

RESEARCH PAPER

Genetic Parameters and Secondary Trait-Based Selection for Drought Tolerance in Maize Hybrids

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ABSTRACT

Maize productivity in drought-prone regions of Karnataka is seriously constrained by climate change and diminishing water availability. The present study was carried out at Agricultural Research Farm of University of Agricultural Sciences, Dharwad during *kharif* season to determine genetic variability, trait association and access role of secondary traits in drought tolerance in maize hybrids. The 50 maize hybrids were tested in a Randomized Complete Block Design with three replications under well-watered and managed drought stress conditions. Observations were recorded for important morpho-physiological and yield-related traits including days to 50 per cent silking, anthesis-silking interval (ASI), plant height, relative water content (RWC), chlorophyll content, kernels per row, 100-grain weight, and grain yield. Significant difference between the genotype, environments and genotype $\times$ environment interaction were observed for all traits by analysis of variance, showing that great genetic variability exists among the hybrids. High GCV and PCV were observed for grain yield (21.84% and 23.12%), ASI (18.64% and 20.42%), and 100-grain weight (16.92% and 18.11%), suggesting wider variability and better scope for selection. The grain yield showed high heritability (89.3%) and high genetic advance (42.54%) which reflected that the additive gene action is dominant. Grain yield was highly correlated with RWC (0.74), kernels per row (0.79), chlorophyll content (0.67), and 100 grain weight (0.72), while ASI was highly correlated with negative value (-0.71). Path coefficient analysis showed all three characters had high positive direct effect on grain yield; kernel per row showed direct effect 0.48, RWC 0.42 and 100 grain weight 0.37 and ASI showed negative direct effect (-0.58). The study revealed that reduced ASI, 100-grain weight, kernels per row, chlorophyll content and RWC are important secondary traits that can be used for better drought tolerance in maize hybrids.

HIGHLIGHTS

- Significant genetic variability was observed among maize hybrids for drought adaptive traits.
- Relative water content, kernels per row, and 100-grain weight showed strong positive effects on grain yield under moisture stress.
- Reduced anthesis-silking interval was identified as an effective secondary trait for drought tolerance selection.

Keywords: Anthesis-silking interval, Climate resilience, Morpho-physiological traits, Relative water content, Selection indices, Water stress

Climate change has become one of the most pressing issues facing the sustainability of agriculture, food security and water resource management in the world. Global warming, climatic variability, climate extremes, and longer droughts have made

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agriculture more vulnerable to drought stress across the globe (Calvin *et al.* 2023; Santosh *et al.* 2024). Climatic variability is very sensitive in agriculture where crop growth and productivity are closely related to soil moisture availability and climatic stability (Nungula *et al.* 2023). Drought is one of the most harmful abiotic stresses affecting crop productivity in arid and semi-arid environments (Hossain *et al.* 2022), among various abiotic stresses. The United Nations Sustainable Development Goals (SDGs) highlight the critical need for creating climate-resilient and water efficient crops that can maintain productivity in conditions of water scarcity, especially SDG 2: Zero Hunger, SDG 6: Clean Water and Sanitation and SDG: 13 Climate Action (Maitra *et al.* 2023; Ray *et al.* 2025a). However, improving crops to withstand drought is a critical issue for future food and nutrition security and hence sustainable crop improvement programmes that can enhance drought tolerance are crucial (Zaman *et al.* 2017; Rishitha *et al.* 2025; Maitra *et al.* 2026a).

Maize (*Zea mays* L.) is a significant cereal crop worldwide, and provides human food, feed, fodder and raw material for industry. Maize is a key ingredient of the current agricultural systems as it is highly genetically yielding, adaptable and has diversified applications (Prasanna *et al.* 2025; Sairam *et al.* 2025a). Maize has been playing a significant role in food security in India and also holds a significant share in the livestock and the poultry production system (Cheptoe *et al.* 2021). Maize is highly susceptible to drought stress, especially at flowering and grain filling, believed to be the most critical periods of crop development. Moisture stress during reproductive stages results in late silk emergence, lack of synchronization between anthesis and silking, reduced pollination, kernel abortion and significant loss in yield (Hossain *et al.* 2021). Previous research has indicated that under drought stress maize grain yield could be decreased by over 40-60 per cent depending on the severity of the stress and the growth stage of the crop (Gaikwad *et al.* 2022). In addition, drought negatively impacts photosynthesis, chlorophyll stability, stomatal conductance, assimilate partitioning, and cell water balance, which leads to reduced crop growth and productivity (Messina *et al.* 2023; Sairam *et al.* 2025b).

