**Climate Resilience of Aromatic Rice Genotypes in Zambia: Genetic Potential and Multi-Environment Performance**

***Abstract***

*This study evaluated the performance of nine aromatic rice genotypes across three environments in Zambia, varying in rainfall, temperature, and rainfall distribution which are Namushekende, Longe and Mt Makulu testing sites.* *Rice production in Zambia faces challenges due to diverse and changing environmental conditions.* *Aromatic rice cultivation in Zambia is gaining attention for its economic potential, driven by the high market demand for its unique aroma and flavor, which is linked to the presence of 2-acetyl-1-pyrroline. Genotype-by-environment (GxE) interactions are a critical consideration in rice breeding, significantly influencing yield stability and a variety's adaptability across diverse agro-ecological zones.*

*The experiments were carried out on three different sites with two sites in Western Province of Zambia. Eight aromatic rice genotypes were assessed for yield and yield component performance across the three sites.* *Data was collected on yield and yield component traits for rice as follows: plant height, days to flowering, days to maturity, number of tillers per hill, culm length, panicle length, number of filled grains per panicle, fertility ratio, 1000 seed weight, grain yield biomass yield and harvest index. Collected data was subjected to analysis of variance using the Jamovi data analysis software (version 2.3.28). Turkey tests were also done to determine the comparison among genotypes in the measured variables. The results showed significant genotype-by-environment interactions, with some genotypes exhibiting drought and heat tolerance, while others were more adapted to high rainfall conditions. Genotypes ZMORY-02, ZMORY-03, ZMORY-04 and ZMORY-05 demonstrated good adaptability to droughty conditions as shown by relatively superior performance at Longe which was characterized by reduced rainfall and high mean temperatures. ZMORY-02 and ZMORY-08 demonstrated good general adaptability, performing well across the three environments. The study highlights the importance of considering specific environmental conditions when selecting and recommending rice varieties for cultivation in Zambia. The findings provide valuable insights for rice breeders to develop high-yielding, adaptable, and environment-specific aromatic rice varieties for Zambia's agroecological regions. Further research, including more extensive field trials and genetic analyses, is warranted to enhance our understanding of the underlying genetic mechanisms and to refine breeding strategies for improved rice productivity and stability.*

***Keywords:*** *Aromatic rice, Genotype-by-environment interactions, Adaptation, rainfall*

**Introduction**

Changing climate and global population pressure pose major concerns to rice (*Oryza sativa* L.) production (Behera et al., 2023). Enhancing rice productivity with broad-spectrum genetic resistance to multiple stresses is an economically feasible and environmentally sustainable alternative (Dugasa et al., 2019).

Rice has a wide span of agro-ecologies to which it is adapted across the globe (Wassman et al,, 2009). Furthermore, the crop is considered a staple constituent of the diets of more than 3.5 billion people and provides 35-85% of calorie uptake globally (Ray et al, 2013). Estimates indicate that in order to keep apace with population growth, rice production should increase by 60-110% by 2050. However, climate change poses a significant threat to agriculture, especially in developing countries, by causing abiotic stresses like drought, which is the most critical factor limiting rice production in rain fed areas (Nelson et al., 2014; Pandey and Shukla, 2015). Aromatic rice is highly valued and in high market demand due to its distinct characteristics like aroma, taste and quality traits (Bhattacharjee & Dey, 2018). Typically, scented rice cultivars are low yielders in contrast to the non-fragrant rice counterparts and are highly susceptible to abiotic stresses i.e. salinity, flooding and drought. However, there is limited published reports are available on diversity and genetic structure of aromatic rice varieties for multiple abiotic stress tolerance (Prodhan & Qingyao, 2020; Dutta et al., 2022). Aromatic rice varieties are prized for their distinct aroma and flavor, primarily attributed to the volatile compound 2-acetyl-1-pyrroline (Mahadevamma et al., 2011). The distinct aroma makes these varieties have high market demand and thus likely to fetch higher prices than normal ones.

