Journal of Applied Research on Medicinal and Aromatic Plants 41 (2024) 100555

Contents lists available at ScienceDirect

Journal of Applied Research on Medicinal and Aromatic Plants

journal homepage: www.elsevier.com/locate/jarmap

Predictive power of YREMs and BLUPs for selecting superior genotypes in perennial crops: A black pepper case study

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ARTICLE INFO

Keywords:
Selection
Stability
Genotype-by-year interaction
BLUP
YREM

ABSTRACT

Black pepper (*Piper nigrum* L.), a highly sought-after spice crop with medicinal properties, requires careful evaluation and selection due to its perennial nature and associated resource requirements. Being a perennial, yield trials across years are feasible and practical in this crop rather than that across locations. However, parameters to assess the yield trial data and/or derive criteria to select superior cultivars with stable performance are lacking in black pepper. In this study, we examined the genotype-by-year interaction (GYI) pattern and its impact on black pepper yield, as well as the selection parameters for identifying stable and high-yielding cultivars. Average Yield Relative Environment Maximum (YREM) and Best Linear Unbiased Predictor (BLUP) emerged as the most effective measures for evaluating cultivar performance, as they accounted for relative yield and stability. Among the evaluated cultivars, OPKM displayed better stability estimates. However, considering high mean yield along with all the stability estimates, the HP 2173 ranked first. Notably, even with single-location multi-year trial data, the single-year YREM and BLUP values showed significant predictive power for future performance which is most preferred in perennial crops. Additionally, the use of multi-year average performance (YREM and BLUP) as quantitative criteria for selecting or rejecting genotypes in future breeding programs proved to be effective.

1. Introduction

Black pepper is the one of the commercial culinary spice crops with medicinal benefits (Khew et al., 2022). It not only adds taste and improves digestion but also has anti-oxidant, anti-cancerous and anti-microbial properties (Takooree et al., 2019). Thus, there is substantial expansion in the global demand for this spice crop and is a potential exchange earner for India. Changing climate has worsened black pepper productivity rendering it sensitive to different environmental conditions and abiotic stresses (De Carvalho et al., 2023).

In black pepper, achieving high yield without compromising quality is a crucial aspect for releasing improved varieties. Crop improvement programs primarily aim to deliver enhanced varieties, and this necessitates the critical evaluation and identification of genotypes that outperform others. The main challenge in plant breeding lies in making selections when only limited information is available, as is often the case. Field evaluation trials for perennial crops, such as black pepper, are costly and require significant time, space, and resources compared to annual crops (Neale and Kremer, 2011). The constraints imposed by these factors make it difficult to evaluate all desired varieties in the same trial and under different environmental conditions. Therefore, conducting evaluations over multiple years becomes an option, considering the variability in environmental conditions across years.

The selection of appropriate procedures for analysing yield trial data plays a pivotal role in improving the efficiency of plant breeding and identifying superior cultivars. It is important to adapt certain concepts from annual crop trials to the evaluation of perennial crop yields and understand their suitability in the perennial system. The analysis of yield trial data and the application of relevant methodologies can enhance the breeding process and aid in the identification of superior cultivars. Selecting suitable varieties in perennial crops is of utmost importance because once planted, these crops remain in the field for a long duration, yielding annually. The replacement of varieties in perennial crops is challenging and often not economically viable. In the perennial crop like

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https://doi.org/10.1016/j.jarmap.2024.100555

Available online 20 May 2024
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black pepper, the long-term performance of a variety becomes of prime importance. A desirable variety should exhibit consistent yield without off-season fluctuations, ensuring a continuous production cycle without periods of low productivity (year on/year off).

It is a known fact that performance/phenotype (P) of an individual genotype depends on its genetic makeup (G), environment (E) and GEI. Better understanding of the genetic architecture and interaction with environment is required. In this regard, conducting Multi-Environment Trials (MET) and analyzing the Genotype × Environment Interaction (GEI) has become a necessity. Temporal environments are highly unpredictable and variable among genotypes (Annicchiarico et al., 2006). Further, evaluation of genotypes across years is considered most reliable (Yan and Rajcan, 2003). Thus, breeding for genotypes stable across temporal environments is challenging rather than spatial environments. Although superior genotypes specific to a location are adopted by the farmers, their stable performance across seasons/ year's holds preference (Spoorthi et al., 2021) especially in perennial crops like black pepper. Further, large GEI due to environments require more resources for establishment of new research station and its maintenance compared to evaluation over years (Kang, 2002).

Additive main effects and multiplicative interactive effects stability analysis model (AMMI) and biplots are widely used to assess the stability of genotypes and pattern of GEI (Mahadevaiah et al., 2021). Only available literature on the pattern of GEI and stability analysis in black pepper using Eberhart and Russel model dates back to 1985 (Ibrahim et al., 1985). Of late, Best Linear Unbiased predictor (BLUP) is increasingly used in assessment of genotype's performance across years and/or locations as it corrects for environmental effects (Piepho et al., 2008). BLUP is considered as a good predictor of genotypic value of the cultivar tested, considering genotype as random effect in mixed model (Piepho et al., 2008). It is likely that yield trials across different environments may result in an unbalanced data. In such scenarios, BLUP can be used to compare genotypes across environments. Further, BLUP can be used to shrink data across environments and used in prediction of genotype performance in the future (Spoorthi et al., 2021).

