# 'Which won where': AMMI and GGE Biplot approach for genotype × environment interaction on yield stability of pigeonpea [*Cajanus cajan* (L.) Millsp.]

*Sabampillai Mahendraraj[1], Marisa Collins[2], Yash Chauhan[3], Vincent Mellor[4] & Rao C.N. Rachaputi[1]*

[1] Queensland Alliance for Agriculture and Food Innovation (QAAFI). The University of Queensland
[2] La Trobe University, Melbourne
[3] Department of Agriculture and Fisheries, Queensland
[4] School of Agriculture and Food Science, The University of Queensland

**Keywords**

Pigeonpea, yield stability, GGE biplot, environment

**Take home message**

The presence of variety (genotype) (G) × environment (E) interaction (G × E) influences production decision making on issues such as time of sowing, location, and selection of varieties. Identifying appropriate varieties and their fit to a particular growing environment would minimise environmental stress and thereby maximise productivity.

**Abstract**

High yield potential and yield stability are the most desirable genetic characteristics for commercial pigeonpea genotypes. The growing environment greatly influences crop growth, leading to substantial variations in yield. Therefore, understanding genotype and its interaction with environment is critical in the development of genotypes with yield stability. Three pigeonpea genotypes were compared for grain yield in seven environments created by different sowing dates at the University of Queensland. Additive mean effects and multiplicative interaction (AMMI) and GGE biplot were used to analyse the genotype-by-environment interaction (G × E).

Grain yields varied widely across the time of sowing with a mean of 2.7 t/ha. Additive mean effects and multiplicative interaction (AMMI) and GGE biplot were used to analyse the genotype-by-environment interaction (G × E) and found highly significant environment (87%) followed by genotype (11%) and G × E effects (2%) on grain yield. The genotype 'Quest' was the highest yielding followed by 'ICP 14425' and 'QPL 1001'. The analysis revealed that 'ICP 14425' consistently performed well in all the environments and was thus considered as the most stable genotype compared to 'Quest' and 'QPL 1001'. 'QPL 1001' performed moderately well in all the environments. However, 'Quest' performed better in the environments associated with sowing dates of 6/12/2017, 9/01/2018 and 20/12/2018 whereas the better sowing environments for 'ICP 14425' were sown on 16/02/2018, 10/10/2018 and 15/11/2018. The outcome of this study has implications for assessing the genotypic adaptation to subtropical environments where photoperiod exceeding 13 h and maximum temperatures reaching > 40°C between latitude 20°S - 30°S. The interaction between genotype, maturity class and growing environment are critical in optimising grain yield in pigeonpea.

## Introduction

Pigeonpea is an important tropical legume widely grown in semi-arid regions of the Indian subcontinent, Africa, and Caribbean Islands. Total world production is 4.3 million tons from 5.3 million ha with an average productivity of 0.8 t/ha. India is the largest producer and consumer followed by Myanmar, Malawi, Kenya, and Uganda (Chand et al., 2014, Kyu, 2016, Tiwari, 2016). It is often intercropped with maize or grown in mixed cropping systems and it plays an important role in production and income for subsistence farmers (Hogh Jensen, 2007). A study conducted in Ghana indicated that pigeonpea-maize rotations increased maize yield by 75 - 200% (Adjei-Nsiah, 2012). In another study where pigeonpea was grown in resource poor soils without inputs produced a reasonable grain yield of 2.5 t/ha (Snapp, 2003). Though, the yield potential of Cajanus cajan is high, it is generally not realized due to biotic and abiotic stresses. Changing environmental conditions along with genotypic characteristics and interaction between environment and variety, might cause large variability in crop yield.

Environments differ in their range of photoperiod and temperatures which can impact crop growth and reproductive development. Various climatic conditions because of global warming and subsequent climate change have considerable impact on rainfall pattern and hence on crop yield (Joshi, 2011). Pigeonpea is a native drought tolerant legume and well adopted to several environments in semi-arid tropics (Saxena, 2008). It is a deep-rooted crop and capable of extracting water from more than 150 cm depth. The capacity to extract soil water from depth is one strategy for mitigating the impacts of climatic uncertainty (Odeny, 2007). Rapid flowering in pigeonpea is triggered by shorter day lengths. Phenological development specially time of flowering can have significant effect on dry matter production and harvest index (Chauhan, 1998).

