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RESEARCH ARTICLE

Prediction of grain yield performance of commercially released finger millet (*Eleusine coracana* L.) varieties based on single- versus multiple-year BLUPs and YREMs

T.E. Nagaraja*, C. Nandini[1], Sujata Bhat, S. Gazala Parveen and J. Meenakshi

Abstract

Breeders effectuate trials to evaluate the performance of the germplasm lines or advanced breeding lines across multiple locations and years to recognize the promising line(s) for commercial cultivation across farmers' fields. The majority of the theories state that cultivars' multiple-year data from a specified location has a higher predictive ability of their future performance than single-year data. To verify this hypothesis, we predicted the cultivars' present performance based on their previous 1- (2020), 2- (2020, 2019), 3- (2020, 2019 and 2018) and 4- (2020, 2019, 2018 and 2017) years' grain yield performance of 77 commercially released finger millet (*Eleusine coracana* L.) varieties for cultivation across various cropping zones in India using (best linear unbiased predictors) BLUP and yield relative to environment maximum (YREM). The results indicated that single-year grain yield data had a reduced ability to recognize superior finger millet varieties. Further inclusion of multiple (4 and 3 years) year grain yield data seemed to predict better than single-year grain yield data. The coefficient of determination of 5-year BLUP and YREM with maximum and minimum yearly BLUP and YREM could be used as a yardstick to accept and reject the cultivars, respectively. The varieties VL 204, RAU 8, ML365, RAU 3, VR 708 and L5 depicted high YREM and BLUP estimates with high mean grain yield and, therefore, they can be adapted to Karnataka state and can be recommended to the farmers for cultivation.

Keywords: BLUP, YREM, predictive ability, finger millet, genotype × environment interaction.

Introduction

Crop yield trials conducted across the globe aid a plant breeder in identifying and select elite and high-yielding varieties/hybrids that can be grown in forthcoming years. The results of such yield trials are hampered due to the ubiquitous presence of the interaction between genotype × environment (GEI), especially temporal variation, which is the largest source of yield variation in contrast to spatial variation (Yan and Rajcan 2003; Annicchiarico et al. 2006; Sood et al. 2016; Spoorthi et al. 2021). Additionally, a familiar theory and the principle to recommend varieties/hybrids for expansive commercial cultivation is that the repercussions of multiple-year crop yield trials are prognostic of their performance in the next year (Yan and Rajcan 2003; Gauch 2013). Surprisingly, seldom plant breeders have experimented with this theory at least in commercially grown crops and none in finger millet [*Eleusine coracana* (L.) Gaertn.]. Plant breeders and farmers are keen to identify those varieties/hybrids that shall give superior yields in the subsequent year rather than long-term mean yield. Scanty studies have supported the theory that multiple-year data is better in predicting varieties'/hybrids' future year performance, Cross and Helm (1986).

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Finger millet is one of the small millet crops, tolerant to many challenging environmental circumstances. It is a blessing for the vast majority of arid and semi-arid zones as it can grow well on low-fertility soils and requires minimal chemical fertilizers (Gull et al. 2014). Finger millet crop has gained the name "famine crop" due to its ability to withstand the infection of storage pests for up to ten years, guaranteeing year-round food supply or even in the event of crop failure (Mgonja et al. 2007). Compared to other cereals, its grains are high in protein, vitamins, minerals, fiber, and energy and resistant to blast (Vadivoo et al. 1998). It is reported that certain finger millet genotypes contain as much as 450 mg of calcium per 100g of grains (Gupta et al., 2011; Kumar et al., 2014). As a result, medication(s) to treat osteoporosis may be created and utilized. In addition, it has beneficial levels of copper, manganese, phosphorus, and iron and considerably higher levels of chromium, magnesium, molybdenum, zinc, and selenium (Tripathi and Platel, 2010). Furthermore, finger millet straw, which contains up to 60% digestible nutrients, works well as animal feed. Numerous finger millet varieties that are adaptable to various states have been released at the central and state levels. Before recommending any specific variety to farmers, it is imperative that we verify their suitability for the local climate and their track record of consistent performance over the years.

