21.3                |
| G10          | TNAU 136S | 109.0                 | 102.5             | 92.5                        | 85.1                | 78.9                | 81.0                | 27.1                | 13.0                | 24.5                |
| G11          | TNAU 137S | 103.0                 | 79.0              | 79.0                        | 92.1                | 80.7                | 72.4                | 30.6                | 12.3                | 18.4                |
| G12          | TNAU 18S  | 115.5                 | 109.5             | 96.5                        | 88.5                | 81.0                | 70.5                | 27.5                | 14.0                | 20.4                |
| G13          | TNAU 139S | 95.0                  | 110.0             | 74.0                        | 68.0                | 70.0                | 61.9                | 23.5                | 10.6                | 21.2                |
| G14          | TNAU 142S | 104.0                 | 87.0              | 89.0                        | 92.9                | 70.6                | 87.8                | 25.7                | 16.1                | 25.6                |
| G15          | TNAU 143S | 103.0                 | 88.0              | 87.5                        | 87.3                | 73.7                | 86.1                | 25.2                | 21.5                | 17.5                |
| G16          | TNAU 145S | 104.0                 | 104.0             | 98.0                        | 91.4                | 75.7                | 90.5                | 24.1                | 16.0                | 20.8                |
| G17          | TNAU 147S | 117.0                 | 110.5             | 95.5                        | 83.0                | 77.9                | 64.1                | 26.2                | 18.4                | 15.9                |
| G18          | TNAU 151S | 111.0                 | 115.0             | 96.5                        | 91.1                | 82.0                | 79.2                | 28.0                | 13.5                | 20.7                |
| G19          | TNAU 45S  | 125.5                 | 107.0             | 97.0                        | 58.9                | 75.1                | 65.8                | 24.9                | 15.1                | 17.5                |
| G20          | TNAU 46S  | 112.0                 | 101.0             | 89.5                        | 77.5                | 74.4                | 68.3                | 26.7                | 14.2                | 21.8                |
| G21          | TNAU 67S  | 116.5                 | 102.5             | 95.5                        | 77.3                | 75.7                | 71.1                | 22.1                | 13.9                | 21.4                |
| G22          | TNAU 71S  | 121.5                 | 108.0             | 96.0                        | 83.7                | 85.3                | 75.9                | 27.8                | 12.3                | 17.1                |
| G23          | TNAU 83S  | 113.5                 | 109.5             | 93.5                        | 93.7                | 76.1                | 69.1                | 26.1                | 14.05               | 24.1                |
| G24          | TNAU 84S  | 104.5                 | 107.5             | 90.5                        | 85.6                | 78.8                | 72.9                | 28.0                | 12.8                | 17.5                |
| G25          | TNAU 86S  | 112.5                 | 110.0             | 98.0                        | 90.9                | 73.5                | 77.2                | 31.5                | 10.2                | 18.2                |
Table 3b: Mean performance of twenty five TGMS lines in rice across three locations for angle of glume opening, stigma exertion, pollen sterility and spikelet sterility.