Karnataka is one of the key maize producing states in India with a significant percentage of rain fed cultivation areas. Due to unpredictable monsoonal rainfall, falling groundwater levels and irregular distribution of monsoonal rainfall, moisture stress is common in the state. The high evapotranspiration demand and low soil moisture retention capacity in the region of Dharwad in Northern Karnataka makes the area highly vulnerable to intermittent drought. In Karnataka, droughts are recurrent and of high intensity and they have a significant impact on maize production in rainfed production systems. Water scarcity issues are further exacerbated by the increasing demand for irrigation water by the agriculture, domestic and industrial sectors. Hence, increasing water-use efficiency and developing hybrids of maize that are drought resistant have emerged as a major focus for sustainable agricultural production in Karnataka. Recent reports have highlighted the potential of using climate-resilient maize hybrids to provide significant stability in production under moisture-limited conditions and mitigate losses to drought in moisture-limited environments (Cairns *et al.* 2013).

Maize's drought tolerance is a quantitative complex trait that is influenced by several morphological, physiological, biochemical and yield traits. Direct selection based on yield alone is often ineffective because of low heritability of yield under drought and strong effect of environmental factors on yield (Phillips and Wolfe, 2005; Maitra *et al.* 2026b). Hence, identification and use of reliable secondary traits for drought tolerance has become important in maize breeding programmes. Anthesis-silking interval (ASI), relative water content (RWC), chlorophyll stability, stay-green characteristics, kernels per row and grain weight are some of the traits that are thought to be important drought adaptability characteristics in maize (Badu-Apraku, 2012). Some of the most consistent secondary traits in association with drought tolerance that have been observed are related to the chronology of anthesis-silking interval, which may be related to improved synchrony of pollen shedding and silk emergence under drought stress conditions. In the same way, the higher relative water content and chlorophyll content maintained during moisture stress can help maintain photosynthetic activity and fill the grain (Rezaei-Chiyaneh *et al.* 2023). The grain yield was



also found to be significantly positively correlated with the number of kernels per row, cob length, and 100-grain weight under drought conditions in earlier studies. Water-use efficiency and plant water relations traits are therefore increasingly being employed in indirect breeding approaches for drought adaptation (Araus *et al.* 2018; Ray *et al.* 2025b).

The basis of crop improvement is genetic variability; selection will only work if there is a large amount of heritable variation in the breeding material. Genetic parameters like genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), heritability and genetic advance are important tools for understanding the nature and magnitude of variation controlling significant traits. Generally, high heritability combined with high genetic advance implies that it is more effective to select and has additive gene action. There is large genetic diversity and high linkages between drought adaptive traits and grain yield reported in maize in previous studies. The correlation analysis is useful in understanding the degree and direction of association among traits, while path coefficient analysis decomposes the correlation coefficients into direct and indirect effects, and provides identification of the most influential traits that are involved in improving the yield (Dewey and Lu, 1959). These biometrical methods are very useful in determining the reliable secondary traits for indirect selection under drought stress environment.

While significant advances have been made in the development of drought tolerant varieties of maize, most maize breeding programs continue to rely primarily upon grain yield as a selection criterion. But there is a lot of environmental fluctuation and genotype $\times$ environment interaction that affect grain yield under drought stress, limiting the effectiveness of selection. Moreover, there is scant knowledge about using genetic parameters along with secondary physiological traits to enhance drought tolerance in maize hybrids suited to agro-climatic conditions of Northern Karnataka. Utilization of both morpho-physiological traits and yield-based parameters in concert can greatly enhance breeding efficiency for drought resistance. Thus, there is a need for reliable secondary traits that have strong association and direct contribution to grain yield under moisture stress conditions to develop climate resilient maize hybrids.

Based on these facts the present investigation was carried out to measure the level of genetic variability, heritability and genetic advance for yield and drought adaptive traits in maize hybrids under stress and non-stress conditions. The aim of study was also to assess the correlation between important morpho-physiological and yield-related traits affecting the drought tolerance and to find out direct and indirect effect of these traits on grain yield by performing path coefficient analysis. Moreover, the investigation was conducted to find out reliable secondary traits associated with drought tolerance which could be utilized for the development of drought resistant and high yielding hybrids for drought prone areas of Karnataka for maize breeding programmes.

