Assessing morphological traits of high yielding aus rice varieties in Bangladesh

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ABSTRACT

Crop improvement relies on the variability observed in morphological characteristics among different plant materials. In pursuit of this goal, an experiment was carried out at the BINA sub-station farm in Barishal, Bangladesh from April to August 2020, utilising five distinct aus rice varieties: Iratom-24, Binadhan-14, Binadhan-19, BRRI dhan48, and BRRI dhan82. The objective was to investigate how morphological traits influenced yield performance. The results of the study unveiled significant correlations between specific morphological characteristics and grain yield. Notably, plants exhibiting larger flag leaves in terms of both length and width, coupled with a smaller leaf angle, tended to produce higher grain yields. Additionally, an increased number of filled grains per panicle, longer grain length, and a higher number of tillers per hill were also associated with greater grain yield. In terms of yield performance among the tested varieties, BRRI dhan48 emerged as the top performer, boasting the highest grain yield. It was closely followed by Binadhan-19 and BRRI dhan82, both of which exhibited commendable yield potential. These findings underscore the pivotal role of morphological traits in determining crop productivity and underscore the importance of selecting and breeding varieties that exhibit favorable characteristics for enhanced agricultural output. To refine our understanding of these relationships, even more effective crop improvement strategies are needed to meet the growing global demand for food.

Introduction

Rice (*Oryza sativa* L.) is one of the major food crops worldwide, especially in Asia, where it serves as a staple dietary for about half of the global population (Bagirov et al. 2020). In Bangladesh, approximately 37.61 MT of rice are produced annually from 11.72 Mha of land. This substantial output serves as the primary food source for the majority of the population. About 76% of the total crop land is under rice cultivation and more than 66% of the total agriculture labour force is engaged in rice production and related works (BBS 2022). Bangladesh suffers from the one of the lowest land–man ratios of the world making it difficult to achieve food security (Rahman and Salim 2013). Rapid population growth and economic development are creating extra pressures for the need to increase food production. Hence, there is a pressing need to enhance rice production to meet the basic human needs and ensure food and nutritional security for the ever-increasing population (Shelley et al. 2016).

In Bangladesh, rice production revolves around three major crops: aus, aman, and boro, each cultivated in different seasons and utilising various varieties suited to diverse climatic conditions. Aman rice is planted in July-August and harvested in November-December; boro rice is planted in December-January and harvested in May-June. Aus rice, grown as a pre-monsoon upland crop, is typically planted in March-April and harvested in July-August. However, due to erratic

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rainfall, limited irrigation, and lower yield potential, many farmers leave their land fallow during this season and are reluctant to cultivate transplanted aus rice (Chowhan et al. 2021). Therefore, the development and selection of suitable varieties are crucial for maximising aus rice production, taking into account location, land type and planting time (Dey et al. 2018; Rahman et al. 2018).

Understanding the relationship between growth and developmental, physiological and yield-related characters helps to select a good yield producing variety. Several studies have been conducted for selecting plant ideotype and selection of yield-related traits, which are easier to measure precisely than yield itself; these have been used as an effective strategy for yield improvement (Kumar et al. 2014).

Morphological and physiological traits have an important role in rice yield production, through improving the efficiency of resource capture (Kakar et al. 2021). High-yielding rice varieties show higher leaf photosynthetic rates and chlorophyll content (Tari et al. 2009; Chang et al. 2016); these factors are related to the variation in biomass production and yield (Ambavaram et al. 2014; Makino 2021). In addition, flag leaf width, length and angle play an important role for grain yield production through translocation of carbohydrate from leaf to the spikelet during grain filling (Davood et al. 2009; Mahesh et al. 2022). Rice yield is directly contributed by grains per panicle. panicle length, and panicle architecture, (Akter et al. 2014; Bai et al. 2016). Thus, rice yield potential is improved by many factors including morphological attributes, harvest index and total biomass production (Badger 2013; Puteh et al. 2014). So, improvement of yield-related morpho-physiological traits has become a priority area over the years (Dutta et al. 2013).

However, climate change in terms of decreasing, shifting and uncertainty of rainfall is anticipated to reduce crop cultivation and production during the Kharif-I (March-July) season in Bangladesh (Rahman et al. 2017). It is crucial for plant scientists to recognize the impact of traits on grain yield in order to identify promising traits for the development and enhancement of rice yield production, particularly under water deficit conditions (Li et al. 2019; Won et al. 2020). Ata-Ul-Karim et al. 2022; Phyu et al. 2020 and Zeng et al. 2017 have shown how variety selection, and environmental and management practices influence yield. Therefore, the present study was conducted to examine how morpho-physiological traits cause yield variation in cultivated high yielding aus rice varieties in Bangladesh.

