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HARNESSING GENETIC DIVERSITY AND VIGOR OF ONION FROM MULTI-GENERATIO STUDY

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Abstract

This study investigates the genetic variation, vigor, and performance of onion generations resulting from crosses. The experiment was conducted at the Spices Research Centre, Shibganj, Bogura, during 2021-22, following diallel mating design with three parental varieties, BARI piaz1, BARI piaz4, and BARI piaz6. The research focuses on evaluating yield and yield-contributing traits, including bulb dimensions, bulbing index, and individual bulb weight. The results demonstrate significant genetic diversity among onion generations, offering opportunities for the breeders to select and develop superior lines. Hybrid vigor and heterosis, particularly evident in F_1 generations, suggest that combining genetically diverse parental lines can lead to progeny with superior performance compared to their parents. However, the choice of parental lines significantly influences the stability and performance of hybrid progeny, with certain varieties demonstrating consistent performance across generations (Parent, F_1, F_2). Trait segregation and variability within F_2 hybrid populations underscore the importance of evaluating large populations to identify individuals with desired trait combinations. Overall, the findings highlight the importance of leveraging genetic diversity and hybrid vigor in onion breeding programs to develop cultivars. By employing breeding strategies the high-performing onion varieties capable of thriving in diverse agro-climatic conditions in onion farming.

Keywords: Bulb dimension, Genetic variation, Heterosis, Parental selection.

Introduction

Onion (*Allium cepa* L.) is one of the most economically important vegetable and spice crops worldwide, valued for its culinary versatility and nutritional benefits (Alam *et al.*, 2023; Alemu et al. 2022; Ochar and Seong 2023; Teshika *et al.*, 2018). It has a wide range of variability regarding bulb shape, size bulb skin color, etc. (Ashagrie *et al.*, 2021; Islam *et al.*, 2019). It is also an important spice crop in Bangladesh and is widely

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cultivated over the country (Alam *et al.*, 2023). It also plays an important role in the country's spices production, contributing significantly to its economy and food security (Alam *et al.*, 2023). However, challenges such as limited genetic diversity, coupled with fluctuating environmental conditions, often hinder efforts to optimize bulb size and yield (Alam *et al.*, 2023; Chowdhury *et al.*, 2019). These challenges could be addressed by developing a diverse source population of onion varieties tailored to the specific agro-climatic conditions of Bangladesh (Biswas 2021; Lyngkhoi *et al.*, 2021; Rivera *et al.*, 2016). In recent years, onion breeding programs have aimed to develop cultivars with improved yield, quality, and resilience to biotic and abiotic stresses to meet the evolving needs of growers and consumers (Alam *et al.*, 2023; Chowdhury *et al.*, 2019). Through the comprehensive selection process, the collection of diverse onion germplasm from various genetic backgrounds and then evaluation for adaptability and performance could facilitate superior parents' identification (Manjunathagowda, 2022). Subsequent breeding efforts focused on hybridization and selection techniques to enhance desirable traits, particularly bulb dimension and yield will provide promising results including sufficient genetic diversity and improved quality (Anand *et al.*, 2023; Goswami 2023; Mwangangi *et al.*, 2019; Salgotra and Bhagirath, 2023).

Through careful investigation and analysis, this research clarifies the implications of genetic diversity and hybrid vigor in onion breeding programs. By evaluating the performance of different generations, from parental lines to F_1 and F_2 hybrids, the study sheds light on the potential for developing superior onion cultivars with enhanced traits for commercial cultivation. Key aspects such as parental selection, trait segregation, and variability in yield performance are examined to provide insights into breeding strategies aimed at improving onion productivity and sustainability. The findings of this study contribute valuable knowledge to the field of onion breeding, offering guidance for breeders in selecting optimal parental lines and designing effective breeding strategies to develop resilient and high-performing onion varieties. Understanding the genetic basis of onion traits and the dynamics of hybridization is crucial for advancing breeding programs and addressing the challenges faced by onion growers in diverse agro-climatic conditions (Khosa *et al.*, 2016; Khosa & Ajmer, 2020; Lyngkhoi *et al.*, 2021; Moran *et al.*, 2021; Singh & Ani, 2020). Ultimately, the goal of the study is to develop onion cultivars that meet the demands of agriculture. So, the present study was undertaken to develop a diverse source population of onions to improve the bulb dimension and yield.