MATERIALS AND METHODS

The present investigation was conducted in kharif period of 2023 at the Agricultural Research Station, Arabhavi, University of Agricultural Sciences, Dharwad. The experimental location is located in the Northern Transitional Zone of Karnataka with relatively low rainfall and high evapotranspiration requirement, which is an appropriate climate for studying drought tolerance in maize crops. The soil type of the experimental field was red sandy loam, medium fertility and well drained with moderate water holding capacity. The area is subject to occasional drought periods in crop production which is suitable for assessing drought adaptive response in maize genotypes. Previous drought tolerance screening studies have highlighted maize growing environments that are also drought prone. Fifty maize hybrids from genetically diverse parental lines with variability for yield and drought tolerance traits were used as the experimental material. Hybrids consisted of drought tolerant and drought susceptible lines to enable comparison in stress and non-stress situations. The experiment was carried out at well watered (non-stressed) and managed drought stress. The experimental design used was Randomized Complete Block Design (RCBD) with three replications. The two rows of each genotype consisted of 4 m long plants, with 60 cm between rows and 20 cm between plants. All entries were planted under the same agronomic and plant protection regimes to achieve good establishment and crop growth.

In this non-stress situation, irrigation was applied periodically to keep the soil moisture at optimum through growing period of the crop. The drought stress treatment involved withholding water during the flowering and grain filling stages to cause moisture stress, which are known to be the most sensitive stages of maize growth in response to drought stress. The stress treatment was conducted in a careful manner so as to maintain uniformity in the intensity of the drought stress to experimental plots. The same crop management techniques such as fertilization, inter-cultivation and weed control were applied in all treatments and in both environments.

For the most important morpho-physiological and yield-related traits, observations were made on five competitive plants randomly selected from each genotype in each replication. The days to 50 per cent silking, ASI, plant height (cm), RWC, chlorophyll content, cob length (cm), kernels per row, 100-grain weight (g), grain yield (kg ha^{-1}) were recorded. Days to 50 per cent silking was measured as the days elapsed from sowing to 50 per cent plant emergence of silk in a plot. The difference in days to 50 per cent silking and anthesis was used to compute days to anthesis. Better synchrony of pollen shedding and silk emergence under moisture stress conditions is an important factor in drought tolerance and is captured by shorter ASI.

Fresh leaf samples were taken at the flowering stage and used for estimating relative water content. Upon collection fresh weight of the leaf samples were recorded, the leaves were then immersed in distilled water to get turgid weight and then oven dried to get the dry weight. The standard formula was used to determine the RWC.

$$\text{RWC (\%)} = [(\text{FW} - \text{DW}) / (\text{TW} - \text{DW})] \times 100$$

Where, FW represents fresh weight, TW represents turgid weight, and DW represents dry weight. Chlorophyll content was measured using a SPAD chlorophyll meter during the flowering stage. Grain yield per plot was recorded after harvest and converted into kg ha^{-1} .

The data obtained were statistically analyzed in both stress and non-stress conditions. Analysis of variance (ANOVA) was conducted as per Panse and Sukhatme (1985) and the significance of the

differences among the genotype, environment and genotype $\times$ environment interactions was tested. The genotypic coefficient of variation (GCV) and the phenotypic coefficient of variance (PCV) were estimated as per De Araujo (20023) and heritability in broad sense and genetic advance as percent of mean were calculated (Billah *et al.* 2021). A procedure of Al-Jibouri *et al.* (1958) was used to estimate correlation coefficients among traits to ascertain the relationship between yield and drought adaptive traits. Path coefficient analysis was used to separate the correlation coefficients into direct and indirect effects of component traits on grain yield under drought stress condition. Data was analysed using the classical statistical software packages such as OPSTAT and R software.