In this study, the estimates of best linear unbiased predictor (BLUP)and yield relative to environment maximum (YREM) are used as performance predictors of finger millet varieties in ensuing years based on single-location single/ multiple-year yield trials. The linear mixed model (LMM) is used to determine the BLUP, wherein the genotypes are regarded as random effects (Piephoet al. 2008). It is especially applicable when unbalanced yield trials are available, as BLUP has the ability to shrink towards the grand mean due to fewer data points (Robinson 1991; Piepho 1994; DeLacy et al. 1996; Molenaar et al. 2018). The BLUP estimate of genotype is a close reflection of its predicted genotypic value and as the aim of the plant breeders is to minimize the distance between actual and predicted genotypic value (Robinson 1991; Gilmour et al. 1997) hence, usage of BLUP is justified in this study. Another estimate, YREM possessing dynamic properties aids in identifying and selecting best performing genotypes, especially when crossover genotype×year interaction (GYI) is prevailing as it is genotype attendance-independent (Yan 1999). It aids in the estimation of genotypes' performance relative to each of the year's best genotypes and this varies every year due to the existence of significant crossover GYI (Yan 1999). The ratio of a cultivar's yield in a specified year to the yield of any cultivar that yielded the maximum in that year is known as the YREM of that cultivar. In the non-attendance of crossover GYI, a cultivar's theoretical average YREM should be 1.00.

In this study, 77 finger millet varieties developed and commercially released for cultivation in various cropping zones in India that are also used as reference sets for DUS (Distinctiveness, Uniformity and Stability) characterization were evaluated for grain yield for five years in a single location to determine the (i) predictive ability of single-year single-location BLUPs and YREMs in finger millet varietal selection for future years (ii) if BLUPs and YREMs from multiple-year trials are more predictive than those from a single-year finger millet yield trial.

Material and methods

The material for the study consisted of 77 commercially released finger millet varieties (Fig. 1). These varieties are maintained in ICAR-All India Coordinated Research Project (AICRP) on Small Millets, University of Agricultural Sciences, Bangalore (UASB) Karnataka, India. The 77 commercially released finger millet varieties were evaluated for five years in α-lattice design 7×11with two replications during *Kharif* 2017, 2018, 2019, 2020 and 2021 at the experimental blocks of Zonal Agricultural Research Station (ZARS), UASBlocated at 13⁰ 05" N latitude and 77⁰ 34" E longitude. Each variety was planted in 4 rows of 3-meter length by following spacing of 30 ×10 cm apart. The proposed package of practiceswas adhered to raise a healthy crop. Grain yield data of each plot were recorded; further, these values were converted to kg/ha and used for statistical analysis. The analysis of variance (ANOVA) for each year and combined ANOVA were performed using R software v.4.2.2.

Determining the estimates of BLUP for finger millet varieties

The estimates of BLUP were obtained using the following statistical model

$$Y_{ab} = \mu + g_a + y_b + gy_{ab} + e_{ab}$$

Where, Y_{ab} = grain yield of finger millet variety 'a' in year 'b', μ = trial mean, g_a = main effect of finger millet variety 'a', y_b = main effect of year' b,' gy_{ab} = finger millet variety 'a' × year 'b' interaction and e_{ab} = residual associated with finger millet variety 'a' and year 'b'. Excluding trial mean, all remaining effects were assumed random with mean zero possessing variances that are normally distributed. To

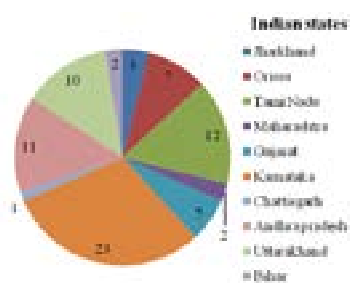

Fig. 1. Proportion of commercially released finger millet varieties in different states used in the study