| Genotype code | Genotype | Angle of glume opening (°) | Stigma exertion (%) | Pollen sterility (%) | Spikelet sterility (%) |
|---------------|----------|----------------------------|---------------------|-----------------------|------------------------|
|               |          | E1 | E2 | E3 | E1 | E2 | E3 | E1 | E2 | E3 | E1 | E2 | E3 | E1 | E2 | E3 |
| G1            | TNAU 14S | 22.5 | 22.5 | 28.5 | 51.6 | 47.0 | 46.6 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G2            | TNAU 93S | 24.0 | 23.0 | 24.5 | 31.9 | 18.9 | 29.8 | 28.2 | 26.2 | 16.5 | 74.8 | 40.1 | 30.2 |
| G3            | TNAU 100S | 20.5 | 28.0 | 25.0 | 47.4 | 34.5 | 39.9 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G4            | TNAU 101S | 22.0 | 28.5 | 23.0 | 48.5 | 35.6 | 40.2 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G5            | TNAU 114S | 27.0 | 26.5 | 22.5 | 30.3 | 31.0 | 34.8 | 39.5 | 100.0 | 100.0 | 100.0 | 70.8 | 50.3 | 100.0 |
| G6            | TNAU 115S | 25.5 | 23.5 | 25.0 | 50.5 | 40.1 | 41.9 | 99.1 | 100.0 | 100.0 | 99.1 | 100.0 | 100.0 |
| G7            | TNAU 116S | 26.5 | 32.0 | 22.5 | 66.1 | 50.2 | 49.3 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G8            | TNAU 124S | 25.0 | 20.0 | 24.0 | 54.2 | 60.9 | 47.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G9            | TNAU 135S | 18.5 | 15.0 | 18.0 | 34.0 | 25.2 | 36.2 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G10           | TNAU 136S | 21.0 | 27.5 | 24.5 | 47.1 | 58.6 | 55.3 | 100.0 | 100.0 | 41.5 | 100.0 | 100.0 | 88.0 |
| G11           | TNAU 137S | 26.5 | 24.5 | 22.0 | 60.2 | 45.0 | 43.6 | 100.0 | 55.0 | 12.8 | 100.0 | 100.0 | 100.0 |
| G12           | TNAU 18S  | 25.0 | 23.5 | 24.0 | 45.9 | 42.7 | 37.2 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G13           | TNAU 139S | 21.5 | 27.5 | 25.5 | 23.1 | 33.1 | 23.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G14           | TNAU 142S | 25.5 | 21.0 | 22.5 | 45.4 | 42.3 | 37.5 | 99.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G15           | TNAU 143S | 27.0 | 32.5 | 24.0 | 42.4 | 35.4 | 27.6 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G16           | TNAU 145S | 20.5 | 21.5 | 22.0 | 52.1 | 51.2 | 45.4 | 92.7 | 100.0 | 100.0 | 89.5 | 100.0 | 100.0 |
| G17           | TNAU 147S | 20.5 | 20.0 | 26.5 | 46.6 | 38.9 | 49.3 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G18           | TNAU 151S | 23.0 | 15.5 | 28.0 | 47.7 | 42.8 | 54.2 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G19           | TNAU 145S | 28.5 | 27.5 | 24.5 | 54.8 | 43.4 | 46.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G20           | TNAU 46S  | 26.0 | 23.5 | 21.5 | 61.4 | 54.6 | 59.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G21           | TNAU 67S  | 18.0 | 18.5 | 22.0 | 54.8 | 45.9 | 54.6 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G22           | TNAU 71S  | 17.0 | 19.5 | 19.5 | 33.2 | 25.5 | 29.3 | 100.0 | 38.0 | 100.0 | 98.0 | 100.0 | 100.0 |
| G23           | TNAU 83S  | 22.5 | 21.0 | 25.0 | 27.6 | 32.7 | 27.4 | 80.1 | 100.0 | 35.4 | 100.0 | 100.0 | 94.6 |
| G24           | TNAU 84S  | 21.5 | 21.0 | 25.5 | 52.1 | 43.9 | 37.0 | 94.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| G25           | TNAU 86S  | 22.0 | 20.0 | 22.5 | 51.0 | 46.6 | 52.9 | 48.8 | 100.0 | 100.0 | 65.1 | 100.0 | 100.0 |
Table 4 Stable TGMS lines for different traits in rice

| Trait                              | Stable genotypes | Mean performance |
|------------------------------------|------------------|------------------|
| Days to 50% flowering (days)       | G17, G12, G25, G2, G23 | 107.6, 105.8, 106.8, 106.2, 105.5 |
| Plant height (cm)                  | G9, G18, G25     | 85.7, 84.1, 80.53 |
| Productive tillers per plant       | G25, G11, G8     | 19.9, 20.4, 22.3 |
| Panicle length (cm)                | G22, G20, G10    | 27.7, 24.8, 24.3 |
| Panicle exsertion (%)              | G2, G24, G16, G14, G13 | 83.2, 82.5, 81.8, 81.0, 80.7 |
| Angle of glume opening (°)         | G19              | 26.8             |
| Stigma exsertion (%)               | G20, G21, G25, G16 | 58.6, 51.8, 50.2, 49.6 |
| Pollen sterility (%)               | G1, G3, G4, G7, G8, G9, G10, G12, G13, G15, G17, G18, G19, G20 and G21 | 100 |
| Spikelet sterility (%)             | G1, G3, G4, G7, G8, G9, G12, G13, G14, G15, G17, G18, G19, G20, G21 and G24 | 100 |
Table 5: Ideal TGMS lines for different traits at different environments

| Trait                           | Environment                          | Vertex genotypes |
|---------------------------------|--------------------------------------|------------------|
| Days to 50% flowering           | E1 (Coimbatore) and E3 (Ambasamudram) | G19              |
|                                 | E2 (Aduthurai)                       | G18              |
| Plant height                     | E1 (Coimbatore) and E3 (Ambasamudram) | G14 and G16      |
|                                 | E2 (Aduthurai)                       | G1               |
| Productive tillers per plant    | E1 (Coimbatore) and E3 (Ambasamudram) | G7               |
|                                 | E2 (Aduthurai)                       | G15              |
| Panicle length                   | E1 (Coimbatore) and E2 (Aduthurai)   | G16 and G22      |
|                                 | E3 (Ambasamudram)                    | G4               |
| Panicle exsertion               | E1 (Coimbatore) and E2 (Aduthurai)   | G1               |
|                                 | E3 (Ambasamudram)                    | G4               |
| Angle of glume opening          | E1 (Coimbatore) and E2 (Aduthurai)   | G15 and G19      |
|                                 | E3 (Ambasamudram)                    | G18              |
| Stigma exsertion                | E1 (Coimbatore) and E3 (Ambasamudram) | G7 and G20      |
|                                 | E2 (Aduthurai)                       | G10              |

Fig. 1: Average Environment Axis (AEA) view of GGE biplot showing the mean performance and stability of genotypes

a) Days to 50% flowering

b) Plant height
c) Angle of glume opening

d) Stigma exsertion

e) Productive tillers

f) Panicle length
g) Panicle exsertion

h) Pollen sterility

i) Spikelet sterility
**Fig. 2** Polygon view of GGE biplot for different traits in TGMS lines