Materials and methods

Experimental site, seeding and management

An experiment was carried out at the BINA (Bangladesh Institute of Nuclear Agriculture) sub-station farm, Rahmatpur, Barishal from April 2020 to August 2020 to observe the growth and yield performance of aus rice in natural growth conditions. The experimental site is located at 24^0 75´ N latitude and $90^0$50´ E longitude at an altitude of 18m above the mean sea level. The area has complex mixtures of calcareous sandy, silty, clay alluvium that are low in organic matter. The general fertility status is medium but deficient in N, which is placed in Bangladesh AEZ 13 (Agro-Ecological Zone). The percentage of sand, silt and clay of the soil at the experimental site is 30%, 38% and 32% respectively. The experimental field is medium high land with moderate drainage.

Five high yielding and drought tolerant aus rice varieties developed by BINA and BRRI (Bangladesh Rice Research Institute) were examined namely, Iratom-24, Binadhan-14, Binadhan-19, BRRI dhan48 and BRRI dhan82. Seeds were soaked in water for 24 hours and then placed in gunny bags for sprouting. Sprouted seeds were sown separately in a seedbed prepared for making rice seedlings. Thereafter, the experimental site was prepared and a basal fertiliser dose of triple superphosphate (110 kg ha^{-1}), muriate of potash (120 kg ha^{-1}), gypsum (60 kg ha^{-1}) and zinc sulphate (5 kg ha^{-1}) incorporated into soil. Urea (180 kg ha^{-1}) was applied in two equal splits at 15 and 30 days after transplanting (DAT) as top dressing. Finally, the 22-day old seedlings were uprooted and transplanted in the experimental plots maintaining lines 20 cm apart with 15 cm spacing between the hills. Intercultural operations were done based on the field situation to ensure proper plant growth.

Experimental design and data collection

The experiment was laid out in a randomised complete block design with three replications where every replication represented as a block and each block was divided into five-unit plots. All the treatments were randomly allocated in the experimental plots. The plot size was 4.0 x 3.0 m with 1 m distance between replications and 0.5 m between plots. To investigate ontogenetic growth characteristics, initial crop sampling commenced at 25 and 35 days after transplanting (DAT), with subsequent samplings conducted at 10-day intervals until harvest. For each treatment, three plants were randomly selected and uprooted for data collection. The collected plants were then oven-dried at 80 ± 2°C for 72 hours and weighed to determine total dry mass (TDM). Rice plants were harvested after 90% maturity of the grains; then data on plant height, panicle length, grain length and width, rachis branches and yield were recorded from ten randomly selected plants from every plot.

Statistical analysis

A normality assessment was conducted on all datasets that contained morphological and yield-contributing characteristics using the Shapiro–Wilk test. A two-way ANOVA was used to compare group means. Mean comparisons were performed using the post hoc least significant difference (LSD) test at $P \leq 0.05$. The statistical analysis was performed using R programming language version 4.2.1 (Wickham 2016).

Regression analysis was used to explore the relationship between grain weight per plant and dry weight per plant, with dry weight per plant as the independent variable.

$$Y = \mu + \beta X + \varepsilon$$

Where, Y indicates the grain weight per plant (g) at 14% moisture content; X indicates the dry weight per plant (g); ϵ is error term.

Results and discussion

Growth and morphological appearances

Growth and development of rice plants were compared visually from the early tillering stage to the maturity stage (Figure 1). At the early tillering stage, there was no apparent difference but maximum tillering stage and flowering stage exhibited differences in plant height. At harvest, plant height was significantly different among the varieties. BRRI dhan48 and BRRI dhan82 exposed the highest plant height and Binadhan-19 produced the shorter plants than the other studied varieties. Rahman et al. 2018 reported that plant height of BRRI dhan48 was 105 cm, which was similar to the present result.