The major constraint to greater production has been that of low yields (Padi, 2003). However, recent studies have revealed a higher yield potential in Queensland, Australia (Rachaputi et al., 2018) and farmers perceive this as one of the summer legume option for Northern Queensland due to its financial and rotational benefits. The major challenge in pigeonpea development has been to develop stable high-yielding varieties with resistance to environmental stresses (Chauhan, 1998). Varietal interaction with growing environment, are critical in determining yield. Incorporating pigeonpea into Northern cropping systems could bring benefits including a new summer legume for the rotation with associated nitrogen fixation. Rhizobia associated with pigeonpea roots are capable of fixing 41 - 280 kg ha-1 of nitrogen (Tripathi et al., 2018., Udensi and Lkpeme, 2012).

The presence of genotype (G) × environment (E) interaction (GEI) influences decisions on issues such as time of sowing, location, and selection of varieties. Understanding and exploiting GEI is the key to increase the agricultural productivity and the basis for successful breeding to develop stable varieties for diverse environments.

The objectives this study are: (i) Understand G × E interaction effects (ii) Evaluate genotypic stability under different environments, (iii) Identify most productive environments (iv) Analyse the role of environmental factors on G × E interaction effects.

**Statistical analysis**

Grain yield (t/ha) was the only measured variable in this research. Analysis of variance (ANOVA) was performed to assess the genotypic, environmental and GEI effects. With the presence of a significant GEI in the data, research outcomes were evaluated for adaptability and yield stability using AMMI and GGE Biplot models using 'R' statistical programming language version: 4.0.3.

Two important statistical technique, AMMI (Additive Main-Effects and Multiplicative Interaction) and GGE Biplot were effectively used by many researchers to evaluate GEI (Chauhan, 1998, Neisse et al., 2018, Santos et al., 2019, Simtowe, 2012, Yau, 1995). AMMI model uses analysis of variance and principal component analysis for better understandings of GEI, it causes and consequences (Neisse et al., 2018), whereas,GGE Biplot considers both additive main effetcs and multiplicative interaction effects. AMMI separates G from GEI and Biplots provides simple graphical analysis for better understanding. Both AMMI and Biplot depend on principal component analysis (PCA) since multi-dimensional data are difficult to represent using Biplots.

**Material and methods**

The experiments were conducted at the horticulture research farm of The University of Queensland Gatton Campus. Varieties were assigned to sub-plots in three replicates in a randomised manner. The plot size was 2.4 m (width) × 4 m (length) and consisted of eight rows spaced at 0.5 m. Plant to plant distance within a row was 15 cm.

The experiment was laid out as a split-plot design with eight dates of sowing, as the main plots and three varieties as subplots (Table 1). The sowing date of 3/11/2017 (affected by water logging) and 13/03/2018 (affected by frost) were excluded from analysis.

The research site had sorghum grown in the previous season. The research site was rotary hoed twice to a depth of 15 cm. Basal fertiliser 'Incitec Pivot Fertilisers®', 'CK-88' (N:P:K:S = 15.1:4:11.5:13.6) was applied 30 days before planting (200 kg/ha).

**Table 1.** Details of field experiments conducted in season 2017/18 and 2018/19 at the University of Queensland's Horticultural Research Farm at Gatton, Queensland.

| Season | Sowing date | Genotypes |
|---|---|---|
| **2017/2018** | 3/11/2017 | Quest, QPL1001 & ICP 14425 |
| | 6/12/2017 | |
| | 9/01/2018 | |
| | 16/02/2018 | |
| | 13/03/2018 | |
| **2018/2019** | 10/10/2018 | Quest, QPL1001 & ICP 14425 |
| | 15/11/2018 | |
| | 20/12/2018 | |

Plots were inoculated with 'Nodule-N®' immediately after sowing by adding inoculum + water suspension (10 g/5 L water). A drip irrigation system was set up using 'T' tapes (Rivulis®, 340 LPH/100 m at 0.55 BAR) and irrigated weekly in summer (Nov to March) and reduced to fortnightly from April to June. A pre-emergent herbicide (*Pendimethalin 440 EC*) was applied within 48 hours of sowing, followed by mechanical weeding as necessary. When 80% of pods turned brown, plants from 2 $m^2$ were harvested at ground level and mature pods were separated and dried at 35°C in a well-ventilated oven for seven days. Dried pods were threshed into seeds, and seed weight recorded.