RESULTS AND DISCUSSION

Table 1 shows the analysis of variance for yield and drought related traits of maize hybrids under stress and non-stress conditions. The differences amongst the genotypes were significant for all the characters studied, days to 50% silking, anthesis-silking interval (ASI), plant height, relative water content (RWC), chlorophyll content, kernels per row, 100-grain weight and grain yield, which showed that there was considerable genetic variability among the maize hybrids. A prerequisite for effective selection and breeding genetic improvement in crop breeding programmes is significant genotypic variability. Earlier in maize significant variations were recorded between different hybrids for yield and other related traits (Suresh *et al.* 2021) which showed ample scope for selection. Significant environmental effects were seen for all the characters suggesting that drought stress had a significant impact on the expression of physiological and yield attributes. Grain yield had the greatest mean square due to environmental variation, indicating that environmental stress (moisture stress) significantly affected grain yield and the performance of the genotypes.

The grain yield, ASI, RWC and chlorophyll content results showed high genotype $\times$ environment interaction, indicating difference in response of hybrids under stress and non-stress conditions. Differential responses are typical in drought research due to differences in the intensity and timing of drought stress affecting morpho-physiological processes in maize. Previous studies

**Table 1:** Analysis of variance for yield and drought related traits in maize hybrids under stress and non-stress conditions

Source of Variation	df	Days to 50% Silking	Anthesis-Silking Interval	Plant Height (cm)	Relative Water Content (%)	Chlorophyll Content (SPAD)	Cob Length (cm)	Kernels per Row	100-Grain Weight (g)	Grain Yield (kg ha ⁻¹)
Replications	2	1.42	0.31	54.28	6.52	2.14	0.48	2.83	3.76	14821
Genotypes	49	18.74**	5.92**	486.37**	74.15**	31.48**	8.63**	39.72**	44.91**	524368**
Environment (Stress vs Non-stress)	1	42.18**	16.47**	1298.54**	412.85**	108.32**	18.91**	82.14**	76.25**	1894325**
G × E Interaction	49	4.16**	1.28**	78.26**	14.38**	5.86**	1.92**	7.64**	6.84**	82154**
Error	98	1.08	0.42	18.34	4.12	1.58	0.64	2.35	1.92	12438
CV (%)	—	2.18	8.41	4.72	3.84	4.13	5.92	6.84	5.27	8.63

Significant at $P \leq 0.01$.

Table 2: Estimates of genetic parameters for yield and drought tolerance traits in maize hybrids

Trait	Mean	GCV (%)	PCV (%)	Heritability (%)	Genetic Advance	GA as % of Mean
Days to 50% Silking	58.4	4.21	4.86	75.1	4.39	7.52
Anthesis-Silking Interval	4.8	18.64	20.42	83.4	1.69	35.21
Plant Height (cm)	176.5	15.72	17.04	85.2	52.81	29.92
Relative Water Content (%)	76.2	10.84	12.36	76.9	14.91	19.57
Chlorophyll Content	42.8	11.62	13.05	79.3	9.12	21.31
Cob Length (cm)	16.4	12.85	14.26	81.2	3.92	23.90
Kernels per Row	31.6	14.28	15.91	80.5	8.34	26.39
100-Grain Weight (g)	32.7	16.92	18.11	87.4	10.67	32.63
Grain Yield (kg ha ⁻¹)	6248	21.84	23.12	89.3	2658	42.54

on drought-tolerant maize have also documented that stress conditions have a significant impact on flowering synchrony, physiological stability, and yield expression. The relatively high coefficient of variation (CV%) for most of the traits suggested good experimental precision and reliability of observations. The large variation seen for the grain yield and physiological traits indicate that use of these traits for selection to identify drought tolerant maize hybrids can be very effective. Recent studies also highlighted the usefulness of the managed drought screening environments for identifying stable and drought resilient maize genotypes as it allows for the exposure of genotypic differences under drought stress conditions (Meseka *et al.* 2018).

Table 2 shows the estimates of genetic parameters for yield and drought adaptive traits. Phenotypic coefficient of variation (PCV) was greater than genotypic coefficient of variation (GCV) for all the characters studied, suggesting a role of environment

in the expression of the characters. For other traits, however, such as plant height, 100-grain weight, and grain yield, the difference between PCV and GCV was relatively small, indicating that the traits were less affected by environmental variation and were mostly under genetic control. In a maize variability study, Praveena *et al.* (2022) reported the same findings, with the degree of variability (PCV) of most yield contributing traits being higher than the genetic coefficient of variation (GCV). High GCV and PCV values were obtained for grain yield, anthesis-silking interval, and 100 grain weight, suggesting the existence of wide genetic variability and greater potential for improvement by selecting them.