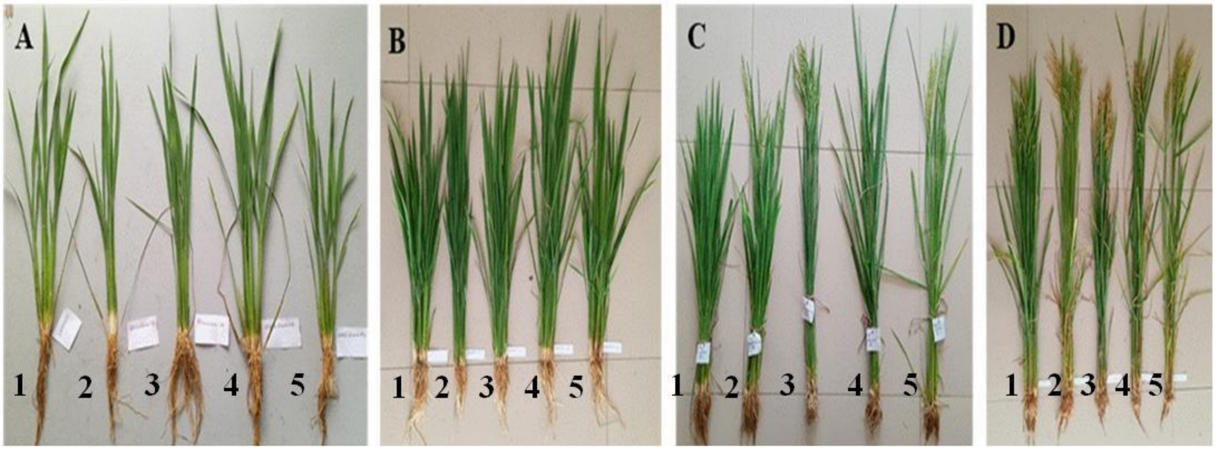

Figure 1: Morphological appearance of five aus rice varieties; 1) Iratom-24, 2) Binadhan-14, 3) Binadhan-19, 4) BRRI dhan48 and 5) BRRI dhan82 in the A: early tillering stage, B: maximum tillering stage, C: flowering stage, D: maturity stage

The tillering ability of rice is directly linked to grain yield and is significantly influenced by environmental conditions (Takai 2023). The highest number of tillers per hill was produced by Iratom-24 and Binadhan-19 and BRRI dhan48 and BRRI dhan82 produced the lowest number of effective tillers per hill. Most of the varieties produced the highest number of tillers at 55 days after transplanting (Figure 2), after which tiller numbers tend to decrease, possibly due to the elimination of non-effective tillers initiated later. This observation aligns with the findings of Khatun et al. (2020).

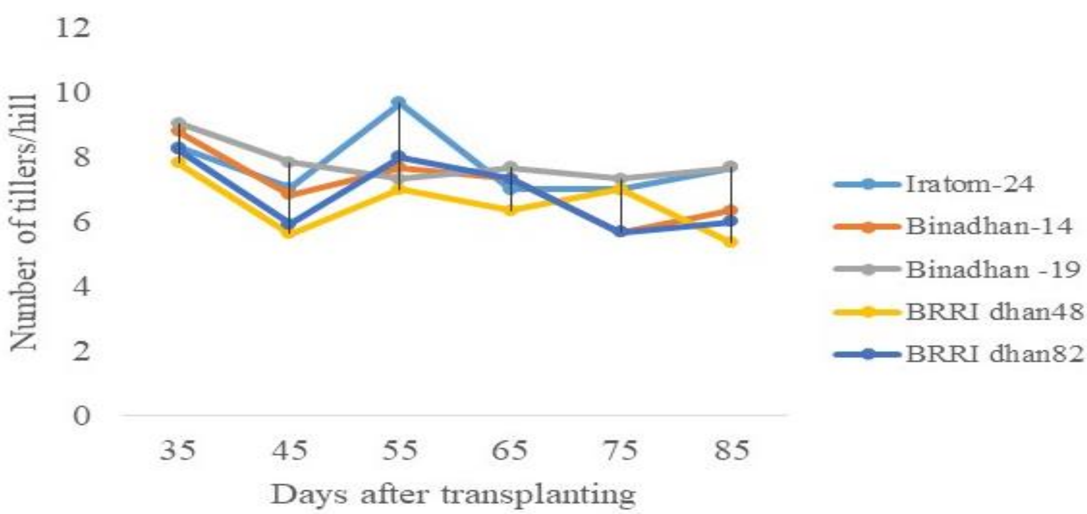

Figure 2: Tillering pattern of five aus rice varieties

In normal rice plants, internode elongation is triggered by the transition to the reproductive growth stage. The relative lengths of each internode of the culm in five varieties, which play a role in determining plant height, are shown in Figure 3. Across all varieties, the contribution of the internodes to total culm length decreases in length from first to fifth. Notably, Iratom-24 lacks the 5th internode, potentially contributing to increased resistance to lodging. The result is consistent with the report of Lan et al. (2023) in rice who stated that the plant height is controlled by the proportional shortening of the internodes and the length of the internode is dependent on its cell growth and development.

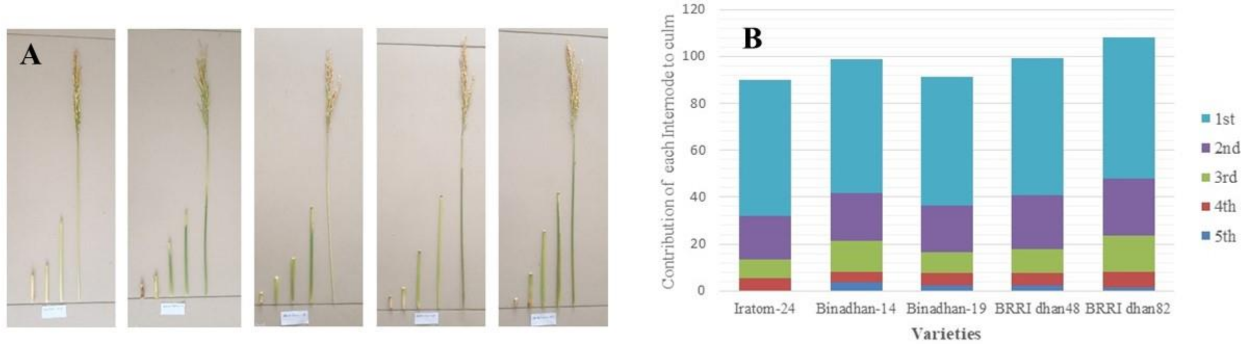

Figure 3: Internode elongation patterns; A. Schematic representation of the upper five internodes of five rice varieties; left to right: Iratom-24, Binadhan-14, Binadhan-19, BRRI dhan48, BRRI dhan82; B. Relative contribution of each internode to the total culm length