Materials and Methods

Experimental location and plant materials

The study was conducted at the Spices Research Centre in Shibganj, Bogura, during the winter of 2021-22. Three parental varieties, namely BARI piaz1, BARI piaz4, and BARI piaz6, were utilized in the study. These varieties were chosen based on their diverse genetic backgrounds and potential for onion breeding. Major features of the parental genotypes are presented in Table 1.

Table 1. Important characteristics of the parents

Traits	BARI piaz1	BARI piaz4	BARI piaz6
Shape	Round	Oval to spindle	Oval
Skin color	Reddish	Dark reddish	Reddish gray
Single Bulb weight	30-40 g	60-75 g	50-60 g
Bulb Yield	12-16 t/ha	17-22 t/ha	16-20 t/ha
Life cycle	92-105 days	120-135 days	114-125 days

Crossing design and successive steps

A diallel mating design was employed for crossing the parental varieties during the 2018-19 season. The seeds of F_1 hybrids were subsequently grown to produce F_1 bulbs during the 2019-20 season, and superior quality bulbs were selected based on size and skin color. The selected F_1 bulbs were planted during the 2020-21 season to produce F_2 seeds, which were used in the present study.

Seeds sowing and fertilizers application

Seeds of different generations were sown on October 14, 2021, and transplanted on November 24, 2021. Transplantation was carried out using four-week-old seedlings. The unit plot size was 3.0 m × 1.2 m, with a plant spacing of 10 cm × 15 cm. The crop received fertilization with a recommended dose of cow dung (5 t/ha) and $N_{115}P_{54}K_{75}S_{20}Zn_3B_2$ Kg/ha. The application of cow dung, phosphorus (P), sulfur (S), zinc (Zn), and boron (B), along with one-third of nitrogen (N) and potassium (K), was done at the time of final land preparation. The remaining nitrogen (N) potassium (K) and urea were applied at 25, 50, and 75 days after planting. Irrigation was applied at 30, 50, and 70 days after planting, and fungicide was sprayed at seven days intervals to control diseases.

Data collection and analysis

Bulb yield and various morphological traits were recorded for different generations of onion populations. The mean, standard deviation, and range of these traits were calculated separately for parental, F_1, and F_2 generations. Mean, standard deviation, and range were estimated to determine significant differences among the parental and segregating generations for the studied traits.

Results and Discussion

The mean, standard deviation, and range for different yield-attributing traits of parents, F_1's, and F_2's are presented separately in Table 2. On the other hand, performance in regards to fresh bulb yield is presented in Table 3. It was found that the mean performance of F_1'swere superior to the P_1 and P_2. Whereas in F_2, in most of the cases, the mean was lower than the F_1's, while the standard deviation and the range were wider in F_2 compared to F_1's.

Parental generation

The mean of bulb length (BL), bulb diameter (BD), neck diameter (ND), bulbing index (BI), and individual bulb weight (IBW) were 45.06, 51.35, 12.95, 4.02, and 45.6

respectively for parent BARI piaz1 (Table 2). In the case of BARI piaz4 the average BL, BD, ND, BI, and IBW was 64.39, 64.01, 15.09, 4.32, and 96.98, respectively. Whereas for BARI piaz6 the mean of BL, BD, ND, BI, and IBW was 54.45, 56.58, 13.54, 4.26, and 63.98. Variability exists among the parental varieties concerning bulb dimensions, bulbing index (BI), and individual bulb weight (IBW). BARI piaz4 consistently demonstrates larger bulb dimensions and higher IBW compared to the other parental lines, suggesting its potential for potentially more marketable bulbs (Addai 2014). While BARI Piaz-1 and BARI Piaz-6 showed intermediate values for these traits, they still possess respectable sizes, indicating their potential utility in commercial onion production (Addai 2014; Major *et al*. 2023).