**Results and Discussion**

***Environmental characterization***

Maximum and minimum air temperatures, photoperiod and in-crop rainfall varied due to different sowing dates. The monthly mean air temperature was consistently lower in season 2018/2019 as compared to 2017/2018. The highest pre-flowering mean maximum temperature was recorded in 20/12/2018 with 34.5°C, whereas the post-flowering maximum temperature (33.3°C (Table 2)) was highest for the 15/11/2018 sowing date. The in-crop rainfall varied between sowing dates. In season 2017/2018, the crop received a significantly higher average rainfall of 681.6 mm distributed throughout the experimental growing season as compared to the 2018/2019 which received a low 297.2 mm (Table 2). The highest cumulative incident radiation from emergence to maturity in 2017/2018 and 2018/2019 was 2862 and 2249 $MJ/m^2$, respectively (Table 2).

**Table 2.** Seasonal growing season changes in cumulative growing season day degree (GDD), daily mean, minimum and maximum temperatures, diurnal temperature variation, photoperiod, rainfall and solar radiation in seasons 2017/2018 and 2018/2019 for pigeonpea sown at specified dates in the field experiments conducted at the University of Queensland, Gatton Campus.

| Sowing date | GDD (°Cd) | $T_m$ (°C) | $T_{min}$ (°C) | $T_{max}$ (°C) | PP (Hrs) | Rainfall (mm) | Radiation ($MJ/m^2$) |
|---|---|---|---|---|---|---|---|
| 6/12/2017 | 1943 | 24.3 | 18.5 | 31.4 | 13.4 | 356.6 | 2862 |
| 9/01/2018 | 1683 | 22.4 | 16.6 | 29.6 | 13.1 | 287.8 | 2512 |
| 16/02/2018 | 1259 | 19.3 | 13.6 | 26.5 | 12.6 | 273.0 | 2045 |
| 13/03/2018 | 994 | 17.6 | 11.3 | 25.4 | 11.4 | 62.2 | 1916 |
| 10/10/2018 | 2027 | 25.0 | 17.8 | 32.6 | 13.6 | 223.2 | 2238 |
| 15/11/2018 | 1610 | 25.8 | 19.0 | 33.2 | 13.5 | 172.0 | 2249 |
| 20/12/2018 | 1987 | 24.7 | 18.1 | 32.0 | 13.3 | 181.4 | 1875 |

† '$T_m$' = Mean temperature, '$T_{min}$' = minimum temperature, '$T_{max}$' = maximum temperature, 'PP' = Photoperiod, 'Environment' = time of sowing, 'GDD' = Cumulative Growing season day degrees.

**AMMI analysis**

The AMMI conjoined analysis of variance for yield (t/ha) showed a significant genotypic (G) and environmental (E) main effect as well as interaction effects (G × E) (***P < 0.001 and ** P < 0.01) with a low coefficient of variation of 10.9% (Table.3). The significant G × E confirmed the differential performance of pigeonpea varieties across different environmental conditions, as reported by Laxman et al. (1990) and Chauhan (1998).

The results confirmed that further analysis could be proceeded with based on the presence of G × E. The first two principal components (PC1 and PC2) were significant with P < 0.01. PC1 explained 84.3% of the variability; the proportion attributed to PC2 was 15.7%. Thus, PC1 and PC2 together explained total variability (100%). The other principal components were insignificant and considered as noise and pooled with residuals. The biplot (Figure 1) was plotted against PC1 and yield.