A longer flag leaf allows for greater light absorption, enhancing photosynthetic capacity and ultimately increasing the production of carbohydrates which play a crucial role in supporting various growth processes. All the tested cultivars showed significant differences in flag leaf angle, flag leaf length and flag leaf width (Table 1). BRRI dhan82 exhibited the largest leaf angle, while the smallest was observed in Binadhan-14. Iratom-24 had the longest flag leaf, followed by BRRI dhan48 and BRRI dhan82, whereas the shortest leaf length was recorded in Binadhan-19, closely followed by Binadhan-14. Narrower flag leaves were found in Binadhan-19, followed by BRRI dhan82, with Iratom-24 having the widest leaf width, all showing statistically significant differences. Iratom-24 showed the highest leaf area considering the flag leaf length and width compared to other varieties (Table 1). The flag leaf structure and position of a cultivar determines the amount of photosynthetic activity (Prakash et al. 2011) which affects grain yield adjusting the canopy structure and other important yield contributing parameters (Fukushima et al. 2011; Makino 2021). However, another study suggested that there was no significant correlation between the photosynthetic rate and flag leaf length at the heading stage (Oishi et al. 2015). In the present study, Iratom-24 had the longest and broadest leaves that might help in producing sufficient assimilates thereby serving in proper growth and development.

Table 1: Comparison of flag leaf in five aus rice varieties

Variety	Flag leaf angle	Flag leaf length	Flag leaf width
Iratom-24	25.3^{b}	34.7^{a}	1.26^{a}
Binadhan-14	10.2^{e}	28.4^{b}	1.03^{b}
Binadhan-19	18.3^{d}	26.0^{b}	0.86^{b}
BRRI dhan48	20.3^{c}	33.9^{a}	1.03^{b}
BRRI dhan82	31.0^{a}	33.7^{a}	1.00^{b}
CV %	6.81	4.16	10.22

Total dry mass production at different growth stages

Biomass serves as a crucial variable in rice crops, with its accumulation throughout growing cycles providing valuable insights for identifying high-producing varieties (Yamashita et al. 2022). The total dry matter (TDM) production in all studied rice varieties increased with age up to maturity except

Binadhan-14 (Figure 4). At most growth stages Iratom-24 had the highest TDM and the lowest TDM was recorded in Binadhan-14 (Figure 4). Higher dry matter production is probably due to better photosynthesis rate and chlorophyll content in leaves (Li et al. 2018). Increased TDM accumulation at 85 DAT indicates TDM partitioning into reproductive parts which ultimately contribute to grain yield production.

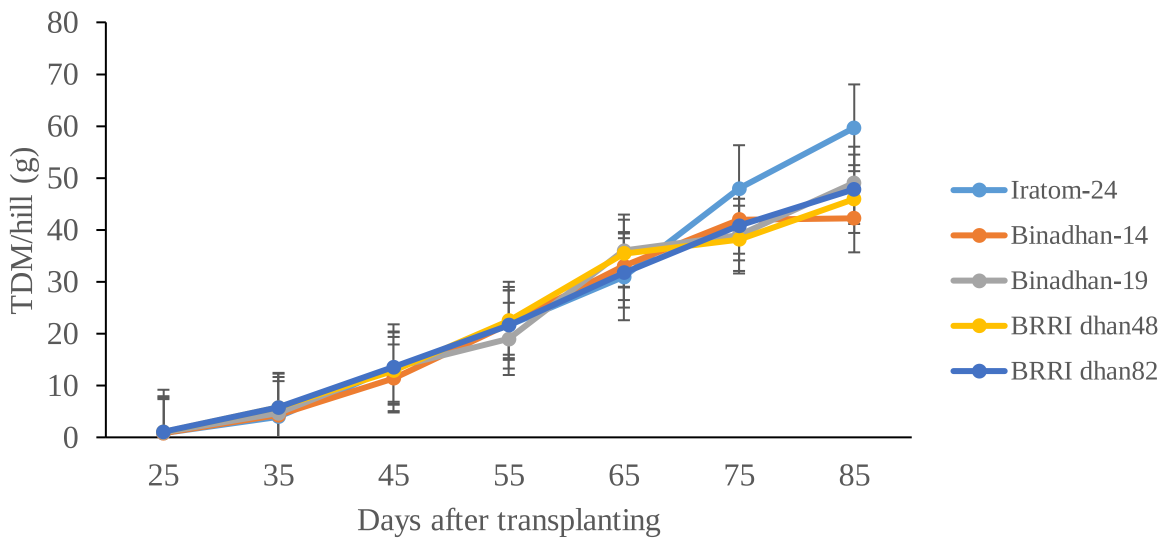

Figure 4: Total dry mass production at different growth stages of five aus rice varieties