Further, Yield Relative to Environment Maximum' (YREM) is yet another measure which measures relative yield as against absolute yield. As it is relatively independent of a genotype's attendance, it is proposed as a good predictor of genotype performance in MET (Yan, 1999). Genotype with maximum yield in a given year is taken as reference to estimate YREM of all the genotypes. Hence, YREM of the genotype with maximum yield in any given year will be one (=1). This estimate is relatively independent of genotypes' attendance. Maximum yield captures the environmental effect and thus YREM is a standardized measure in which the environmental effect is removed (Yan, 1999).

Although black pepper yield in response to changes in weather has been modeled (Kandiannan et al., 2011), much of the research in black pepper has been focused on improving the yield and quality rather than stability. In this regard, integrated measures of yield and stability such as stability index (SI) derived using AMMI model and stability-modified yield (YS) derived using average YREM have significance. Further, few researchers reported that the genotypes' performance across multiple years is better predictor of their future years or years' performance (Ma and Stützel, 2014; Yan and Rajcan, 2003). However, multi-year trials have practical limitations disturbing timely selection of parent(s) or cultivar(s) (Spoorthi et al., 2021). Therefore, it is important to determine the minimum number of years of cultivar evaluation sufficient to give better prediction of future years' performance. If it is possible to predict performance of a genotype with single-year or two-years testing, then we can save the resources and time involved in multi-year testing.

The productivity of black pepper is influenced by changing environmental conditions, necessitating the identification of genotypes that excel across different environments. Traditional breeding methods rely on costly and time-consuming field evaluations, making it challenging to assess all desired varieties under various conditions. Therefore, multi-year trials are essential for evaluating genotype performance and stability over time. To address this, we employed the AMMI model and BLUP analysis, which have proven effective in assessing genotype stability and genotype-by-environment interactions. Despite limited research on stability analysis in black pepper, integrated measures like stability index (SI) and stability-modified yield (YS) are valuable for evaluating yield and stability concurrently. We also investigated whether single-location single-year YREM and BLUP values could predict future performance, aiming to streamline genotype selection processes and optimize resource allocation in black pepper breeding programs, with this background, in our present study we hypothesized and tested that (1) yield performance of black pepper genotypes alters with the temporal environment, (2) BLUP and YREM are reliable estimates to evaluate genotypes' performance across years, and, (3) single-location single-year YREM and BLUP for yield are potential predictors of their performance in future years in black pepper.

2. Material and methods

The experimental material comprised ten genotypes, including five hybrids, one germplasm accession, two open-pollinated progenies, and two IISR released varieties utilized as controls (Shivakumar et al., 2020) (Supplementary Table 1). The experiment was conducted at the ICAR-Indian Institute of Spices Research (IISR) Experimental Farm in Peruvannamuzhi, Kozhikode, Kerala, India (11°36′34″N 75°49′12″E), over the years 2017–18, 2018–19, and 2019–2020. The experimental design was a Randomized Block Design with three replications, each consisting of 10 plants spaced at 4 m × 4 m intervals. Yield assessments were conducted by recording dry berry yield per vine from five randomly selected plants per replication. Standard agricultural practices were followed to ensure optimal crop growth and development (Devasahayam et al., 2015).

2.1. Statistical analysis

The data recorded from three replicates of each genotype in each year was used for the statistical analysis. Year-wise analysis of variance (ANOVA) was performed using Genstat version 16.0 software. The error mean squares across three years were tested for homogeneity using Levene's test and found homogenous.

2.2. GGE biplots

If significant differences in genotype-environment interaction were observed, GGE biplot analysis was employed to assess interaction and yield stability (Yan, 2001). The GGE biplot was constructed using the first two principal components (PC1 and PC2) derived from environment-centered yield data. Genstat version 16.0 software was utilized for GGE biplot analysis. Scores of PC1 were plotted against PC2 in the GGE biplot analysis. The GGE biplot was further utilized to generate graphs for mean performance and stability analysis, discrimination and representativeness of test years, mean vs. stability, which-won-where/what patterns and ranking genotypes. Angles between year vectors in the GGE biplot were used to assess the correlation between pairs of years.

2.3. AMMI analysis

Additive main effects and multiplicative interactive effects stability analysis model (AMMI) analysis were performed to assess genotype (*G*) and year (*Y*) main effects, and multiplicative effect of genotype × year interaction (*GYI*). The data across three years was pooled to perform stability analysis using *AMMI-2* model (Gauch, 2013) implemented in Genstat version 16.0. Stability of the genotypes was assessed based on AMMI Stability Value (ASV) calculated as,

$$V = \sqrt{\left[\frac{SSIPCA1}{SSIPCA2}(IPCA1Score)\right]^2 + (IPCA2Score)^2}$$

Where, SSIPCA1 and SSIPCA2 are the sum of squares of the IPCA1 and IPCA2 (i.e. first two IPCs), respectively. Further, 'stability index' (SI) was estimated to measure yield in relation to stability. Stability index for a genotype is given by, SI=rASV+rY, where, rASV is the rank of the genotype based on ASV and rY is the rank of the genotype based on yield.

2.4. Estimation of YREM

The yield relative to environment maximum (YREM) (Yan, 1999) was given by $Y_{ij}= \bar{X}_{ij}/ MAX_j$, where, for a given black pepper genotype *i*, Y_{ij} and $\bar{X}_{ij}$ are the YREM and mean yield in the year *j*; while MAX_j is the maximum yield (for any genotype) observed in the year j. It takes the value from 0 to 1 and is devoid of the environmental effect. The performance of a given genotype in any single year was measured by its 'yearly YREM' while that in n-years was measured by its 'n-year YREM'. 'n-year YREM' is the average of the 'yearly YREM' of a genotype across the years. Within the tested years, the minimum and maximum of the yearly YREM denotes 'minimum yearly YREM' and maximum yearly YREM', respectively.