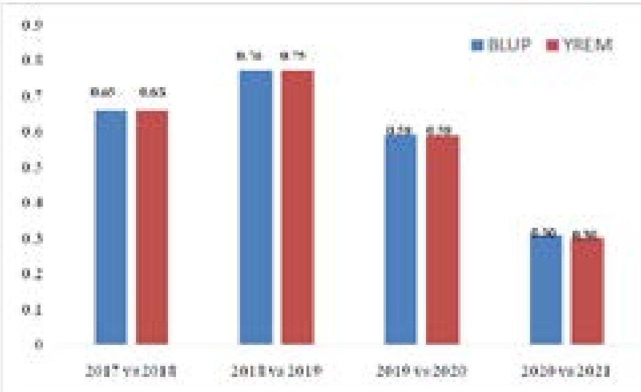

Fig. 2. Estimates of correlation coefficient between previous and next year's grain yield relative to environment maximum (YREMs) and best linear unbiased predictors (BLUPs) of 77 finger millet genotypes

estimate variances attributable to finger millet varieties, year and finger millet varieties × year interaction (here GYI) restricted maximum likelihood method was used. The software 'Meta R' developed by CIMMYT, Mexico, was used to obtain the estimates of BLUP.

Determining the estimates of YREM for finger millet varieties

The YREM is calculated as $Y_{ab} = X_{ab}/MAX_{ab,}$ where Y_{ab} and X_{ab} are the YREM and mean grain yield, respectively, of finger millet varieties' a' in year 'b'. MAX_b is the maximum yield (of any finger millet variety) observed in year 'b'. The estimates of YREM were determined using 'Microsoft Excel' software. Since the main effect year is removed, YREM is considered a standardized yield. The YREMvalueranges from 0 to 1. Performance of a finger millet variety in any single year is regarded as 'yearly YREM'. Whereas, the performance of a finger millet variety in n-years, which is the average of the 'yearly YREM' over the years, is considered as "n-year YREM". The minimum and maximum of the yearly YREM within the tested years is termed as "minimum yearly YREM" and "maximum yearly YREM", respectively.

Computation of predictive ability of single location multiple-year grain yield data

Both BLUP and YREM were used to estimate the grain yield performance. The correlation coefficients between finger millet varieties'BLUP and YREM estimated from previous 2- (2020 and 2019), 3- (2020, 2019 and 2018) and 4- (2020, 2019, 2018 and 2017) years data and those estimated from the present-year data were used to compute the predictiveability of single location multiple-year data.

Computation of criterion to identify and select superior finger millet varieties

Linear regression was used to estimate the coefficient of determination. The average 5 years of BLUP and YREM were plotted against the minimum and maximum BLUP and YREM of each of the 77 finger millet varieties across each of the

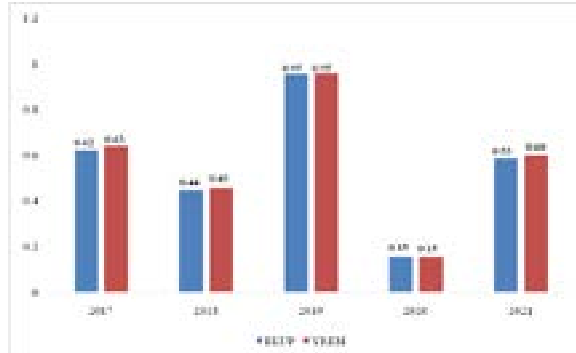

Fig. 3. Estimates of coefficient of determination of 1-year grain yield relative to environment maximum (YREMs) and best linear unbiased predictors (BLUPs) of 77 finger millet genotypes with their across four independent years' average YREMs and BLUPs

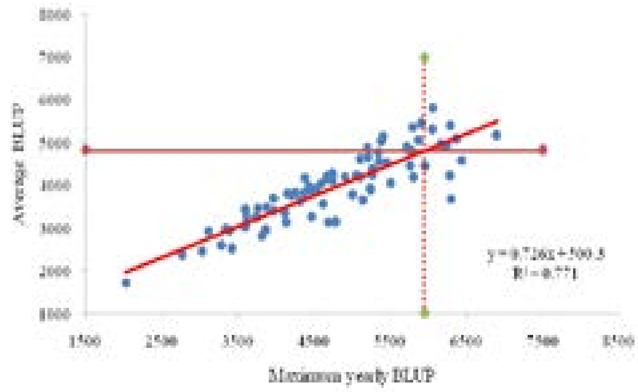

Fig. 4. Relationship between maximum yearly BLUPs and 5-year average BLUP of 77 finger millet genotypes