**Table 3.** Analysis of variance of yield of pigeonpea varieties and sum of squares decomposition and their level of significance at (***P < 0.001 and **P < 0.01).

| Source of variation | Df | SS | MS | F-value | Pr (>F) |
|---|---|---|---|---|---|
| Environment (E) (87%) | 5 | 59.89 | 11.9 | 216.5 | < 0.001*** |
| Replicate (E) | 15 | 0.83 | 0.05 | 0.8 | 0.70$^{NS}$ |
| Genotype (G) (11%) | 2 | 2.95 | 1.47 | 20.4 | < 0.001*** |
| G × E (2%) | 10 | 2.38 | 0.23 | 3.3 | < 0.01** |
| PC1 (84.3%) | 6 | 2.11 | 0.35 | 4.8 | <0.01** |
| PC2 (15.7%) | 4 | 0.39 | 0.09 | 1.4 | < 0.01** |
| Residuals | 30 | | | | |
| Grand Mean (t/ha) | 2.8 | | | | |
| CV (%) | 10.9 | | | | |

Genotypes and environments closer to the center have smaller G × E. It shows that the mean grain yield of the varieties can be ranked as Quest > ICP 14425 > QPL 1001. Among these varieties, ICP 14425 was the more stable variety than Quest and QPL 1001 because it lies closer to the first principal component, which explains most of the variability (84.3%) (Figure 2).

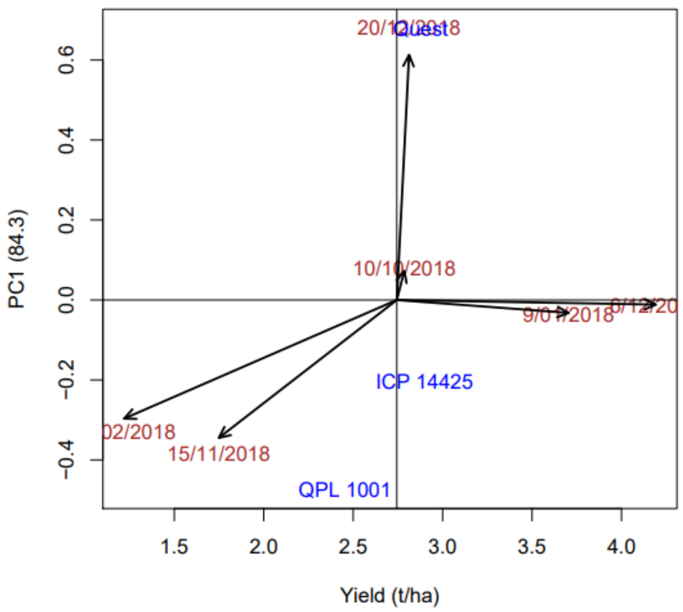


**Figure 1.** AMMI biplot for (PC1 vs Yield) for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

The environment with the highest yield was 6/12/2017 and followed by 9/01/2018. The yield obtained from the 6/12/2017, 09/01/2018, 10/10/2018 and 20/12/2018 sowing environments were greater than the mean yield across the environment. The lowest-performing sowing environments were 16/02/2018 and 15/11/2018 (Figure 1).