Stability modified YREM (YS_i) is a derivative of YREM that integrates YREM and stability (S_i) and measures stability relative to average yield (Yan, 1999). Stability index for the genotype *i* is given by, $S_i= \bar{Y}/(\bar{Y}+ws_i)$, where $\bar{Y}$ is grand mean of YREM across years; *w* is the weight given by the breeder as per his attitude towards risk; s_i is the standard deviation of YREM for genotype *i*. S_i can take the values from 0 to 1 and can be used to calculate stability modified yield or stability modified YREM (YS_i) as per breeder's interest. Stability modified YREM (YS_i) of the genotype *i* was estimated as the product of average yield *(Y)* and the stability of the genotype *i* (S_i) (Yan, 1999). The YREM and Stability modified YREM were calculated using Microsoft office Excel version 2402.

2.5. Estimation of BLUP

BLUP is a popular and reliable method of analyzing multi-environment trials (Olivoto et al., 2019). BLUP of genotypes were estimated using the statistical model, $Y_{ij}= \mu+g_i+y_j+gy_{ij}+e_{ij}$, where, Y_{ij} is the yield of black pepper genotype *i* in the year *j*; $\mu$is trial mean; g_i is the main effect of the genotype *i*;y_j is the main effect of the year *j*;gy_{ij} is the interaction between genotype *i* and year *j*; e_{ij} is the residual associated with the *i* genotype and *j* year. The trial mean (μ) was declared as fixed effect while all other effects were considered as random. BLUP was estimated using residual maximum likelihood (REML) method implemented in META-R software from CIMMYT (Alvarado et al., 2020).

2.6. Predictive power of BLUP and YREM

Predictive power of single year YREM and/or BLUP was measured using correlation coefficient between the YREM and BLUP of one year with that of the following years. Similarly, predictive power of multiple years' data was assessed by the correlation coefficient between BLUP and average YREM estimated from data of a number of previous years and the data from the present/ current year (Spoorthi et al., 2021; Yan and Rajcan, 2003).

2.7. Criterion to select superior genotypes

Minimum yearly YREM and BLUP as well as maximum yearly YREM and BLUP of ten black pepper genotypes within the tested years was regressed against their 3-year YREM and BLUP. Coefficients of determination were estimated using the linear regression equation. Further, threshold minimum yearly YREM and BLUP and the maximum yearly YREM and BLUP were estimated using 3-year mean +1 SD using the linear regression equation (Spoorthi et al., 2021). Genotypes with less than threshold minimum yearly YREM and BLUP were less adapted while the genotypes with threshold maximum yearly YREM and BLUP were more adapted cultivars (Yan, 1999).

3. Results and discussion

3.1. Variance distribution among G, Y and GYI

The ten black pepper genotypes/cultivars considered in the study varied significantly among themselves across the multi-year evaluation for yield (Supplementary table 2). The temporal environments represented by three consecutive years differed significantly. The cultivar performance was influenced by the temporal environments (Table 1). The genotype main effects contributed predominantly towards total variation. However, 27.81 % of total variation was attributable to GYI. Further, variation attributable to GYI was majorly captured by the first IPC (Interaction Principal Component) to an extent of 99 %. Significant contribution of genotype main effects to the total variation suggested broad adaptation or stability. In contrary, prevalence of narrow adaptation or instability among the genotypes was depicted by the significant GYI (Gauch Jr., 2013). These results indicated that the ten genotypes considered in the study included those with both wide and narrow adaptation providing opportunities for the breeder. Since GYI is considered, the environmental variables corresponding to a particular year might be involved in specific adaptability of the genotypes to that year. Three of the genotypes namely, HP 728, HP 780 and OPKM showed lower AMMI stability value (ASV) which indicated them as stable genotypes. However, as per the stability index which combines both yield and stability, HP2173 showed stable high yield followed by OPKM and Thevam (Table 2).

3.2. GGE biplots

GGE biplots help in qualitative assessment of the stability of genotypes to a given environment/ year through graphical representation of genotypes being scattered based on their respective IPC scores (Li et al., 2017). Thus, relationship among the environments and the relationship between genotypes can be visualized through different biplots. Length of the year's vector and angle between the year's vector and average environment coordinate (AEC) are used to infer on the discriminating ability and representativeness of the years using *Discriminating ability and representativeness GGE biplot* (Fig. 1a). The three temporal environments defined by the years 2018, 2019 and 2020 did not vary vastly as depicted by the acute angle between respective year's vector with ASC. Further, lengths of the vectors across three years were relatively similar and longer indicating similarity of the environments in discriminating the genotypes. The arrowed line passing through the origin of biplot is the AEC and the year 2019 was average environment represented with small circle on AEC (Fig. 1a). *Mean yield vs. stability GGE biplot* aids in assessing the genotype's performance relative to their stability. The single arrowed AEC is directed towards higher mean yield across years and hence genotypes facing towards arrow have higher yield than those which are opposite to the arrow. In our study, HP2173 showed higher mean yield among all the genotypes tested. Further, the genotypes are projected from AEC line at variable lengths based on their relative stability. Shorter the length of the projection of a genotype, greater will be its stability and vice-versa. In the present study, HP1411, HP780 and Coll820 were highly stable with their points projective on the AEC followed by Coll1090 (Fig. 1b).