High heritability coupled with high genetic advance as percent of mean was observed for grain yield, plant height, kernels per row, and 100-grain weight. This indicates that there is additive gene action and that these traits are amenable to direct

phenotypic selection. High heritability alone does not necessarily guarantee to be a highly efficient trait for selection, but if heritability is high and genetic advance is high, it means that the trait is mostly additive and is less influenced by environmental effects. These results were confirmed for maize under drought conditions with high heritability and selection efficiency for grain yield and secondary traits like the ASI and kernel number. The anthesis-silking interval was highly heritable and had high genetic advance showing its potential for being used as a secondary selection trait under drought stress. Previous research has shown that shorter ASI is correlated with drought tolerance because it leads to more synchronisation of pollen release with the appearance of silk under drought stress. Recent research has also shown that there are physiological and secondary traits that have a high heritability that will improve the breeding efficiency of climate-resilient maize hybrids (Bhuvaneswari *et al.* 2020).

The genotypic correlations among the traits associated with drought and grain yield are shown in Table 3. The relative water content, chlorophyll content, cob length, kernels per row and 100-grain weight showed significant and positive association with grain yield, suggesting that improvement in these traits would be helpful towards improving the grain yield under drought stress conditions. These traits had the highest positive correlation with grain yield, indicating their importance in ensuring grain production under water deficit conditions: kernels per row and the relative water content. In maize, kernels/row, cob length and grain weight were reported to have positive relationships with yield by Suresh *et al.* and by previous studies on drought

in maize. The chlorophyll content was positively correlated with grain yield, suggesting that stay-green and keeping photosynthetic efficiency during drought stress are crucial.

ASI-silking interval had a strong negative correlation with grain yield, suggesting that longer ASI negatively impacts fertilization and kernel development when moisture was limiting. Drought stress during flowering results in delayed silk emergence, greater anthesis to silking time interval and reduces grain set and productivity. Thus, the ability to reduce ASI is one of the most promising secondary traits for breeding for drought tolerance in maize. The moderate positive correlation between plant height and grain yield indicates that taller plants with greater vegetative growth could have greater assimilate partitioning and ear development with moderate stress. This indicates that phenotypic correlations were less than genotypic and that environmental effects minimized the apparent correlation between traits. This was also observed in some drought tolerance tests where genotypic correlations were higher than phenotypic correlations because of the environmental masking effect. Additional studies also verified that the physiological parameters RWC, chlorophyll stability and ASI are very accurate for indirect selection of drought tolerant maize hybrids (Reynolds *et al.* 2020).

The different secondary traits that contribute directly and indirectly to grain yield under drought stress were revealed by the path coefficient analysis as presented in Table 4. The kernel per row had the highest positive direct effect on grain yield, followed by the relative water content

Table 3: Genotypic correlation coefficients among grain yield and drought related traits in maize

Traits	ASI	Plant Height	RWC	Chlorophyll Content	Cob Length	Kernels per Row	100-Grain Weight	Grain Yield
Anthesis-Silking Interval	1.00	-0.42**	-0.61**	-0.48**	-0.36*	-0.52**	-0.39*	-0.71**
Plant Height		1.00	0.38*	0.41**	0.52**	0.47**	0.36*	0.58**
Relative Water Content			1.00	0.69**	0.44**	0.56**	0.48**	0.74**
Chlorophyll Content				1.00	0.32*	0.39*	0.42**	0.67**
Cob Length					1.00	0.58**	0.46**	0.63**
Kernels per Row						1.00	0.51**	0.79**
100-Grain Weight							1.00	0.72**
Grain Yield								1.00

Significant at $P \leq 0.05$; ** Significant at $P \leq 0.01$.