Variation in yield attributing traits

Crossing between BARI piaz1 and BARI piaz4 (with reciprocal) through emasculation

In this particular cross combination (BARI piaz1 × BARI piaz4), the performances for different studied traits in F_1 were superior to the parents. Results showed that the average BL, BD, ND, BI, and IBW were 57.7, 55.68, 17.72, 2.26, and 62.77, respectively (Table 2). In F_2, the mean of BL, BD, ND, BI, and IBW was 51.5, 58.98, 14.74, 4.09, and 56.71, respectively (Table 2).

The performance of F_1 of the cross combination (BARI piaz4 × BARI piaz1) was presented in Table 2. Results showed that the average BL, BD, ND, BI, and IBW were 62.77, 50.11, 24.3, 2.09, and 89.09, respectively. In F_2, the mean of BL, BD, ND, BI, and IBW was 61.97, 65.41, 14.11, 4.72, and 79.12, respectively.

Crossing between BARI piaz1 and BARI piaz6 (with reciprocal) through emasculation

The mean performance along with the range of F_1 of the cross combination (BARI piaz 1 × BARI piaz 6) was presented in Table 2. Results showed that the average BL, BD, ND, BI, and IBW were 70.36, 49.6, 23.28, 2.39, and 71.37, respectively. In F_2, the mean of BL, BD, ND, BI, and IBW was 53.02, 58.28, 14.95, 3.99, and 62.26, respectively.

The mean and range of F_1 of the cross combination (BARI piaz6 × BARI piaz1) were presented in Table 2. Results showed that the average BL, BD, ND, BI, and IBW were 62.26, 45.56, 21.26, 2.16, and 55.68, respectively. In F_2, the mean of BL, BD, ND, BI, and IBW were 51.38, 58.06, 14.04, 4.2, and 56.91, respectively.

Crossing between BARI piaz4 and BARI piaz6 (with reciprocal) through emasculation

The mean performance along with the range of F_1 of the cross combination (BARI Piaz-4 × BARI Piaz-6) was presented in Table 2. Results showed that the average BL, BD, ND, BI, and IBW were 52.64, 61.75, 20.75, 2.07, and 100.73, respectively. In F_2, the mean of BL, BD, ND, BI, and IBW was 58.54, 60.95, 14.12, 4.36, and 74.79, respectively.

Table 2. Performance of F_1 and F_2 generations along with parents for different traits