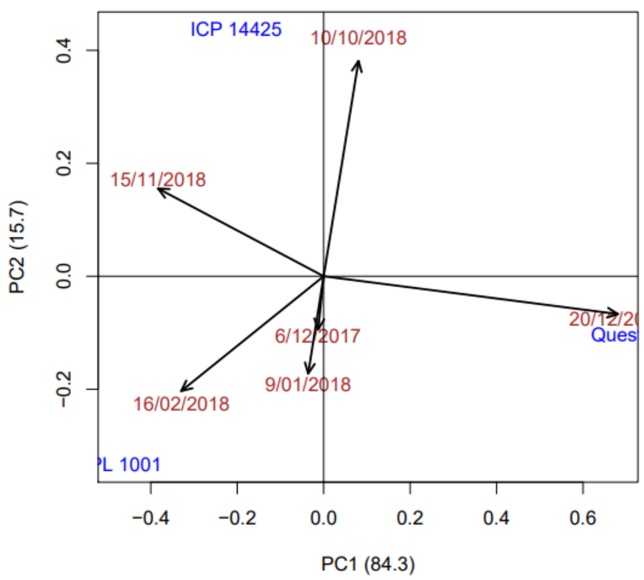


**Figure 2.** AMMI biplot for (PC1 vs PC2) for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

The most stable environments corresponded with the sowing dates were 6/12/2017, 9/01/2018 and 10/10/2018 (Figure 2). Adaptation of genotypes to various environmental conditions appears associated with different sowing dates. For instance, ICP 14425, an indeterminate type, is more stable than Quest and QPL 1001, which are determinate types. Chauhan (1998) also found differences in the adaptation of determinate and indeterminate varieties. The presence of indeterminateness might provide greater environmental plasticity allowing the crop to be a better fit for a wider range of environments.

**GGE Biplot analysis**

Since PC1 and PC2 explained 100% of total variability among other principal components, these two components were used to visually represent the data. When characterising the environments according to the genotypic performances, the most stable sowing environment for these genotypes was 16/02/2018, followed by 09/01/2018 and 6/12/2018 since these environments fell within the concentric rings of the biplot (Figure 3). On the other hand, the environments 15/11/2018, 10/10/2018 and 20/12/2018 were relatively less stable and 20/12/2018 was the least stable environment.

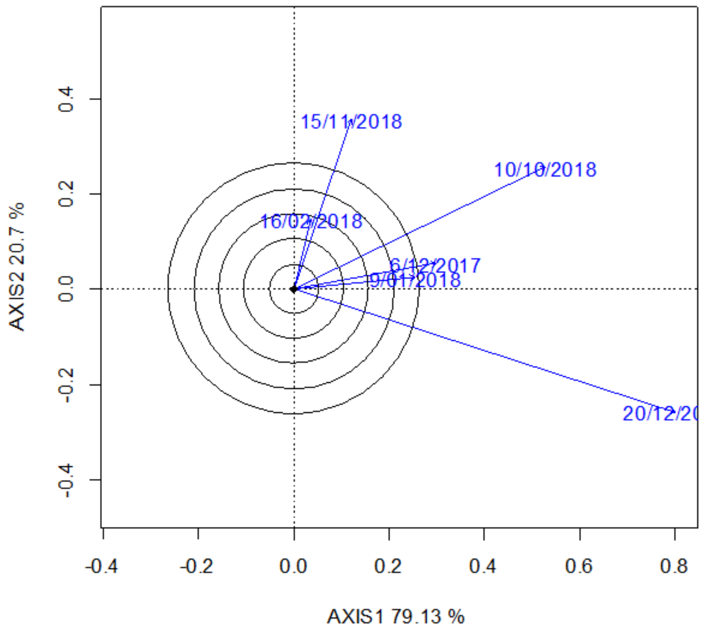


**Figure 3.** AMMI biplot for environmental characterisation for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

The “Which won Where” plot allowed visual grouping of environments based on G × E on yield. The vertices of the triangle comprise genotypes and six environments which were clustered into three mega environments (Figure 4).

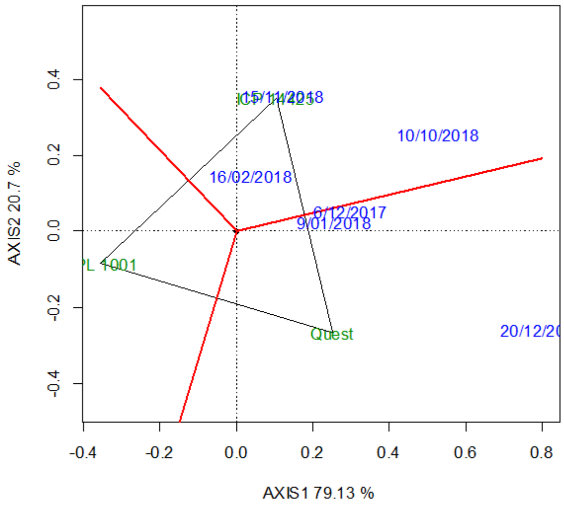


**Figure 4.** "Which won where/What" GGE biplot for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

As for relative performances across environments, variety Quest was in the vertex of the mega-environment formed by 6/12/2017, 9/01/2018 and 20/12/2018 indicating that this variety had the highest yield in these environments. Similarly, variety ICP 14425 was the best variety in the mega-environment formed by 16/02/2018, 10/10/2018 and 15/11/2018. However, variety QPL 1001 was in a region with no allocated environment, which means it performed relatively lower in all the environments, perhaps be due to its genetic potential. The model allows individual genotypes to be assessed for their relative yield performance in each environment and unique temperature and photoperiod regimes (Figure 4).