Aromatic rice cultivation in Zambia is gaining attention for its economic potential, driven by the high market demand for its unique aroma and flavor, which is linked to the presence of 2-acetyl-1-pyrroline (Bradbury et al., 2008). This premium-quality rice fetches higher prices in both local and international markets, offering farmers an opportunity to improve their livelihoods (Diako et al., 2020). However, the production of aromatic rice faces significant challenges due to Zambia's diverse agroecological conditions, including erratic rainfall patterns, prolonged droughts, and rising temperatures (IPCC, 2021). Recent studies have highlighted the importance of genotype-by-environment interactions in identifying rice varieties that can thrive under specific climatic stresses, such as drought or excessive rainfall (Kumar et al., 2014). For instance, drought-tolerant aromatic rice genotypes have shown promising yields in low-rainfall regions, while others perform well in high-rainfall areas (Saito et al., 2011). By leveraging these findings, Zambia can develop and promote climate-resilient aromatic rice varieties tailored to its agroecological zones, thereby enhancing productivity and food security (Mabhaudhi et al., 2019). With targeted research, improved agronomic practices, and supportive policies, aromatic rice cultivation has the potential to become a cornerstone of sustainable agricultural development in Zambia (Tembo & Sitko, 2013).

Genotype-by-environment (GxE) interactions are a critical consideration in rice breeding, significantly influencing yield stability and a variety's adaptability across diverse agroecological zones (Kang, 2013). Recognizing the impact of GxE is essential for developing rice varieties that are well-suited to specific environmental conditions, such as those encountered in Zambia (e.g., GRZ, 2017). Numerous studies have demonstrated that GxE interactions affect key agronomic traits, including grain yield, plant height, and time to maturity (Yan and Kang, 2003). The increasing environmental variability associated with climate change further underscores the need to develop climate-resilient rice varieties (IPCC, 2021). Consequently, incorporating GxE analysis into breeding programs enables the development of more effective and targeted breeding strategies, ultimately contributing to enhanced rice productivity and sustainable production systems, particularly in regions like Zambia.

A study was undertaken during the 2023/24 growing season to assess the performance of selected rice genotypes over three different environments in Zambia spanning two agro-ecological regions.

**Materials and Methods**

**Fig 1: map of Study Sites**



The experiments were carried out on three different sites with two sites in Western Province of Zambia (Namushekende and Kaoma) and once in Lusaka Province (Chilanga)

**Table 1: Weather Data**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **SITE/SEASON** | **RAINFALL**  **(mm)** | **RAIN DAYS** | **TEMPERATURE** | | |
| Max.(0C) | Min.(0C) | Average .(0C) |
| **Mt Makulu 2023/2024** | 753.9 | 42 | 30.0 | 18.0 | 23.4 |
| **Namushakende 23/24** | 543.20 | 40.00 | 32.0 | 20.23 | 27.2 |
| **Longe (23/24)** | 125 | 9 | 38 | 24 | 31 |

**Trial Genotypes**

Eight aromatic rice genotypes were assessed for yield and yield component performance across the three sites. The genotypes were as listed in the table below:

**Table 2: List of Rice Genotypes Evaluated**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Entry No** | **Parentage** | **Pedigree/ Genotype** | **Variety** | **Status** | **VCU** | **Source** |
| 1 | WITA 1/ Pusa Basmati | WAB 2066-12-FKR4-2-TGR1-2 | Zmory-01 | Test genotype | Aromatic | Africa Rice |
| 2 | FEDEARROZ 50/IR 77298-14-1-2-10//IRRI.  123/IR07F287///SANHUANGZHAN NO 2/IRRI 146//IR 45427-2B-2-2B-1-1.IR 4630-22-2-5-1-3 | ZMORY-03 |  | Test genotype | Aromatic | IRRI |
| 3 | WAS 181-B-1-1 | ZMORY-09 |  | Test genotype | Aromatic | Africa Rice |
| 4 | SAHEL 108/IR 4630-22-2 | ZMORY-02 |  | Test genotype | Aromatic | Africa Rice |
| 5 |  | ZMORY-05 |  | Test genotype | Quality/Yield |  |
| 6 |  | ZMORY-04 |  | Test genotype | Quality/Yield |  |
| 7 |  | ZMORY-07 |  | Test genotype | Aromatic |  |
| 8 | *O. glaberrima* X *O. sativa* | ZMORY-06 | NERICA-1 | Check variety | Aromatic upland |  |

**Land Preparation and Sowing**

The land preparation process began with the removal of surface vegetation, followed by tilling and harrowing to mix and overturn the soil. The field was then prepared for experimentation, with 30cm high borders created to facilitate flooding irrigation and the field was divided into 7.5m2 units. Seedlings were nurtured in nursery beds for 14 days before being transplanted into the field, where they were carefully spaced 15 cm apart within rows and 30cm apart between rows, with two seedlings per station and five rows per plot.