Morphological characters at harvest

Details of different parameters related to phenological characteristics are given in Table 2. The longest time (days) for heading was recorded for Iratom-24 and the lowest days for Binadhan-19. However, it is recommended that Binadhan-19 is suitable for a four crop-based pattern (aman-mustard-mungbean-aus) in Bangladesh. Iratom-24 produced the maximum number of tillers/plant, followed by Binadhan-19 and BRRI dhan48. It noted a variation in the number of total tillers due to varietal differences (Akter et al. 2019). The straw weight showed significant difference among the studied varieties; Iratom-24 produced the highest straw yield and the lowest was recorded in BRRI dhan82 (Table 2).

Table 2: Morphological and yield attributes of five Aus rice varieties

Variety	**Heading date**	**Plant height (cm)**	**Tiller/ plant (No)**	**Primary rachis (No)**	**Secondary rachis (No)**	**Grain length (cm)**	**Grain width (cm)**	**Straw weight/ hill (g)**	**Panicle length (cm)**	**Filled grains/ panicle (No)**	**Unfilled grains/ panicle (No)**	**1000 seeds weight (g)**	**Yield/m^2 (g)**
Iratom - 24	July 29	103^{ab}	7.7^{a}	12.0^{a}	47.7^{a}	0.93^{a}	0.33^{a}	27.6^{a}	23.9^{a}	134^{a}	43^{a}	27.6^{a}	559^{ab}
Binadhan-14	July 16	94^{bc}	5.0^{b}	10.3^{ab}	46.3^{a}	0.96^{a}	0.26^{ab}	22.7^{ab}	23.9^{a}	123^{a}	26^{b}	23.0^{b}	488^{b}
Binadhan-19	July 10	93^{b}	7.0^{a}	9.7^{b}	31.7^{c}	0.95^{a}	0.23^{b}	22.4^{ab}	21.4^{b}	86^{b}	25^{b}	23.2^{b}	569^{ab}
BRRI dhan48	July 14	106^{a}	7.0^{a}	10.3^{ab}	44.0^{ab}	0.56^{a}	0.23^{b}	23.0^{ab}	23.1^{ab}	124^{a}	27^{b}	21.9^{b}	591^{a}
BRRI dhan82	July 11	106^{a}	6.3^{a}	8.7^{b}	32.7^{bc}	0.80^{a}	0.23^{b}	16.0^{b}	23.6^{ab}	111^{ab}	30^{b}	22.7^{b}	569^{ab}
CV %	-	15.8	6.6	1.8	11.5	3.97	9.0	10.2	2.4	29.9	28.4	12.4^{b}	25.45

Yield and yield contributing characters

Rice yield is dependent not only on the numbers of grains produced per unit area but also on the panicle length, individual grain size and weight. Variations in yield contributing characters such as panicle length, number of filled and unfilled grains/panicle and 1000-grain weight were significant (Table 2). The lowest unfilled grains/panicle was recorded in Binadhan-19 followed by Binadhan-14 and BRRI dhan48 and the highest number of unfilled grains was recorded in Iratom-24. Iratom-24 and Binadhan-14 produced the longest panicles and Binadhan-19 had shorter panicles. Grain size is a critical trait in rice, influencing grain weight through factors such as grain length, width, thickness, and the length-to-width ratio. The grain width of Iratom-24 was higher than others (Figure 5). This trait not only affects yield but also contributes to the visual appearance of the grains (Harberd 2015). The highest number of primary and secondary rachis branches was recorded in Iratom-24 followed by BRRI dhan48 and Binadhan-14 (Table 2). Iratom-24 displayed erect and dense panicle compared to other varieties (Fig. 6) which might help in higher grain yield production. It was reported that rice production increased due to selecting yield and yield contributing characters during the course of rice cultivation (Akter et al. 2019; Wang and Li (2008) and can be estimated on the performance of panicle length, grain number per panicle, grain size, grain fertility, 1000-seed weight and rachis branches of the panicle (Yan et al. 2013).

Figure 5: Panicle characterisation; A Panicle architecture B Variations in seed structure of five aus rice varieties

The highest grain yield was recorded in BRRI dhan48 followed by Binadhan-19, BRRI dhan82, Iratom-24 and Binadhan-14 produced the lowest grain yield (Table 2). These results suggest that the yield can be increased with the increased grains per panicle which comes from increased secondary branches in rice.