The "Mean vs Stability" GGE biplot (Figure 5) allowed the evaluation of varieties by their yield and stability characteristics. The blue circle in the middle represents the mean environment, an 'ideal' environment created on coordinated means of all the environments. The green line with the arrow indicates the mean environmental axis and the direction in which the arrow points to a higher mean yield. The second axis represents genotypic stability, where the varieties closer to the origin are more stable (Neisse et al., 2018).

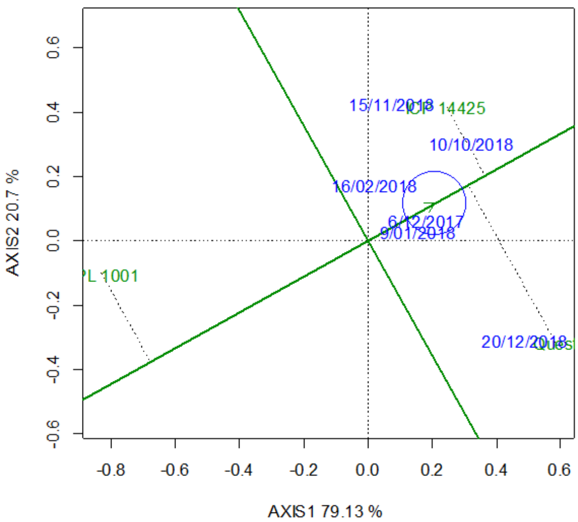


**Figure 5.** "Mean vs stability" GGE biplot for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

According to Figure.5, the mean yield of the varieties was QPL 1001 < Genotypic Mean < Quest < ICP 14425. Among the three varieties, ICP 14425 was the most stable and Quest was the most unstable variety. The instability in Quest was due to its good performance at the 20/12/2018 time of sowing compared to the other sowing environments, whereas ICP 14425 constantly performed in all the environments. Results indicated that the varieties with the highest yield potential were not always most stable, particularly in challenging seasons.

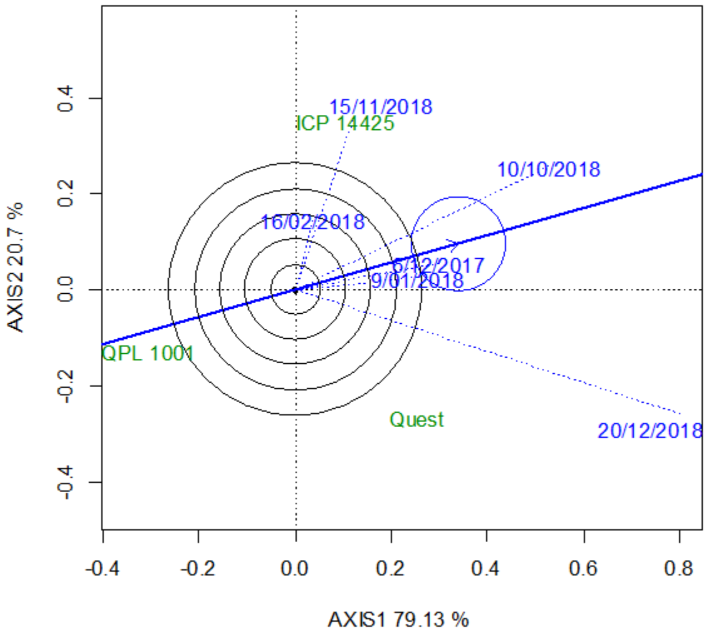


**Figure 6.** "Discriminativeness vs representativeness" GGE biplot for the environments.

The "discriminativeness vs representativeness" GGE biplot evaluates the environments to identify superior varieties for a mega-environment. In the present analysis, environments with shorter vectors (16/02/2018, 6/12/2017 and 9/01/2018) discriminate less for varieties, and all the varieties tend to perform equally in those environments (Figure 6). On the other hand, the sowing environments 15/11/2018, 10/10/2018 and 20/12/2018 had long vectors and high discriminativeness for varieties. Alternatively, an environment with a smaller angle with a mean-environment axis has higher representativeness. Therefore, the sowing environments 6/12/2017 and 9/01/2018 had a shorter vector and narrower angle than other environments and should be recommended as highly productive and stable environments for tested varieties.