**Fertilizer application**

Two weeks after transplanting, once the seedlings were established, a basal dressing of 200 kg/ha of Compound D fertilizer (10N:20P:10K) was applied evenly to each plot. Later, a top dressing of 100 kg/ha of Urea (36%N) was split into two applications: 50 kg/ha at the advanced vegetative stage, and another 50 kg/ha at the panicle initiation stage. Other operations such as weed management and general crop protection were carried out according to recommended practices for rice production.

**Harvesting and Threshing**

Harvesting was done as each genotype attained 100% grain maturity, Hand Sickle was used for cutting straw at the base while individual polythene bags were used to thresh by hitting with a right stick on panicles from separate experimental units to avoid mixing of genotypes.

**Experimental Design and Data Management**

Trials on all three sites were laid out in a Randomized Complete Block Design (RCBD) with four replications. Data was collected on yield and yield component traits for rice as follows: plant height, days to flowering, days to maturity, number of tillers per hill, culm length, panicle length, number of filled grains per panicle, fertility ratio, 1000 seed weight, grain yield biomass yield and harvest index.

Collected data was subjected to analysis of variance using the Jamovi data analysis software (version 2.3.28). Turkey tests were also done to determine the comparison among genotypes in the measured variables.

**Results**

**Analysis of Variance**

Results from analysis of variance indicate that location had a highly significant (p<0.001) effect on all traits studied, indicating that the environment played a crucial role in the ultimate performance of rice genotypes. Anova also indicated that genotype had a highly significant (p<0.001) effect on all traits except the harvest index. This indicates that the rice variety used will determine the level of crop performance in the studied traits. Significant genotype effects also indicate that the rice genotypes evaluated had considerable differences in genetic constitution thus impacting their differential response to environmental changes. Furthermore, genotype-by-location interaction effects were highly significant (p<0.001) for all traits which entails that the performance of rice genotypes in the experiment differed across sampled environments (Table 3). In their study on genotype by environment interactions among rice genotypes in yield and related traits, Huang et al (2021) also established significant genotype, environment and genotype by environment interactions among eighty-nine rice genotypes for yield and related traits.

**Table 3: Mean Squares from Analysis of Variance**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Mean Squares** | | | | | | | | | | | |
| Source of Variation | Days to Maturity | Plant Height | Productive  Tillers | Culm  Length | 1000  Grain weight | Grains/Panicle | Spikelet/Panicle | Fertility Ratio | Grain Yield | Biomass Yield | Harvest  Index |
| Location | 12418.9\*\*\* | 5736.1\*\*\* | 78.25  \*\*\* | 3190  \*\*\* | 327.4  \*\*\* | 18611.5  \*\*\* | 4237  \*\*\* | 7220.5  \*\*\* | 2.08x108  \*\*\* | 2.98x108  \* | 14213  \*\*\* |
| Genotype | 394.5  \*\*\* | 1301  \*\*\* | 38.29  \*\*\* | 752  \*\*\* | 74.58  \*\*\* | 1986.3  \*\*\* | 2946  \*\*\* | 363.9  \*\*\* | 1.15x106  \*\*\* | 9.96x107  ns | 271.7  \*\*\* |
| Genotype x Location | 213.1  \*\*\* | 584.1  \*\*\* | 14.86  \*\*\* | 420  \*\*\* | 28.  \*\*\* | 1357.1  \*\*\* | 1282  \*\*\* | 298.8  \*\*\* | 1.29x106  \*\*\* | 7.01x107 | 424.6  \*\*\* |
| Error | 7.65 | 18.5 | 6.01 | 192 | 1.67 | 71.2 | 185 | 13.9 | 113926 | 7.09x107 | 39.6 |