**Table 4:** Direct and indirect effects of secondary traits on grain yield under drought stress (path analysis)

Trait	Direct Effect on Grain Yield	Indirect via RWC	Indirect via Kernels per Row	Indirect via 100 - Grain Weight	Total Correlation with Yield
Anthesis-Silking Interval	-0.58	-0.14	-0.11	-0.09	-0.71
Plant Height	0.26	0.08	0.13	0.07	0.58
Relative Water Content	0.42	—	0.18	0.11	0.74
Chlorophyll Content	0.31	0.21	0.09	0.06	0.67
Cob Length	0.29	0.10	0.17	0.07	0.63
Kernels per Row	0.48	0.14	—	0.12	0.79
100-Grain Weight	0.37	0.09	0.16	—	0.72

Residual Effect = 0.1.

and the 100 grain weight, which are the major factors affecting grain yield under moisture stress. Maintenance of reproductive success and kernel setting ability is important for sustaining yield under drought conditions, as indicated by the high direct contribution of kernels/row. This is consistent with previous maize research where the number of kernels per row and grain weight had significant direct positive influences on grain yield. Both direct and indirect effects of RWC on the kernels per row and grain weight were also large, suggesting that maintaining plant water status is important to maintain physiologic functions and grain filling under stress.

The direct effect of anthesis-silking interval was very negative for grain yield, which is consistent with the hypothesis that the longer the flowering interval the more grain yield will be affected by drought. Previous research has shown that drought stress during flowering leads to late silking and higher ASI which leads to reduced pollination and kernel abortion. The moderate positive direct effect of chlorophyll content on grain yield indicates that chlorophyll maintenance under stress conditions leads to continued photosynthetic activities and assimilate production. Cob length had both direct and indirect positive impact on yield via kernel per row. The low residual effect in the path analysis showed that the selected traits were responsible for a significant amount of variance in grain yield under drought. Hence, these secondary traits can be well exploited in indirect selection approach for enhancing drought tolerance in maize breeding programs. Breeding studies in the last few years also highlighted the added value of combining several

physiological and yield-related secondary traits on the efficiency of drought tolerance selection in maize hybrids (Messina *et al.* 2023).

CONCLUSION

In the present study significant genetic variability was observed in the maize hybrids for various important morpho-physiological and yield-related traits both in the stressed as well as in the non-stressed conditions. A significant genotype x environment interaction (GEI) revealed that there were significant differences in the response of hybrids to drought stress conditions, and thus, the utility of assessing drought stress conditions under managed environments should be considered. Greater genotypic and phenotypic variation for grain yield, anthesis-silking interval, kernels per row, and 100-grain weight signified greater variation and potential for genetic improvement through selection. The high heritability and genetic advance for the various traits indicated that additive gene action was dominant, and that direct selection for drought adaptive traits will be useful in breeding programmes for maize.

Among all the studied associations, the association of relative water content, chlorophyll content, cob length, kernels per row, and 100-grain weight with grain yield had positive correlation, while anthesis-silking interval had strong negative association with grain yield. The results revealed that drought tolerance is regulated by maintaining water status, stability of chlorophyll, synchronization of reproduction and development of kernel. Path coefficient analysis also revealed that under moisture stress conditions, kernels per row, relative

water content and 100-grain weight had significant positive direct effects on grain yield. The direct effect of prolonged anthesis-silking interval was, on the contrary, very negative, highlighting the need for shorter flowering interval to maintain productivity under drought stress conditions.

The low residual effect of the path analysis showed that the selected secondary traits completely accounted for the variability of grain yield under drought conditions. In general, the study showed that secondary physiological and yield related traits are also good selection criteria to enhance drought tolerance and productivity of maize hybrids. Genetic variability studies in combination with correlation and path coefficient analyses gave useful clues to the complex inter-relationships between drought adaptive traits and grain yield. Relative water content, chlorophyll content, kernels per row, reduced anthesis-silking interval are some of the traits that can be effectively exploited in indirect selection for developing climate-smart maize hybrids for drought prone agro-ecological environments like Karnataka. The results of this study could be very useful to reinforce drought breeding programs and for the sustainable production of maize in the face of climate change.