(a) Pollen sterility  
(b) Spikelet sterility  
(c) Angle of glume opening  
(d) Stigma exsertion
e) Days to 50% flowering  

f) Panicle length  

g) Plant height  

h) Panicle length
i) Panicle exsertion

Fig. 3 Comparison of environments with ideal environment

a) Pollen sterility

b) Spikelet sterility
Balestre et al., (2010) evaluated 20 genotypes of upland rice and identified two cultivars viz., BRS Pepita and MG1097 as ideal in terms of stability and adaptability. Donoso-Ñanculao et al., (2015) using GGE biplot technique identified that Quila 241319 was the best genotype across three locations for grain yield and stability in temperate climate.

Jay Laxami et al., (2017) did ‘which won where’ analysis and found that mega environment 1 with two locations E2 and E3 had G10 as winning genotype, and in E1 and E4 falling in mega environment 2, G8 was the winning genotype. Farshadfar et al., (2013) identified genotype G17 (X96TH41K4) in environment E1, E3, E4 and E6, G12 (X96TH46) in environments E5, E7 and E8 and G19 (FLIP-82-115) for environment of E2 as the winning genotypes respectively in chickpea. In soybean, genotypes C 17 (PS 1556) and C 11 (VLS 89) were identified as winning genotypes for grain yield at Majhera, Palampur and Almora and C 34 (VLS 59) at Bajaura by Bhartiya et al., (2017).

**Evaluation of environments based on GGE biplot**

In two line breeding of hybrid rice, particularly using Thermosensitive Genic Male Sterility system, identifying suitable locations for hybrid seed production is crucial where the sterility inducing temperature is prevailing during the critical stages. Hence the trait pollen and spikelet sterility % were used as selection criterion for evaluation of environments in our study. Figure 3 depicts the representative and discriminative ability of the locations studied. The cosine of angle between environment vector and the Average Environment Axis (AEA) helps to identify the correlation between the genotype performance in that environment and across the environment (Yan et al., 2007). The length of the vector of the test environment measures
the ability to discriminate genotypes in the test environment. Test environments making small angle with the AEA was considered as the most representative environment (Oyekunle et al., 2017).

Accordingly, the environment E2 (Aduthurai) was placed nearer to the ideal environment with long vector as well as small angle with the AEA followed by E1 (Coimbatore) and E3 (Ambasamudram) for pollen sterility and spikelet sterility. Thus E2 (Aduthurai) was ideal environment for both pollen and spikelet sterility was considered as stable and suitable environment for all genotypes. In earlier studies by Sairekha et al., (2018), the same location Aduthurai was identified to be stable for both pollen and spikelet sterility in TGMS lines.

The environment E3 (Barisal) was reported as ‘ideal’ environment followed by E1(Gazipur), E2 (Comilla) and E5 (Satkhira) for stability of yield in hybrid rice by Akter et al., (2015). Environment E2 (Late transplanting) and E3 (System of rice intensification) were reported as closest to the ideal environment for basmati rice by Jay Laxami et al., (2017). Susanto et al., (2015) reported that among the five environments tested, three environments viz., E1 (Subang, DS 2012), E2 (Karawang, DS 2012), and E3 (Indramaru, DS 2012) were identified to be good for discriminative and representative environment for yield trait of high Fe content rice lines.

**Relationship among environments**

The correlation between the environments represented by the vectors of all three environments facilitates the determination of the relationship between the environments. Cosine of angle between the locations shows the correlation among them (Yan, 2001). Acute angle represents positive, obtuse angle depicts negative and large GxE and right angle represents no correlation between environments (Yan and Tinker, 2006).

GGE biplot for relationship among the tested locations for pollen and spikelet sterility % is shown in Figure 4. In case of pollen and spikelet sterility, acute angle was observed among the three environments, thus it shows there was strong positive correlation between the environments.

In the present study, TNAU 14S (G1), TNAU 100S (G3), TNAU 101S (G4), TNAU 116S (G7), TNAU 124S (G8), TNAU 135S (G9), TNAU 18S (G12), TNAU 139S (G13), TNAU 143S (G15), TNAU 147S (G17), TNAU 151S (G18), TNAU 45S (G19), TNAU 46S (G20) and TNAU 67S (G21) were best performing and stable genotypes in terms of pollen sterility % and spikelet sterility %. Among them, TNAU 151S (G18) and TNAU 124S (G8) are found to be stable and best performing in terms of productive tillers, TNAU 139S (G13) for panicle exsertion, TNAU 45S (G19) for angle of glume opening, TNAU 67S (G21) for stigma exsertion, TNAU 46S (G20) for stigma exsertion and panicle length, respectively. High and stable pollen and spikelet sterility could be achieved in Environment E2 (Aduthurai) and it was considered as stable environment. Thus the present investigation has led to identification of ideal TGMS lines and ideal environment for hybrid seed production using two-line breeding.

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