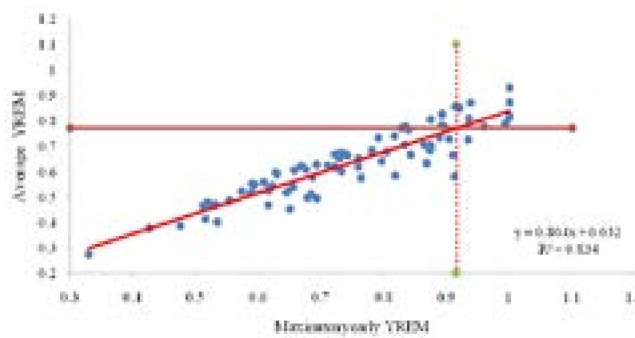

Fig. 5. Relationship between maximum yearly grain yield relative to environment maximum and 5-year average YREM of 77 finger millet genotypes

five years, respectively. An average of 5 years + 1 standard deviation (SD) of BLUP and YREM of grain yield were used to estimate minimum and maximum yearly BLUP and YREM based on a linear regression equation. The BLUP and YREM estimates that are less than the yearly minimum and more than the yearly maximum correspond to an average of 5 years + 1SD of BLUP and YREM of grain yield were used as threshold quantitative criteria to discard and select superior genotypes, respectively.

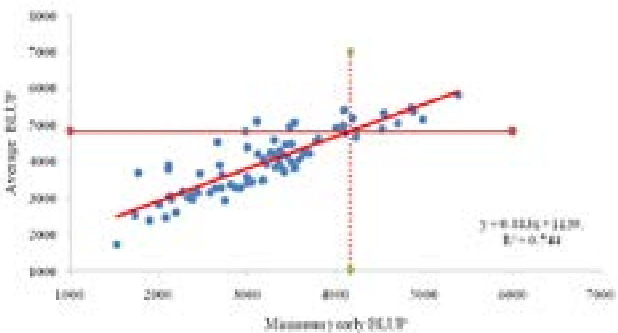

Fig. 6. Relationship between minimum yearly best linear unbiased predictors and 5-year average BLUP of 77 finger millet genotypes

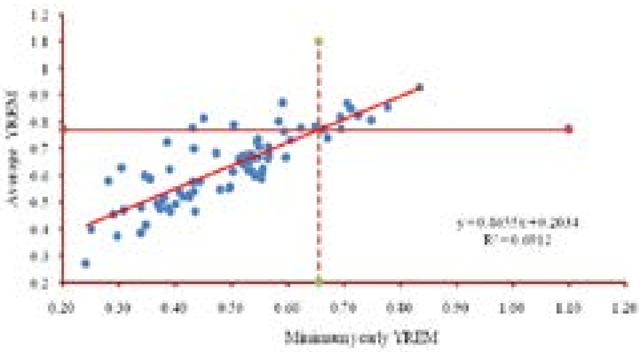

Fig. 7. Relationship between minimum yearly grain yield relative to environment maximum and 5-year average YREM of 77 finger millet genotypes

Results and discussion

Components of variance

The mean sum of squares due to genotypes was highly significant in each of the years (Table 1). The mean sum of squares due to genotypes, years and genotype × year interaction was significant across years, which indicated that there existed considerable differences in the finger millet genotypes for grain yield and they exhibited differential response for year-to-year variation (Table 2). The variation due to genotypes was higher than that due to genotype × year interaction main effect, whereas the variation due to year main effect was the least (Table 2). Relatively higher variation exclusively due to genotypes indicated the prospects to recognize superior and stable finger millet varieties that could attain maximum potential grain yield.

Predictive ability of a single-year grain yield data

The correlation coefficients for BLUP ranged from 0.30 to 0.76 and 0.30 to 0.75 for YREM, all being highly significant (p <0.001; Fig. 2). The predictive ability of a single-year grain yield trial is measured by the correlation coefficient between finger millet varietal performance in one year and that in the next year. We observed that the estimates of correlation coefficients of BLUP and YREM between two consecutive years were similar. For example, the estimates of correlation coefficients of both BLUP and YREM for the years 2017 *vs* 2018 were 0.65. In contrast, the estimates of correlation coefficients of each consecutive year were moderate and did not vary exceptionally high, indicating that single-year grain yield data has less ability to recognize superior and cull out inferior finger millet varieties. Contrastingly, Yan (1999) evaluated winter wheat at nine locations for five years (1989–1993) and concluded that in a given location, single-year YREMs were good predictors of their performance for subsequent years. Thereafter, Yan and Rajcan (2003) concluded from soybean yield data of a decade (1991 to 2000) that single-year 'tBLUP' was a good predictor of their next year/multiple years' performance. Subsequently, Spoorthi et al. (2021) provided evidence that single-year YREMs and BLUPs offered adequate ability to predict dolichos bean genotypes' single-year/multiple-year performance.