Dry matter allocation per spikelet from heading to maturity is important for higher grain yield in rice. The poor grain filling might be related to poor partitioning of assimilates to the grain in rice (Puteh et al. 2014). The highest total dry mass and its distribution into seed yield per plant were found in Iratom-24 followed by BRRI dhan48. Binadhan-14 produced comparatively the low yield with lowest TDM over its growth period. Thus, it is observed that the grain yield increased with increased total dry matter production and grain yield strongly correlated with total dry mass production (Fig. 7). These results indicated that higher dry matter production during grain filling is helpful for grain filling in rice as also previously reported by Li et al. (2023).

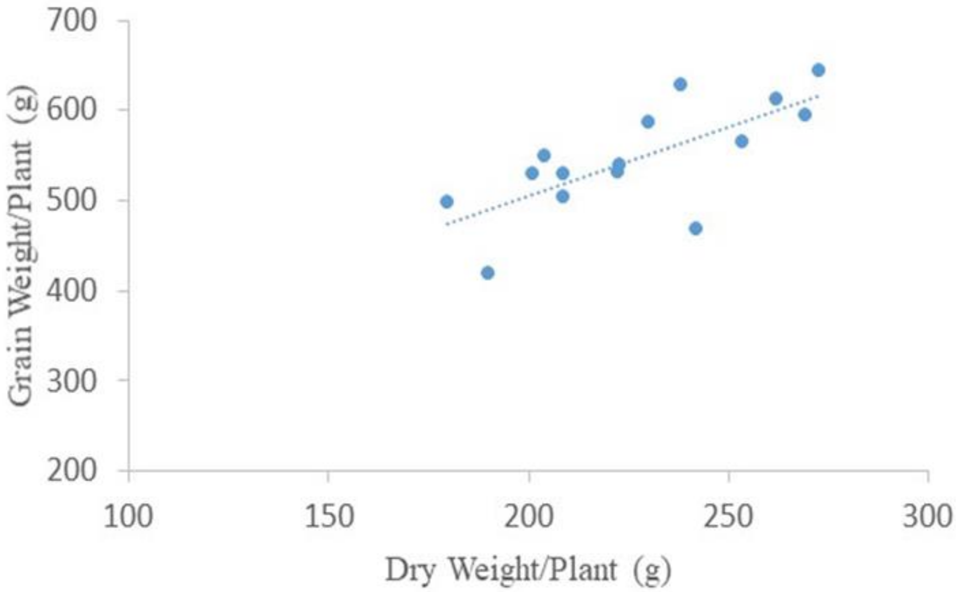

Figure 6: Relationship dry weight and grain weight per plant

Conclusion

Varieties which had better dry matter partitioning and exhibiting longer flag leaves in terms of both length and increased number of filled grains per panicle, longer grain length, and a higher number of tillers per hill were also associated with greater grain yield production. Here, BRRI dhan48 and Iratom-24 showed superiority in yield contributing characters but Iratom-24 produced comparatively lower yield due to maximum number of unfilled grains. This information will help the farmers as well as the rice breeders for selecting and developing superior rice varieties in future.

References

Akter, M.B., M.T. Islam, M.M.A. Mondal, M.I. Hoque, M. Kamruzzaman, M.H. Nafis, A. Sultana and, M.S. Ali. 2019. "Morpho-physiological Basis of Yield Performance of Early Maturing Rice Varieties in Bangladesh." *Annual Research and Review in Biology* **32 (5)**: 1–13.

Akter, M.B., R. Piao, B. Kim, Y. Lee, E. Koh, and H-J. Koh. 2014. "Fine Mapping and Candidate Gene Analysis of a New Mutant Gene for Panicle Apical Abortion in Rice." *Euphytica* **197**: 387–398.

Ambavaram, M.M.R., S. Basu, A. Krishnan, V. Ramegowda, U. Batlang, L. Rahman, N. Baisakh, and A. Pereira. 2014. "Coordinated Regulation of Photosynthesis in Rice Increases Yield and Tolerance to Environmental Stress." *Nature Communications* **5**:5302.

Ata-Ul-Karim, S.T., H. Begum, V. Lopena, T. Borromeo, P. Virk, J.E. Hernandez, G.B. Gregorio, B.C. Collard, and Y. Kato. 2022. "Genotypic Variation of Yield-Related Traits in an Irrigated Rice Breeding Program for Tropical Asia." *Crop and Environment* **1 (3)**: 173–81.

Badger, M.R. 2013. "Role of Plant Leaf Development in Optimizing Photosynthetic

Efficiency, Capacity, Growth and Yield." In *Applying Photosynthesis Research to Improvement of Food Crops. Proceedings of a Workshop held at the Australian National University*. Canberra 20–26.

Bagirov, V., S. Treshkin, A. Korobka, F. Dereka, S. Garkusha, V. Kovalev, L. Esaulova, and S. Kizinek. 2020. "Scientific Support of the Rice Growing Industry of the Agroindustrial Complex of the Russian Federation in Solving the Problems of Food Security." *E3S Web of Conferences* **210 (1554)**: 05006.