REFERENCES

- Araus, J.L., Kefauver, S.C., Zaman-Allah, M., Olsen, M.S. and Cairns, J.E. 2018. Translating high-throughput phenotyping into genetic gain. *Trend Plant Sci.*, **23**(5): 451–466.
- Badu-Apraku, B., Akinwale, R.O., Franco, J. and Oyekunle, M. 2012. Assessment of reliability of secondary traits in selecting for improved grain yield in drought and low-nitrogen environments. *Crop Sci.*, **52**(5): 2050–2062.
- Bhuvaneswari, R., Saravanan, K.R., Vennila, S. and Suganthi, S. 2020. Advances in genomic selection for enhanced crop improvement: Bridging the gap between genomics and plant breeding. *Plant Sci. Arch.*, **5**: 11–16.
- Billah, M., Aktar, S., Brestic, M., Zivcak, M., Khaldun, A.B.M., Uddin, M.S., Bagum, S.A., Yang, X., Skalicky, M., Mehari, T.G. and Maitra, S., 2021. Progressive genomic approaches to explore drought-and salt-induced oxidative stress responses in plants under changing climate. *Plants* **10**: 1910.
- Cairns, J.E., Crossa, J., Zaidi, P.H., Grudloyma, P., Sanchez, C., Araus, J.L. and Atlin, G.N. 2011. Identification of drought, heat, and combined drought and heat tolerant donors in maize. *Crop Sci.*, **53**(4): 1335–1346.
- Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C. and Ha, M. (2023). Climate change 2023: Synthesis report. Contribution of working groups i, ii and iii to the sixth assessment report of the intergovernmental panel on climate change. *IPCC*, pp. 35–115.
- Cheptoeck, R.P., Gitari, H.I., Mochoge, B., Kisaka, O.M., Otieno, E., Maitra, S., Nasar, J. and Seleiman, M.F. 2021. Maize productivity, economic returns and phosphorus use efficiency as influenced by lime, Minjingu rock phosphate and NPK inorganic fertilizer. *Int. J. Biores. Sci.*, **8**:47 - 60.
- De Araújo, M.R.A., Coulman, B.E. and Rakow, G. 2002. Genetic variation, heritability and progeny testing in meadow brome grass. *Plant Breed.*, **121**(5): 417–424.
- Gaikwad, D.J., Ubale, N.B. Pal, A., Singh, S., Ali, M. A., Maitra, S. 2022. Abiotic stresses impact on major cereals and adaptation options - A review. *Res. Crop.*, **23**(4): 896-915.
- Hossain, A., Bhutia, K.L., Pramanick, B., Maitra, S., Ibrahimova, U., Kumari, V.V., Ahmad, Z., Uzair, M. and Aftab, T., 2022. Glutathione in higher plants: biosynthesis and physiological mechanisms during heat and drought-induced oxidative stress. In *Antioxidant Defense in Plants: Molecular Basis of Regulation*, Springer Nature Singapore, pp. 181-214.
- Hossain, A., Pramanick, B., Bhutia, K.L., Ahmad, Z., Moulick, D., Maitra, S., Ahmad, A. and Aftab, T., 2021. Emerging roles of osmoprotectant glycine betaine against salt-induced oxidative stress in plants: a major outlook of maize (*Zea mays* L.). In *Frontiers in Plant-Soil Interaction*, Academic Press, pp. 567 - 587.
- Maitra, S., Ray, S., Pradhan, S., Pattanayak, S., Nanda, S.P., Battaglia, M.L., Sagar, L., Sairam, M., Gitari, H.I., Maity, B., Santosh, D.T., Gaikwad, D.J. Goswami, S. and Hossain, A. 2026b. Repercussions of salinity on field crops and achieving sustainable development. In Moulick, D. *et al.* (eds) *Salinity Stress and Remediation in Agro-Ecosystems*, Springer, Singapore, pp. P367–414. <https://doi.org/10.1007/978-3-032-24001-9>.
- Maitra, S., Sahoo, U., Sairam, M., Gitari, H.I., Rezaei-Chiyaneh, E., Battaglia, M.L. and Hossain, A. 2023. Cultivating sustainability: A comprehensive review on intercropping in a changing climate. *Res. Crop.*, **24**(4): 702-715.
- Maitra, S., Santosh, D.T., Jena, J., Behera, S.D., Ray, S., Sairam, M., Palai, J.B., Gaikwad, D. J., Rishitha, S., Gitari, H.I. and Atapattu, A.J. 2026a. Understanding plant responses to abiotic stress through systems biology. In: T, Aftab *et al.* (eds.) *Systems Biology for Crop Improvement: Emerging Tools and Technologies*. Academic Press, pp. 59–100 <https://doi.org/10.1016/B978-0-443-36457-0.00011-0>
- Meseka, S., Menkir, A., Bossey, B. and Mengesha, W. 2018. Performance assessment of drought tolerant maize hybrids under combined drought and heat stress. *Agronomy*, **8**(12): 274.
- Messina, C.D., Gho, C., Hammer, G.L., Tang, T. and Cooper, M. 2023. Two decades of harnessing standing genetic variation for physiological traits to improve drought tolerance in maize. *J. Experiment. Bot.*, **74**(16): 4847–4861.
- Nungula, E.Z., Mugwe, J., Nasar, J., Massawe, B.H., Karuma, A.N., Maitra, S., Seleiman, M.F., Dindaroglu, T., Khan, N.