Comparing AMMI and GGE biplot analysis, AMMI retained 84.3% and 15.7% for PC1 and PC2, and GGE biplot retained 79.13% and 20.7%, respectively. The sum of total variation retained by both PC1 and PC2 was similar. This result was consistent with other studies performed by Hongyu *et al*. (2015) and Neisse *et al.* (2018). The GGE biplot explains only a fraction of the total variability, there is a possibility to evaluate a variety as stable if its variability is not significantly explained by both principal components.

**Conclusion**

The combination PCA and GEE biplot analysis allowed environments to be analysed based on their unique temperature and photoperiod regimes and assess the relative performance of individual genotypes across growing environments. The analysis revealed that ICP 14425 constantly outperformed in all the environments and was considered as the most stable genotypes compared to Quest and QPL 1001. QPL 1001 moderately performed in all the environments. Alternatively, the environments 6/12/2017 and 9/1/2018 were highly productive and stable environments for these genotypes.

**References**

Chauhan YS, Wallace DH, Johansen C, Singh L (1998) Genotype-by-environment interaction effect on yield and its physiological bases in short-duration pigeonpea. Field Crop Research 59, 141-150.

Hogh Jensen H, Myaka FA, Sakala WD, Kamalongo D, Ngwira A, Vesterager J, Odgaard M, Adu Gyamfi JJ (2007) Yields and qualities of pigeonpea varieties grown under smallholder farmer' conditions in Eastern and Southern Africa. African Journal of Agricultural Research, 2, 269-278.

Joshi VC, Acharya S, Patel JB, Vaghela KO (2011) Genotype x Environment Interaction for Grain Yield in Pigeonpea. Annals of Arid Zone, 50, 163-165.

Neisse AC, Kirch JL, Hongyu K (2018) AMMI and GGE Biplot for genotype × environment interaction: a medoid–based hierarchical cluster analysis approach for high–dimensional data. Biometrical Letters, 55, 97-121.

Padi F (2003) Correlation and Path Coefficient Analyses of Yield and Yield Components in Pigeonpea. Pakistan Journal of Biological Sciences, 6.

Rachaputi CNR, Motuma Bedane G, James Broad I, Sepp Deifel K (2018) Genotype, Row Spacing and Environment Interaction for Productivity and Grain Quality of Pigeonpea (Cajanus cajan) in sub-tropical Australia. Biosciences, Biotechnology Research Asia, 15, 27-38.

Santos PR, Oliveira TRA, Skeen P, Nascimento MR, Costa KDS, Araújo ER, Pereira HS, Costa AF (2019) GGE Biplot and REML/BLUP based-analysis of yield stability and adaptability for common beans in multi-environment trials. Revista Brasileira de Ciências Agrárias - Brazilian Journal of Agricultural Sciences, 14, 1-8.

Simtowe F (2012) Determinations of Agricultural Technology adaptation: the Case of Improved Pigeonpea Varieties in Tanzania. Alliance for Green Revolution in Africa.

Yau SK (1995) Regression and AMMI Analysis of Genotypes x Environment Interactions: An Empirical Comparison. Agronomy Journal, 87, 121-126.

**Acknowledgements**

I would like to acknowledge the financial support of the Australian Government and University of Queensland through the “Australian Government Research Training Program Scholarships”.

**Contact details**

Dr Mahendraraj Sabampillai
Queensland Alliance for Food and Agricultural Innovation
The University of Queensland, Gatton, QLD 4343, Australia
Email: m.sabampillai@uq.edu.au

**Date Published**

March 2023

® Registered trademark