Bai, X., H. Zhao, Y. Huang, W. Xie, Z. Han, B. Zhang, Z. Guo, L. Yang, H. Dong, W. Xue, G. Li, G. Hu, Y. Hu, and Y. Xing. 2016. "Genome-Wide Association Analysis Reveals Different Genetic Control in Panicle Architecture Between *Indica* and *Japonica* Rice." *Plant Genome* **9 (2)**.

BBS. 2022. "Yearbook of Agricultural Statistics 2021. 33rd series." Bangladesh Bureau of Statistics (BBS), Statistics and Informatics Division (SID), Ministry of Planning, Government of the People's Republic of Bangladesh. Dhaka, Bangladesh

Chang, S., T. Chang, Q. Song, X-G. Zhu, and Q. Deng. 2016. "Photosynthetic and Agronomic Traits of An Elite Hybrid Rice Y-Liang-You 900 with a Record-High Yield." *Field Crops Research* **187**:49–57.

Chowhan, S., M.K.J. Ali, K. Nahar, M.M. Rahman, M.I. Ali, and M. Islam. 2021. "Yield and Morpho-Physical Characters of Some Modern Aus Rice Varieties at Khagrachari." *Plant Science Today* **8 (1)**: 155–60.

Davood, B.T., A. Gazanchian, H.A. Pirdashti, and M. Nasiri. 2009. "Flag Leaf Morphophysiological Response to Different Agronomical Treatment in a Promising Line of Rice (*Oryza sativa* L.)." *American-Eurasian Journal of Agricultural and Environmental Sciences* **5 (3)**: 403–408.

Dey, R., M. Biswas, M.N. Hossain Miah, and P. Mandal. 2018. "Agronomic Performances of Rice Varieties at Different Transplanting Ages." *International Journal of Plant and Soil Science* **6 (3)**: 124–39.

Dutta, P., P.N. Dutta, and P.K. Borua. 2013. "Morphological Traits as Selection Indices in Rice: A Statistical View." *Universal Journal of Agricultural Research* **1 (3)**: 85–96.

Fukushima, A., H. Ohta, R. Kaji, K. Nakagomi, M. Yamaguchi, and X Zhengjin. 2011. "Yielding Ability and Morphological Traits of Erect Panicle Rice." *Tohoku Journal of Crop Science* **54**:19–20.

Harberd, N.P. 2015. "Shaping Taste: The Molecular Discovery of Rice Genes Improving Grain Size, Shape and Quality." *Journal of Genetics and Genomics* **42 (11)**: 597–599.

Kakar, N., R. Bheemanahalli, S. Jumaa, E. Redoña, M.L. Warburton, and K.R. Reddy. 2021. "Assessment of Agro-Morphological, Physiological and Yield Traits Diversity Among Tropical Rice." *PeerJ* **9**:e11752.

Khatun, S., M.M.A. Mondal, M.I. Khalil, M. Roknuzzaman, and M.M.I. Mollah. 2020. "Growth and Yield Performance of Six Aman Rice Varieties of Bangladesh." *Asian Research Journal of Agriculture* **12 (2)**: 1–7.

Kumar, P., Y. Prashanth, N.V. Reddy, S.S. Kumar, and P.V. Rao. 2014. "Character Association and Path Coefficient Analysis in Maize (*Zea mays* L.)." *International Journal of Applied Biology and Pharmaceutical Technology* **5 (1)**: 257–260.

Lan, D., L. Cao, Y. Wang, M. Liu, F. Ma, P. Yan, X. Zhang, J. Hu, F. Niu, S. He, J. Cui, X. Yuan, J. Yang, Y. Wong, and X. Luo. 2023. "The Identification and Characterization of a Plant Height and Grain Length Related Gene *hfr131* in Rice." *Frontiers in Plant Science* **14**:1152196.

Li, M., D. Zhu, M. Jiang, D. Luo, X. Jiang, G. Ji, L. Li, and W. Zhou. 2023. "Dry Matter Production and Panicle Characteristics of

High Yield and Good Taste Indica Hybrid Rice Varieties." *Journal of Integrative Agriculture* **22 (5)**: 1338–1350.

Li, R., M. Li, U. Ashraf, S, and J. Zhang. 2019. "Exploring the Relationships Between Yield and Yield-Related Traits for Rice Varieties Released in China from 1978 to 2017." *Frontiers in Plant Science* **10**:543.

Li, Y., N. He, J. Hou, L. Xu, C. Liu, J. Zhang, Q-F. Wang, X. Zhang, and X. Wu. 2018. "Factors Influencing Leaf Chlorophyll Content in Natural Forests at the Biome Scale." *Frontiers in Ecology and Evolution* **6**:64.

Mahesh, G., Y. Chandramohan, D. Saida Naik, and S. Narender Reddy. 2022. "Study on Flag Leaf and its Penultimate Leaves for Their Association with Grain Yield in Rice (*Oryza sativa* L.)." *Biological Forum* **14 (2)**: 270–274.