\*\*\* Significant at p=0.01 \* Significant at p=0.05

**Mean Performance of Rice Genotypes**

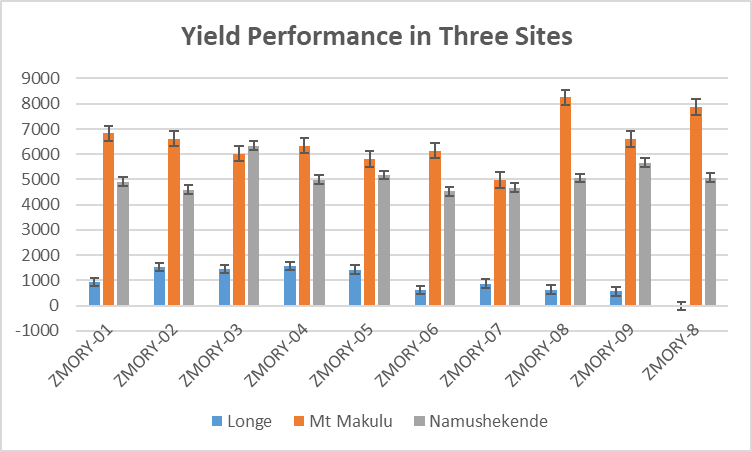
Considerable variation was observed for days to maturity among rice trial genotypes with the shortest maturity duration recorded on ZMORY-06 (92.8 days) and the latest maturity duration for ZMORY-04 (108.1 days). Considerable variation was observed for culm length among rice trial genotypes, with the longest culm recorded on ZMORY-07 (80 cm) and the shortest on ZMORY-02 (50.8 cm). Significant differences were observed for panicle length, with the longest panicle recorded on ZMORY-01 (22.2 cm) and the shortest on ZMORY-03 (20.5 cm).

Plant height varied noticeably among genotypes, with the tallest plant recorded on ZMORY-07 (111 cm) and the shortest on ZMORY-02 (72.2 cm). The number of tillers showed substantial variation, with the most tillers recorded on ZMORY-09 (12.76) and the fewest on ZMORY-07 (6.43). Seed weight differed significantly among genotypes, with the heaviest seed recorded on ZMORY-07 (29.4 g) and the lightest on ZMORY-03 (20.3 g). The number of grains per panicle varied significantly, with the most grains recorded on ZMORY-04 (129) and the fewest on ZMORY-02 (96.9).

Spikelets per panicle also showed significant variation, with the most spikelets recorded on ZMORY-04 (150) and the fewest on ZMORY-06(112). Fertility percentage differed substantially among genotypes, with the highest fertility recorded on ZMORY-04 (85%) and the lowest on ZMORY-08 (68.4%). Grain yield per hectare varied significantly, with the highest yield recorded on ZMORY-03 (4601 kg/ha) and the lowest on ZMORY-06 (3508 kg/ha). The harvest index percentage showed significant variation, with the highest harvest index recorded on ZMORY-03 (68.1%) and the lowest on ZMORY-09 (49.3%).

**Table 4: Mean Performance of Rice Genotypes in Yield and Yield Components**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Genotype** | **Days to**  **Maturity** | **Culm**  **Length** | **Panicle**  **length** | **Plant**  **height** | **Tillers** | **Seed**  **Weight** | **Grains/**  **Panicle** | **Spikelets/**  **Panicle** | **Fertility** | **Grain**  **Yield** | **Harvest**  **Index** |
| ZMORY-01 | 103.3abc | 66.3bc | 22.2 | 88.3bc | 11.07bc | 20.8bc | 119.7bc | 156bc | 77ab | 4225ab | 56.2bc |
| ZMORY-02 | 94.7ab | 50.8a | 20.9 | 72.2a | 10.98bc | 20.6bc | 102ab | 112a | 76.8ab | 4247ab | 53.9b |
| ZMORY-03 | 102.1abc | 52.4a | 20.5 | 73.5a | 10.5bc | 20.3bc | 111.6bc | 136ab | 83.7c | 4601bc | 68.1d |
| ZMORY-04 | 108.1cd | 66.5bc | 21 | 77.6ab | 13.44d | 24.9d | 129c | 150bc | 85c | 4297ab | 57.5bc |
| ZMORY-05 | 110.5d | 66.8bc | 20.4 | 90.4bc | 11.61bc | 22.7bc | 96.9a | 118a | 81.6bc | 4140ab | 59.8cd |
| ZMORY-06 | 92.8a | 62.3ab | 20 | 78.8ab | 9.42ab | 24.7ab | 98.5ab | 112a | 84.6c | 3508a | 50.5ab |
| ZMORY-07 | 112.4d | 80d | 20.9 | 111d | 6.43a | 29.4a | 77.1a | 114a | 68.5a | 3760a | 55.6bc |
| ZMORY-08 | 103.7abc | 54.6a | 20.7 | 76.8ab | 9.52ab | 23.7ab | 103.5ab | 151bc | 68.4a | 4607bc | 56b |
| ZMORY-09 | 100.7abc | 66.2bc | 20.7 | 82.5b | 12.76cd | 22cd | 111bc | 141ab | 80bc | 4278ab | 49.3a |
| **Grand Mean** | 103.1 | 62.9 | 20.8 | 83.5 | 10.6 | 23.2 | 105.5 | 132.2 | 78.4 | 4184.8 | 56.3 |
| LSD | 4.63 | 3.9 | 4.1 | 3.3 | 0.68 | 0.7 | 1.6 | 9.2 | 0.8 | 3.4 | 1.2 |
| CV | 7.1 | 15 | 14.3 | 15.6 | 19.3 | 20.3 | 18.3 | 13.2 | 8.2 | 12.5 | 9.8 |