Which won where/what GGE biplot offers an advantage of determining the mega-environments indicating the presence or absence of cross-over GEI (Fig. 1c) (Yan and Rajcan, 2002). Although it is more suitable for discerning spatial environments, valid inferences could be drawn from single-location multi-year data if the breeder has noted for

Table 1
AMMI Analysis of variance of black pepper genotypes for yield.

Source	Degrees of freedom	Sum of squares	Per cent contribution	Mean squares	F statistic	P value
Genotypes (G)	9	116.89	55.10	12.988	152.94	<0.001
Year (Y)	2	36.27	17.10	18.133	240.75	<0.001
Genotype × Year (GYI)	18	58.99	27.81	3.277	38.59	<0.001
IPCA 1	10	58.49	99.15 of GYI SS	5.849	68.88	<0.001
IPCA 2	8	0.5	0.85 of GYI SS	0.063	0.74	0.6575
Residuals	0	0	-	-	-	-
Error	54	4.59	-	0.085	-	-

Table 2
Yield and stability parameters of the ten black pepper genotypes.

SL. No.	Genotype	Mean yield ()	ASV	SI (AMMI)	YS_i	Average YREM	BLUP across 3years
1	Coll1090	0.82	0.77	19	0.91	0.24	1.17
2	Coll820	1.30	0.52	15	1.49	0.34	1.53
3	HP1411	2.48	0.32	8	3.16	0.61	2.41
4	HP2173	**4.89**	2.32	11	**5.41**	**0.95**	**4.21**
5	HP728	1.61	**0.18**	9	1.93	0.38	1.76
6	HP780	2.24	**0.18**	**6**	2.80	0.56	2.23
7	OPKM	**3.16**	**0.29**	**5**	**4.29**	**0.79**	**2.92**
8	P24o4	1.01	0.46	15	1.11	0.26	1.31
9	Sreekara	1.89	0.65	14	2.37	0.52	1.97
10	Thevam	**2.65**	0.43	**8**	**3.34**	**0.69**	**2.54**

environmental variables specific to those years. *Which won where/what GGE biplot* equality lines divides the biplot in sectors with a polygon view. The genotype at the vertex of the polygon in each sector is the winning genotype for the year(s) marked within that sector. Among the three years, 2019 and 2020 were in the same sector where HP2173 was projected as winning genotype. Similarly, the genotype OPKM was the winning genotype during 2018 (Fig. 1c). These results indicated that the environmental variables during 2018 varied from that during 2019 and 2020. *Ranking the genotypes* relative to an ideal genotype placed at the center of concentric circles in the GGE biplot provides insights for their selection. An ideal genotype has high mean and high stability, indicated as the point on AEC (wide adaptation) in the GGE bi-plot in the positive direction and has a vector length equal to the longest vector of the genotypes on the positive side of AEC (Anilkumar et al., 2018). In our study, OPKM was adjudged as ideal genotype. Further, the genotype Thevam was considered as desirable genotype which is placed near to the ideal genotype (Fig. 1d).

3.3. Selection of genotypes with stable high performance

Several parameters have been developed for the selection of genotypes based on both high mean yield and high stability across years. In the present study, we compared the ranking of ten genotypes based on different parameters such as mean yield, ASV, AMMI stability index (SI), 3-year YREM, BLUP and stability modified YREM. The genotype OPKM was among the top three ranks according to all the parameters (Table 2).

According to SI (AMMI) derived from the cumulative ranks of ASV and mean yield, four genotypes namely, OPKM, HP780, Thevam and HP1411were stable high performers. Further, the genotype HP2173 showed moderate stability and it was the best yielding genotype across three years. However, the genotype Coll1090 was the poor performer with unstable performance.

The temporal environments represented by multi-year trials are highly unpredictable. Yield relative to environment maximum (YREM) is a measure which enables quantification of such unpredictable crossover GEI (Mahadevaiah et al., 2021). The genotype with YREM of 1.0 is most stable high yielding cultivar while deviation of YREM from 1.0 is attributed to unpredictable crossover GEI. For example, average YREM of HP2173 is 0.95 which implies that 5 % yield loss is due to unpredictable crossover GEI. HP2173 showed highest YREM followed by OPKM and Thevam. In the study conducted by Shivakumar et al., (2020), the genotypes HP2173, OPKM, and Thevam were recognized as superior in terms of their performance in yield-related traits. Average Stability modified YREM (YS) is a combined measure where average YREM is supplemented with stability parameter. YREM provides reliable measure of a genotype's consistent performance. The ranking of the genotypes based on YS followed similar trend as that based on YREM (Table 2 and Supplementary table 3). Further, the coefficients of determination between genotypes' YREM and yield stability were significantly high i.e. >97 % (Fig. 2). These results imply that the best and poor genotypes identified based on YS are identified by their YREM. In other words, selection based on YREM alone gives the same result as the selection based on YS (Yan, 1999). Thus, YREM alone can be used in cultivar selection without incorporation of stability, which has negligible effect.

BLUP is an estimate which measures the true genotypic value of an individual while correcting for the environmental effects. The BLUP across 3-years also revealed that HP2173, OPKM and Thevam were the stable high yielding genotypes. Interestingly, the mean yield of the genotypes reflected a similar trend of genotypes' ranking. This is because the magnitude of genotype main effects is predominant over the magnitude of GYI as indicated in Table 2.