Makino, A. 2021. "Photosynthesis Improvement for Enhancing Productivity in Rice." *Soil Science and Plant Nutrition* **67(5)**: 513–519.

Oishi, A., Y. Tanaka, Z. Xu, and T. Shiraiwa. 2015. "Investigation of Lines with High Photosynthetic Capacity Among a Population Derived from a Cross Between an Erect Panicle Rice and Non-Erect Panicle Rice." *Proceedings of the 239th Meeting of the Crop Science Society of Japan*. 87.

Phyu, P., M.R. Islam, P.C. Sta Cruz, B.C.Y. Collard, and Y. Kato. 2020. "Use of NDVI for Indirect Selection of High Yield in Tropical Rice Breeding." *Euphytica* **216**:1–9.

Prakash, M., A. Anandan, and B.S. Kumar. 2011. "Varietal Variations in Flag Leaf Area and Yield in Mutant Lines of PY 5 Rice." *Karnataka Journal of Agricultural Sciences* **24 (4)**: 525–526.

Puteh, A.B., M.M.A. Mondal, M.R. Ismail, and M.A. Latif. 2014. "Grain Sterility in Relation to Dry Mass Production and Distribution in Rice (*Oryza sativa* L.)." *Biomed Research International* **2014**:2014:302179

Rahman, M.A., S. Kang, N. Nagabhatla, and R. Macnee. 2017. "Impacts of Temperature and Rainfall Variation on Rice Productivity in Major Ecosystems of Bangladesh." *Agriculture and Food Security* **6 (10)**. DOI:10.1186/s40066-017-0089-5

Rahman, N.M.F., M.A.A. Mamun, R. Ahmed, M.I. Hossain, M.A. Qayum, M.A. Aziz, M. Hossain, and M.S. Kabir. 2018. "Stability and Adaptability Analysis of BRRI Developed Aus Varieties in Different Locations of Bangladesh." *Bangladesh Rice Journal* **22 (1)**: 65–72.

Rahman, S., and R. Salim. 2013. "Six Decades of Total Factor Productivity Change and Sources of Growth in Bangladesh Agriculture (1948–2008)." *Journal of Agricultural Economics* **64 (2)**: 275–294.

Shelley, I.J., M. Takahashi-Nosaka, M. Kano-Nakata, M.S. Haque, and Y. Inukai. 2016. "Rice Cultivation in Bangladesh: Present Scenario, Problems, and Prospects." *Journal of International Cooperation for Agricultural Development* **14**:20–29.

Takai, T. 2023. "Potential of Rice Tillering for Sustainable Food Production." *Journal of Experimental Botany* **75 (3).** DOI:10.1093 /jxb/erad422.

Tari, D.B., A. Gazanchian, H.A. Pirdashti, and M. Nasiri. 2009. "Flag Leaf Morphophysiological Response to Different Agronomical Treatments in a Promising Line of Rice (*Oryza sativa* L.)." *American-Eurasian Journal of Agricultural and Environmental Sciences* **5**:403–408.

Wang, Y., and J. Li. 2008. "Molecular Basis of Plant Architecture." *Annual Review of Plant Biology* **59 (1)**: 253–279.

Wickham, H. 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org.

Won, P., H. Liu, N.P.M.C. Banayo, L. Nie, S. Peng, R. Islam, P.C. Sta. Cruz, B.C.Y. Collard, and Y. Kato 2020. "Identification and Characterization of High-Yielding, Short-Duration Rice Genotypes for

Tropical Asia." *Crop Science* **60 (5)**: 2241–2250.

Yamashita, M., C. Ootsuka, H. Kubota, S. Adachi, T. Yamaguchi, K. Murata, T. Yamamoto, T. Ueda, T. Ookawa, and T. Hirasawa. 2022. "Alleles of High-Yielding Indica Rice that Improve Root Hydraulic Conductance Also Increase Flag Leaf Photosynthesis, Biomass, and Grain Production of Japonica Rice in the Paddy Field." *Field Crops Research* **289**:108725.

Yan, W., H. Liu, Z. Xiangchun, Q. Li, J. Zhang, L. Lu, T. Liu, H. Liu, C. Zhang, Z. Zhang, G. Shen, W. Yao, H. Chen, S. Yu, W. Xie, and Y. Xing. 2013. "Natural Variation in Ghd7.1 Plays an Important Role in Grain Yield and Adaptation in Rice." *Cell Research* **23 (7)**: 969–971.

Zeng, D., Z. Tian, Y. Rao, G. Dong, Y. Yang, L. Huang, Y. Leng, J. Xu, C. Sun, G. Zhang, J. Hu, L. Zhu, H. Gao, X. Hu, L. Guo, G. Xiong, Y. Wang, J. Li, and Q. Qian. 2017. "Rational Design of High-Yield and Superior-Quality Rice." *Nature Plants* **3 (4)**: 283–294.