Predictive ability of multiple-year grain yield data

In this study, the estimates of correlation coefficients of finger millet varieties' present-year (2017, 2018, 2019, 2020 and 2021) BLUPs and YREMs with those of previous multiple (2, 3 and 4)-years were highly significant. Correlation coefficients of BLUPs and YREMs of the reference present-year 2021 with those of the previous 1 year were least and those of the reference present-year 2019 with the previous-2 years were highest. The correlation coefficient (both BLUP and YREM) for the prediction (p <0.01) was significant and varied with the reference present year (Table 4). Whereas the magnitude of cultivar performance for the year 2021 with respect to a single year (2020) was 0.30; the correlation coefficients for the previous 2-years (2020 and 2019) were 0.58 and 0.61, while for the previous 3-years (2020, 2019 and 2018) were 0.68 and 0.69; whereas, for the previous 4-years (2020, 2019, 2018 and 2017) the correlation coefficients were 0.76 and 0.77 for BLUP and YREM, respectively (Table 4). The estimates of BLUP and YREM should have a higher correlation coefficient for multiple-year grain yield data than single-year grain yield data to support the hypothesis that multiple-year grain yield data can predict the performance of varieties better than the latter (Yan and Rajcan 2003). The estimates of correlation coefficients of BLUP and YREM for single years were not high in contrast to multiple years. Consecutively, the same trend was seen when 2019 was the reference present year. On contrast, the performance prediction in the reference present year 2020 did not improve by including grain yield data from additional 2 and 3 years. For two (2019 and 2021) of the four years, multiple-year grain yield data gave the best prediction. In general, the inclusion of multiple (4 and 3 years) year grain yield data seemed to predict better than single-year grain yield data. As evident, the results of this study favored the above-stated hypothesis.

Table 1. Year-wise analysis of variance for grain yield of 77 finger millet genotypes

Source of variation	Degrees of freedom	Mean squares				
		2017	2018	2019	2020	2021
Genotypes (G)	76	1802741	2215865	1414439	3167811	2449170
Replication	1	18921	459	5897	7772	76440
Replication(Block)	6	1256	130470	5318	6604	9928
Residuals	70	6505	104483	13487	6824	17196

Table 2. Combined analysis of variance for grain yield across 5 years of 77 finger millet genotypes

Source of variation	Degrees of freedom	Sum of squares	Mean Sum of Squares	F-statistic	
Genotype	76	548530222	7217503	241.05	$<2e^{-16}$
Replication	1	32637	32637	1.09	0.29
Year (Y)	4	3785765	946441	31.06	$<2e^{-16}$
Replication(Block)	1	3826	3826	0.12	0.72
G × Y interaction (GYI)	304	291271766	958131	32.00	$<2e^{-16}$
Residuals	383	11467458	29941		

Table 3. Estimates of correlation coefficient between 77 finger millet genotypes' YREMs and BLUPs based on one to four previous years and that based on present year

Year	Previous 1 year		Previous 2 years		Previous 3 years		Previous 4 years	
	BLUP	YREM	BLUP	YREM	BLUP	YREM	BLUP	YREM
2021	0.30	0.30	0.58	0.613	0.68	0.69	0.76	0.77
2020	0.58	0.58	0.437	0.44	0.41	0.413	-	-
2019	0.76	0.76	0.899	0.897	-	-	-	-
2018	0.65	0.65	-	-	-	-	-	-
2017	-	-	-	-	-	-	-	-