3.4. Prediction using single year and two-year performance of genotypes

Generally, genotype's performance across multi-location multi-year trials is used to predict its performance in the next year (Yan and Rajcan, 2003). In our study, we tested and compared the predictive power of previous-single year and previous-two-year trials to predict performance of next year. One-year YREM showed better correlation with 3-year YREM than one-year yield with that of average yield across three years (Fig. 3). These results indicated that single-year YREM was a better representative of 3-year YREM than single-year yield. This implied that one-year YREM can be used to predict the performance of genotypes in future years. Further, it also implied that single-location multi-year trials will also provide reliable estimates for the selection of genotypes which is of paramount interest in black pepper, a perennial crop.

The correlation coefficients between present year YREM and BLUP with their previous year YREM and BLUP were comparable and highly significant (Fig. 4).Similarly, correlation coefficients between present year YREM and BLUP (2020) with their previous two-years YREM and BLUP were also highly significant and comparable (2018 and 2019). With respect to the year 2020, the magnitude of correlation coefficients between present year YREM and BLUP with those of previous year (2019) was more than that with those of previous two years (2018 and 2019) (Supplementary table 4).These results indicated that single-year (previous year) YREM and BLUP of genotypes were good predictors of their performance in the succeeding (present) year. Similar results were reported by Spoorthi et al., (2021) in dolichos bean.

3.5. Selection of genotypes based on quantitative criteria

The coefficient of determination between genotypes' single-year performance (YREM and BLUP) and that of independent two years

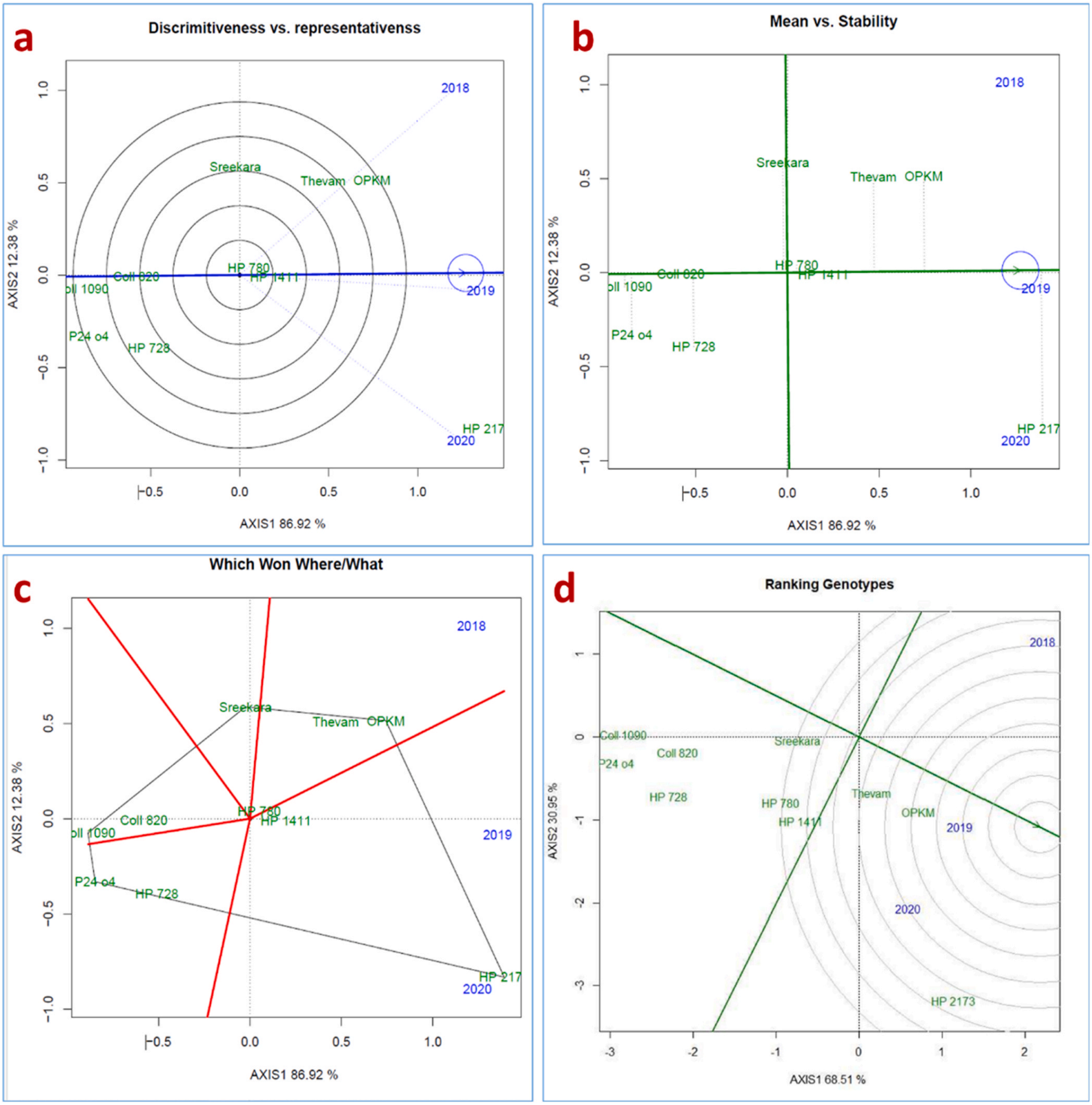

Fig. 1. GGE biplot representing the pattern of genotype × year interaction. a. Discriminating ability and representativeness view; b. Mean performance vs. stability view; c. which won where/what view and; d. ranking genotypes relative to ideal genotype view of GGE biplot.