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**Fig 2: Yield Performance in three study sites**

**Yield Performance in Each of the Test Sites**

Analysis of aromatic rice genotype performance at Longe, the test site with the lowest rainfall (125 mm) and fewest rain days (9) but highest maximum (38°C) and average (31°C) temperatures, revealed that ZMORY-02, ZMORY-03, ZMORY-04 and ZMORY-05 had significantly higher yields, indicating drought and heat tolerance, while ZMORY-05 also performed relatively well, suggesting some drought tolerance. ZMORY-03 and ZMORY-08 performed well at Namushekende, which had a relatively high average temperature (27.2°C), suggesting they may be heat-tolerant. ZMORY-08 and ZMORY-09 had high yields at Mt. Makulu, which had the highest rainfall (753.9 mm) and most rain days (42), indicating they are adapted to high rainfall conditions. ZMORY-01 also performed well at Mt. Makulu, suggesting some level of adaptation to high rainfall. ZMORY-02 showed consistent yields across all three environments, indicating good general adaptability. ZMORY-08 performed well across multiple environments, suggesting good adaptability and stability.

**Discussion**

The results of this study demonstrated significant effects of both genotype and environment on the performance of aromatic rice genotypes. This finding aligns with previous research by Huang et al. (2021) which also observed significant genotype, environment, and genotype-by-environment interactions in rice. The significant genotype effect across most traits highlights the genetic diversity among the evaluated genotypes and their inherent potential for differential performance. The significant environmental effect underscores the importance of considering environmental factors in rice breeding and cultivation programs. The highly significant genotype-by-location interaction further emphasizes that the performance of a particular genotype can vary considerably across different environments. This indicates that the optimal genotype for a specific location may not necessarily perform well in another, necessitating site-specific variety recommendations as demonstrated by the differential agronomic performance of ZMORY-02, ZMORY-03, ZMORY-04 and ZMORY-05 across the different agro-ecologies.

The observed variation in days to maturity, culm length, plant height, tiller number, panicle length, seed weight, number of grains per panicle, spikelets per panicle, fertility percentage, grain yield, and harvest index among the genotypes highlights the potential for genetic improvement in these traits. Genotypes like ZMORY-06 demonstrated superior performance in terms of grain yield and harvest index, while others like ZMORY-07 exhibited early maturity. These findings provide valuable information for breeders to select and develop high-yielding and adaptable aromatic rice varieties.

**Conclusion**

This study revealed significant genotypic and environmental influences on the performance of aromatic rice genotypes. The observed genotype-by-environment interaction highlights the importance of considering specific environmental conditions when selecting and recommending rice varieties for cultivation in Zambia. Genotypes such as ZMORY-03 demonstrated superior performance in terms of grain yield and harvest index, while others like ZMORY-06 exhibited early maturity. These findings provide valuable insights for rice breeders to develop high-yielding, adaptable, and environment-specific aromatic rice varieties for Zambia’s agroecological regions. Genotypes ZMORY-02, ZMORY-03, ZMORY-04 and ZMORY-05 should be considered for deployment in hot and semi-dry conditions as well as sources of genes for breeding rice varieties adapted to hot and dry agro-ecologies. ZMORY-08 and ZMORY-09 are adaptive to very wet conditions typical in traditional rice production agroecologies. Further research, including more extensive field trials and genetic analyses, is warranted to enhance our understanding of the underlying genetic mechanisms and to refine breeding strategies for improved rice productivity and stability.

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