Quantitative criteria to identify superior/inferior finger millet varieties

The coefficient of determination(R^2) of finger millet varieties' single-year BLUPandYREM across four independent years' average BLUP and YREM was kin and ranged from 15 to 95% with averages of 53.80 and 55.60%, respectively (Fig. 3).In our study, the quantitative criterion was determined by plotting finger millet varieties' 5-year average BLUP and YREM estimates against the yearly maximum and minimum estimates of BLUP and YREM. A similar coefficient of determination (R^2) of finger millet varieties' single-year BLUP and YREM with four independent years' average BLUP and YREM signifies that it accounts for approximately 50% of the variation in their performance across multiple years. Such results emphasize the need to devise a quantitative criterion that aids in the identification and selection of superior varieties besides scraping out the poor performers. The outcome of the coefficient of determination of 5-year BLUP and YREM with maximum yearly BLUP and YREM suggests that supreme finger millet varieties recognized in any particular year have an inclination to accomplish better grain yield levels over multiple years; those that are incompetent in any single-year are likely to accomplish poor grain yield levels across multiple years.

The R^2 of 5-year BLUP and YREM with maximum yearly BLUP and YREM was 77.13% (Fig. 4) and 83.49% (Fig. 5), respectively, while R^2 of 5-year average BLUP and YREM with minimum yearly BLUP and YREM were 74.49% (Fig. 6) and 69.12% (Fig. 7), respectively. The better-performing finger millet variety had a 5-year average BLUP of 4818 kg/ha grain yield and YREM of 0.77. This result is consistent with the maximum yearly BLUP of 5946 kg/ha of grain yield (Fig. 4) and YREM of 0.91 (Fig. 5). The 5-year average BLUP and YREM enabled differentiating the better performing finger millet varieties from those of poor performers. This evidence emphasizes that in any given year, any finger millet variety with BLUP 5946 kg/ha and YREM of 0.91 has the potential to produce an average BLUP of 4818 kg/ha and average YREM

Table 4. Average YREM and Mean grain yield of top 20 Finger millet varieties

S. No.	Varieties	Average YREM of 5 years	Mean Grain yield (q/ha)
1	Co 7	0.93	37.24
2	HR 374	0.87	38.86
3	VL 204	0.87	54.97
4	GN 5	0.85	37.93
5	MR 2	0.85	45.05
6	GN 2	0.82	37.7
7	PS 11	0.82	29.59
8	Co 10	0.81	37.05
9	Kalyani	0.8	17.29
10	RAU 8	0.8	50.92
11	PAIYUR 1	0.79	41.86
12	ML 365	0.78	49.13
13	RAU 3	0.78	48.01
14	VR 708	0.78	48.01
15	PPR 2350	0.77	36.99
16	VL 324	0.77	49.07
17	GN 4	0.76	26.83
18	KOPN 235	0.74	30.22
19	Indaf 3	0.73	44.75
20	L 5	0.73	45.82

Table 5. Average BLUP and Mean grain yield of top 20 Finger millet varieties

S.No	Varieties	Average BLUP value	Mean grain yield (q/ha)
1	Co 12	5810.29	58.37
2	VL 204	5441.15	54.97
3	HR 911	5406.72	54.2
4	MR1	5360.9	53.23
5	GPU 66	5314.98	54.09
6	PR 202	5157.93	47.66
7	GPU 28	5150.34	52.07
8	Co 5	5070	54.87
9	RAU 8	5058.35	50.92
10	KMR 301	5041.77	51.1
11	ML 365	4940.63	49.13
12	PRM 1	4925.1	50.03
13	VR 708	4874.84	48.01
14	VL 324	4855.4	49.07
15	PR 230	4842.33	48.04
16	RAU 3	4830.49	48.01
17	GPU 48	4778.92	48.36
18	K 7	4644.25	46.97
19	L 5	4597.52	45.82
20	VR 762	4586.58	45.72

of 0.77 over many years and therefore, such varieties can be identified as superior ones. Similarly, the finger millet varieties with a 5-year average BLUP <4818 kg/ha and YREM <0.77 correspond to a minimum yearly BLUP of 4164 kg/ha and YREM of 0.65, respectively. It indicates that in any given year, the finger millet varieties with BLUP <4164 kg/ha andYREM <0.65 for grain yield are likely to produce an average BLUP of 4818 kg/ha and average YREM of 0.77 for grain yield over many years and thus aids in identifying the poor performers.