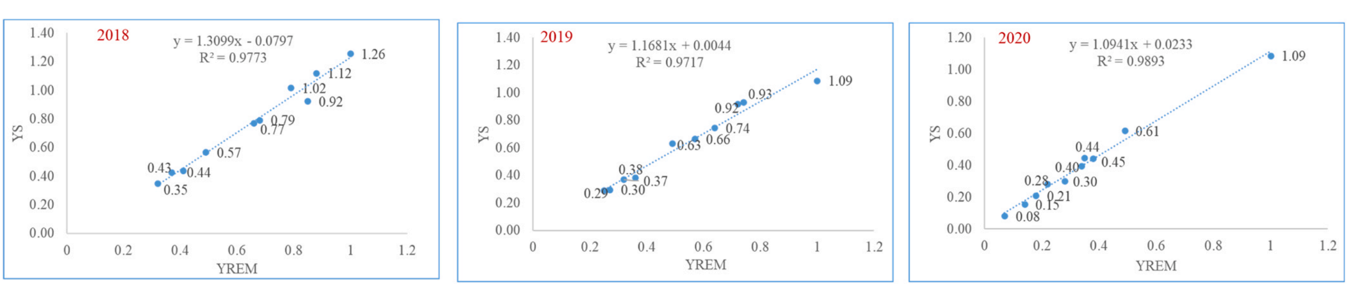

Fig. 2. Relationship between stability-modified YREM and YREM of ten black pepper cultivars.

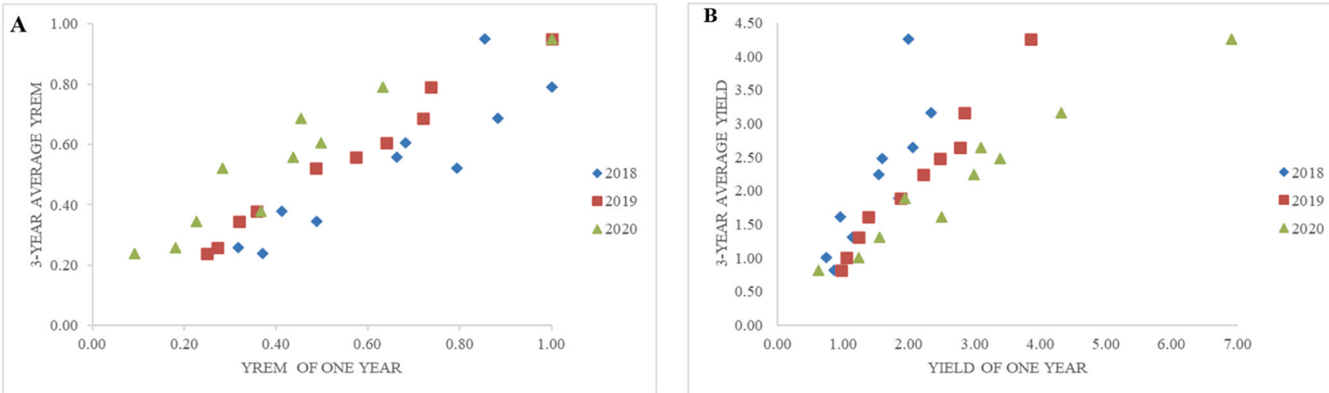

Fig. 3. Relationship between A) one-year YREM with 3-year YREM and B) one year yield performance with average yield across three years.

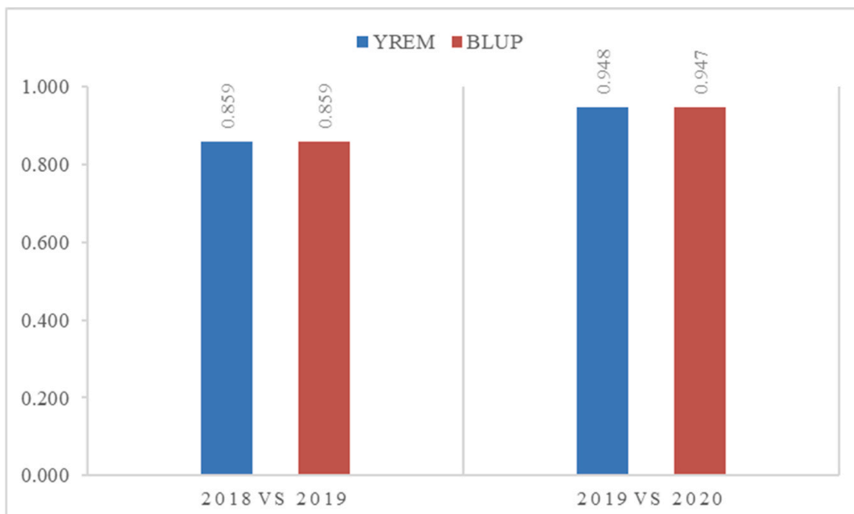

Fig. 4. Estimates of correlation coefficients between previous and next year's YREM and BLUP of black pepper genotypes.