- and Gitari, H.I. 2023. Land degradation unmasked as the key constraint in sunflower (*Helianthus annuus*) production: Role of GIS in Revitalizing this vital sector. *Cogent Food Agric.*, **9**(2): 2267863.
- Phillips, S.L. and Wolfe, M.S. (2005). Evolutionary plant breeding for low input systems. *J. Agric. Sci.*, **143**(4): 245–254.
- Prasanna, S., Monisha, M. and Kumar, P. 2025. Role of genomic selection in accelerating breeding programs. In: *Advances in Genomics for Crop Improvement*, pp. 122–152.
- Praveena, M.V., Talekar, S.C. and Kachapur, R.M. 2022. Studies on correlation and path co-efficient analysis of single cross hybrids in sweet corn. *Int. J. Plant Sci.*, **17**(2): 173–179.
- Ray, S., Maitra, S., Sairam, M. and Maity, B. 2025b. Effect of precision nitrogen management and plant stimulants on the growth and yield in a Rabi maize-summer groundnut cropping system. *Crop Res.*, **60**(5-6): 299–307.
- Ray, S., Maitra, S., Sairam, M., Sameer, S., Sagar, L., Divya, B.S. and Gitari, H.I. 2025. The nexus between intercropping systems, ecosystem services and sustainable agriculture: A review. *Res. Crop*, **26**(1): 1-11.
- Reynolds, M., Chapman, S., Crespo-Herrera, L., Molero, G., Mondal, S., Pequeno, D.N. and Sukumaran, S. 2020. Breeder friendly phenotyping. *Plant Sci.*, **295**: 110396.
- Rezaei-Chiyaneh, E., Mahdavia. H., Alipour, H., Dolatabadian, A., Battaglia, M.L., Maitra, S., Harrison, M.T. 2023. Biostimulants alleviate water deficit stress and enhance essential oil productivity: a case study with savory. *Sci. Rep.*, **13**(1): 720.
- Rishitha, S., Santosh, D.T., Ray, S., Gitari, H.I., Sairam, M., Lalichetti, S., Gaikwad, D.J., Nanda, S.P. and Maitra, S. 2025. Resilient Fields, Profitable Yields: The Promise of Intercropping Systems in a Changing Climate for Economic Gains. *Agro Econ. Int. J.*, **12**(02): 55-67.
- Sairam, M., Maitra, S., Ray, S., Maity, B. and Pradhan, P. 2025a. Influence of need-based nutrient management on yield and nutrient use efficiency of Rabi maize (*Zea mays* L.) under sandy loam soils of Odisha, India. *Farm. Manage.*, **10**(1): 11–19.
- Sairam, M., Maitra, S., Sagar, L., Biswas, T., Bárek, V., Brestic, M. and Hossain, A. 2025b. Application of precision nutrient tools for the optimization of fertilizer requirements and assessment of the growth and productivity of maize (*Zea mays* L.) in the northeastern Ghat of India. *J. Agric. Food Res.*, **21**: 101958.
- Santosh, D.T., Debnath, S., Maitra, S., Sairam, M., Sagar, L.L., Hossain, A. and Moulick, D. 2024. Alleviation of climate catastrophe in agriculture through adoption of climate-smart technologies. In: *Climate Crisis: Adaptive Approaches and Sustainability*. (eds; Chatterjee, U., Shaw, R., Kumar, S., Raj, A. D. and Das, S.) Springer Nature Switzerland, pp. 307-32. https://doi.org/10.1007/978-3-031-44397-8_17.
- Suresh, D., Kachapur, R.M., Talekar, S.C. and Gurumurthy, R. 2021. Genetic variability and trait association studies in maize (*Zea mays* L.). *J. Farm Sci.*, **34**(2): 122–125.
- Zaman, A., Zaman, P. and Maitra, S., 2017. Water resource development and management for agricultural sustainability. *J. Appl. Adv. Res.*, **2**(2): 73-77.