Therefore, the results of the present study also aided in deciphering threshold BLUP of >5946 kg/ha and YREM of >0.91 and BLUP of <4164 kg/ha and YREM of <0.65 to recognize superior varieties and scrap inferior varieties, respectively. These results are in line with those reported by Yan (1999), suggesting a yearly YREM of 0.94 and 0.84 as a yardstick to recognize superior and toss out inferior wheat cultivars, respectively, based on multi-year and multi-location trials.

The results of the predictive ability of single-year *vs*. multiple-year grain yield trials for next-year varietal performance were meager and have concluded assorted results. Cross and Helm (1986) compared numerous hybrid maize selection strategies and concluded previous 1- or 2-year data were better than those based on previous 3-year data and Gellner (1989) concluded the same. Bowman (1998) concluded that one-year trial data was sufficient to select mid-season corn hybrids and 2-year multi-location trial data in soybean and wheat. Ma and Stutzel (2014) exemplified that for a specified location, 'tBLUP' based on 2-year performance data had maximum strength to predict superior winter wheat varieties using the data of 11 years (1991 to 2001) country-wide trials conducted in Germany. Perhaps due to the inclusion of very few and unbalanced numbers of hybrids across more than three consecutive years, Cross and Helm (1986), Gellner (1989) and Bowman (1998) were unable to compare predictions of cultivar performance for next year. On the contrary, in our study, we used 5-year grain yield trial data due to the usage of mixed models to determine the BLUP estimates of cultivars enabled us to examine the merits of using multiple-year data and conclude that the use of multiple-year data allows more finger millet varieties to be evaluated conclusively as supported by Yan and Rajcan (2003).

Selection of genotypes with stable high performance based on BLUP and YREM values

For the purpose of selecting genotype types that exhibit high mean yield and high stability across years, a number of criteria have been developed. About 20 genotypes were ranked according to various criteria in the current study, including mean yield,5-year YREM and BLUP. The YREM value is the yield relative to the maximum. It is a superiority index, and the larger the value of a genotype the more superior it is(Yan,1999). The genotype with a YREM of 1.0 is the most stable high-yielding cultivar, while the deviation of YREM from 1.0 is attributed to unpredictable crossover (Shivkumar et al., 2024). BLUP values are estimated by adjusting errors and non-heritable components. These estimates indicate the true potential of the genotypes.

The top twenty genotypes based on YREM and BLUP estimates, along with their mean grain yield, are listed in Tables 4 & 5, respectively. The genotypes having high YREM and BLUP estimates could be desirable for the cultivation and can be recommended to the farmers because they give stable yield across years. The mean grain yield values of varieties VL 204 GN 5 (54.97 q/ha), MR 2 (45.05 q/ha), ML 365 (49.13 q/ha), RAU 3 (48.01 q/ha), VR 708 (48.01 q/ha), VL 324 (49.07 q/ha) and L5 (45.82 q/ha) have high and their corresponding YREM estimates are also high indicating the robustness of these estimates (Table 4). Among these varieties, VL 204 were VL 324 were released from Uttarakhand state, but they performed stable over 5 years in the present location of Karnataka. Hence, these varieties can be recommended to farmers for cultivation. Similarly, VR 708 and RAU 3 were released from Andhra Pradesh and Bihar, respectively and they performed better in Karnataka.

Similarly, the varieties Co12 (58.37 q/ha), VL 204 (54.97 q/ha), HR 911 (54.20 q/ha), MR 11 (53.23 q/ha), GPU 66 (54.09 q/ha) have high mean values and their corresponding BLUP estimates are also high (Table 5). This indicated these varieties were stable with less environmental influence. The varieties VL 204, RAU 8, ML365, RAU 3, VR 708, L5 have high YREM and high BLUP values with high mean grain yield. This suggests that these varieties can be adopted in Karnataka state and can be recommended to the farmers for cultivation.

Authors' contributions

Conceptualization of research (SB, CN); Designing of the experiments (SB, CN); Contribution of experimental materials (SB, CN); Execution of field/lab experiments and data collection (SB, CN); Analysis of data and interpretation (TEN, GPS, CN, JM); Preparation of the manuscript (TEN, GPS, CN, JM).

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