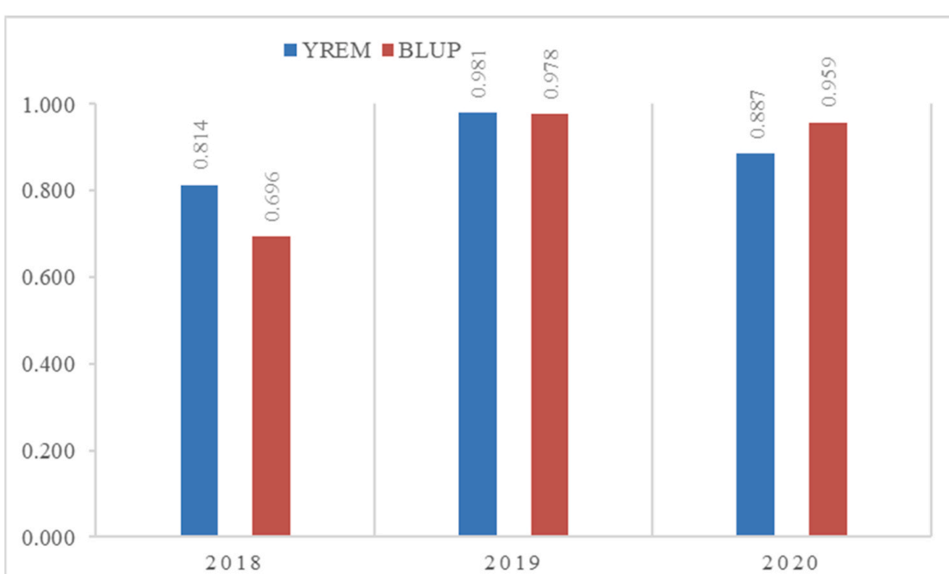

Fig. 5. Estimates of coefficients of determination of one-year YREM and BLUP performance regressed with that of the two independent years.

ranged from 69 % to 98 % (Fig. 5). These results indicated that the genotypes' single –year YREM and BLUP explains at least 69 % of the variation in their performance across multiple years. This provided the impetus to develop a quantitative criterion for the selection of better performing genotypes and rejection of poor performing genotypes. The quantitative criterion was derived by plotting genotypes' 3-year YREM and BLUP against the minimum and maximum yearly YREM and BLUP. The threshold minimum and maximum yearly values corresponded to the genotypes' performance over the years and were thus used as criteria to select or discard the genotypes.

The coefficients of determination between genotypes' 3-year YREM and BLUP with their corresponding minimum yearly values were 92 % and 70 %, respectively (Fig. 6). These results indicated that the genotypes which perform poorly in any single-year is likely to perform poorly across multiple years. Similarly, the coefficient of determination between genotypes' 3-year YREM and BLUP values and their corresponding maximum yearly values were 90 % and 95 %, respectively (Fig. 7). These results indicated that the best performing genotypes identified in any single year is likely to perform better across multiple years. Similar findings were reported by Spoorthi et al., (2021) in Dolichos bean.

The use of three-year average YREM and BLUP in our study provided valuable insights for genotype selection and rejection. We found that genotypes with a three-year average YREM below 0.53 and BLUP below 2.14 kg vine^{-1} were categorized as poor performers. These values corresponded to the minimum yearly YREM of 0.41 and BLUP of 1.50 kg vine^{-1} (Fig. 6). Genotypes falling below this threshold were suggested for rejection, as they were likely to perform poorly in future years. Specifically, Coll1090, Coll820, P24O4, and HP728 were identified as poor performers based on their three-year YREM and BLUP values falling below the respective threshold values. Conversely, genotypes with a three-year average YREM above 0.53 and BLUP above 2.14 kg vine^{-1}, corresponding to the maximum yearly YREM of 0.66 and BLUP of 2.9 kg vine^{-1}, were considered the best performers. Notably, HP2173, OPKM, Thevam, HP1411, and HP780 demonstrated better performance with their three-year YREM and BLUP values surpassing the respective threshold values. Similar results were reported in crops like wheat and Dolichos bean (Yan, 1999; Spoorthi et al., 2021). When breeders are faced with the challenge of evaluating a large number of genotypes in multi-environment trials, limited resources may prevent the inclusion of all genotypes in further breeding efforts. Traditional breeding methods for perennial crops often involve a long evaluation period, which can delay the identification and release of superior genotypes (Van Nocker and Gardiner, 2014). However, the use of advanced statistical approaches like YREM (Yield Relative Environment Maximum) and BLUP (Best Linear Unbiased Prediction) can help expedite the selection process and accelerate the release of improved varieties.

Yield relative environment maximum (YREM) and Best Linear Unbiased Prediction (BLUP) are preferred stability statistics for evaluating crop performance across diverse environments. YREM assesses a genotype's performance relative to the best environment, while BLUP incorporates information from multiple environments to provide robust predictions. Compared to other parameters based on absolute yield, YREM and BLUP offer more reliable assessments, considering relative performance across environments. In contrast, AMMI and GGE biplot are graphical tools used to analyse genotype-environment interactions, offering visual insights into how different genotypes perform across various environmental conditions. For perennial crops, YREM and BLUP are particularly advantageous as they enable the assessment of stability over multiple years, considering fluctuations in environmental conditions. They facilitate the generation of long-term predictions and estimation of genetic gain, aiding breeders in making informed decisions for crop improvement over successive generations.

4. Conclusion

This study introduces the use of Yield Relative Environment Maximum (YREM) and Best Linear Unbiased Prediction (BLUP) as quantitative criteria for selecting the best performing genotypes and assessing the predictive power of single-year YREM and BLUP in predicting future performance in perennial crops, specifically using black pepper as a model crop. The study suggests that an YREM value below 0.41 and a BLUP value below 1.50 kg vine^{-1} can be used as thresholds to reject inferior genotypes, while a YREM value above 0.66 and a BLUP value above 2.9 kg vine^{-1} can be used to select superior genotypes. Among the evaluated cultivars, OPKM displayed better stability estimates. However, considering high mean yield along with all the stability estimates, the HP 2173 ranked first. Despite using single-location multi-year trial data, the study found that single-year YREM and BLUP values exhibited significant predictive power in forecasting the future performance of genotypes. Additionally, the study suggests that using multi-year average performance (YREM and BLUP) as quantitative criteria to select or reject genotypes in future breeding programs is an effective approach. By shedding light on the successful application of YREM and BLUP in black pepper, we believe this research offers valuable insights applicable to other perennial crops as well.

CRediT authorship contribution statement

Mundagodu S. Shivakumarumarms:Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sasikumar B. Pillai**:Writing

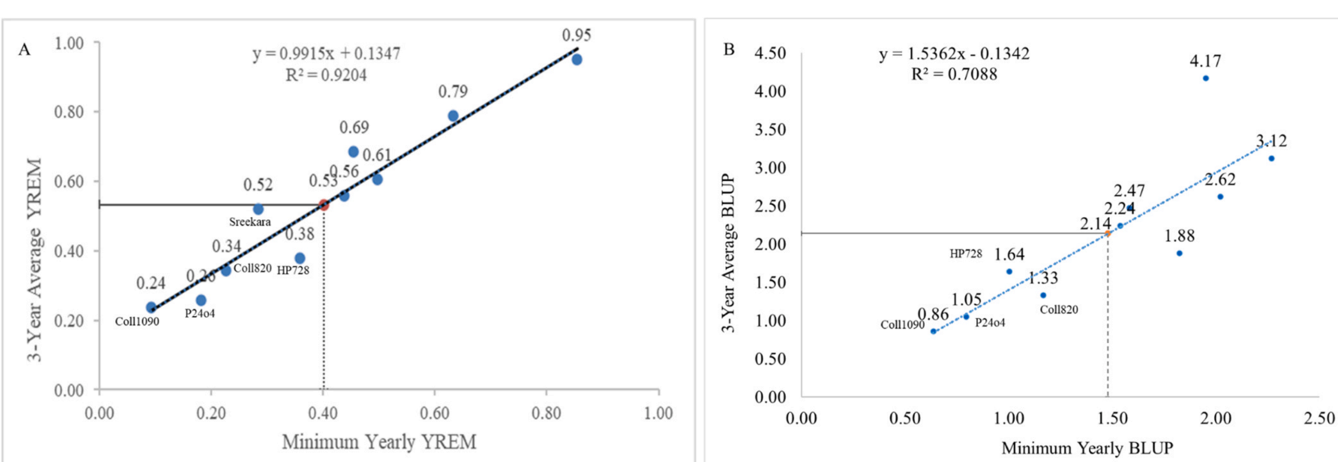

Fig. 6. Relationship between 3-year YREM for ten black pepper cultivars and their minimum yearly A. YREM and B. BLUP.

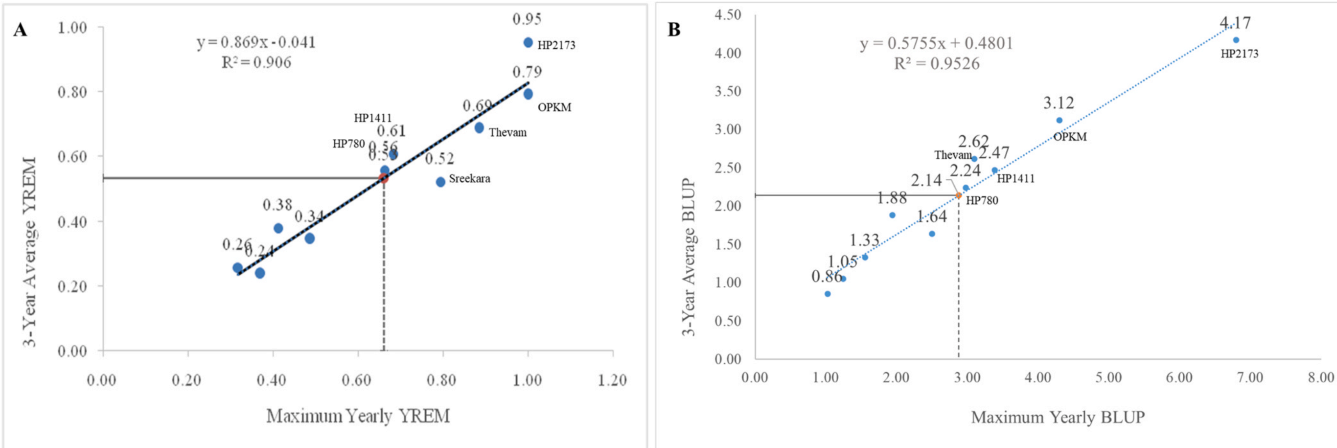

Fig. 7. Relationship between 3-year YREM for ten black pepper cultivars and their maximum yearly A. YREM and B. BLUP.

– review & editing, Resources, Project administration, Conceptualization. **Koryampalli V. Saji:**Writing – review & editing, Supervision, Resources, Investigation, Conceptualization. **Hosahalli J. Akshitha**: Writing – review & editing, Writing – original draft, Data curation. **Nagenahalli C. Sunitha**:Writing – original draft, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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