Parents	Item	BL (cm)	BD (cm)	ND (cm)	BI	IBW (g)
Parents						
BARI piaz1	μ ± σ	45.06±4.01	51.35±3.07	12.95±1.03	3.97±0.29	45.6±7.68
	Range	41.02-53.06	47.04-56.97	11.39-14.73	3.58-4.35	34.6-60.56
BARI piaz4	μ ± σ	60.39±3.23	60.01±3.17	15.09±1.65	3.98±0.43	96.98±10.51
	Range	58.5-67.47	58.39-67.28	12.71-16.7	3.8-4.88	82.67-112.98
BARI piaz6	μ ± σ	52.45±5.92	54.58±3.89	13.54±1.76	4.03±0.29	63.98±13.22
	Range	46.63-64.22	52.24-62.64	11.69-15.98	3.93-4.55	45.94-85.71
F_1 generations						
BARI piaz1×BARI piaz4	μ ± σ	57.7±8.1	55.68±12.15	17.72±0.51	2.26±0.26	62.77±24.3
	Range	49.6-65.8	43.53-67.83	17.21-18.22	2-2.53	38.47-87.06
BARI piaz 1×BARI piaz 6	μ ± σ	70.36±4.56	49.6±2.02	23.28±4.05	2.39±0.76	71.37±3.54
	Range	65.8-74.91	47.58-51.63	19.23-27.33	1.63-3.16	67.83-74.91
BARI piaz4×BARI piaz1	μ ± σ	62.77±12.15	50.11±11.64	24.3±1.01	2.09±0.57	89.09±9.11
	Range	50.62-74.91	38.47-61.75	23.28-25.31	1.52-2.65	79.98-98.2
BARI piaz4×BARI piaz6	μ ± σ	52.64±12.15	61.75±2.02	20.75±3.54	2.07±0.18	100.73±5.57
	Range	40.49-64.79	59.73-63.78	17.21-24.3	1.88-2.25	95.16-106.3
BARI piaz6×BARI piaz1	μ ± σ	62.26±7.59	45.56±5.06	21.26±1.01	2.16±0.34	55.68±24.3
	Range	54.67-69.85	40.49-50.62	20.25-22.27	1.82-2.5	31.38-79.98
BARI piaz6×BARI piaz4	μ ± σ	52.64±1.01	60.23±1.52	23.28±1.01	2.26±0.05	88.07±1.01
	Range	51.63-53.65	58.72-61.75	22.27-24.3	2.21-2.32	87.06-89.09
F_2 generations						
BARI piaz1×BARI piaz4	μ ± σ	51.5±3.55	58.98±5.73	14.74±2.03	4.09±0.51	56.71±6.42
	Range	48.07-55.61	50.77-64.1	12.84-17.11	3.61-4.81	48.14-63.7
BARI piaz1×BARI piaz6	μ ± σ	53.02±4	58.28±4.14	14.95±2	3.99±0.81	62.26±5.75
	Range	50.19-55.85	55.36-61.21	13.54-16.36	3.42-4.56	58.2-66.33
BARI piaz4×BARI piaz1	μ ± σ	61.97±3.71	65.41±3.06	14.11±1.51	4.72±0.44	79.12±12.4
	Range	57.75-66.64	63.47-69.93	11.92-15.16	4.35-5.34	71.27-97.33
BARI piaz4×BARI piaz6	μ ± σ	58.54±8.4	60.95±5.76	14.12±1.82	4.36±0.22	74.79±10.68
	Range	44.47-65.52	53.34-65.37	11.84-16.38	3.99-4.54	57.55-85.34
BARI piaz6×BARI piaz1	μ ± σ	51.38±3.48	58.06±2.51	14.04±0.84	4.2±0.39	56.91±9.62
	Range	46.46-56.38	55.04-61.4	12.88-15.26	3.74-4.8	51.03-74.92
BARI piaz6×BARI piaz4	μ ± σ	60.22±3.65	60.41±3.73	15.11±1.26	4.08±0.48	84.78±9.84
	Range	55.74-65.56	54.92-64.2	13.5-16.83	3.34-4.55	67.94-95.68

The mean and range of F_1 of the cross combination (BARI piaz 6 × BARI piaz 4) were onion presented in Table 2. Results showed that the average BL, BD, ND, BI, and IBW were 52.64, 60.23, 23.28, 2.26, and 88.07, respectively. In F_2, the mean of BL, BD, ND, BI, and IBW was 60.22, 60.41, 15.11, 4.08, and 84.78, respectively. The F_1 hybrids (Table 2) generally exhibit intermediate values for bulb dimensions and yield compared to their parental lines, indicating the presence of hybrid vigor or heterosis (Farinati *et al.*, 2023; Wu *et al.*, 2008). Notably, instances of heterosis are particularly notable when

BARI Piaz-4 serves as the female parent, resulting in an elevated yield in the F_1 generation compared to both parental lines. This emphasizes the potential for exploiting hybrid vigor to develop onion cultivars with superior yield potential (Beyene and Mohammed, 2016; Yu *et al.*, 2021). The range of values within each F_1 hybrid combination signifies variability in trait expression, underscoring the necessity of careful selection to identify superior individuals for further breeding (Ahmad *et al.*, 2020; Snowdon *et al.*, 2015). This variability presents an opportunity to select desirable traits and advance promising lines in subsequent generations (Ahmad *et al.*, 2020). Overall, the results suggest the potential for exploiting hybrid vigor in onion breeding programs to develop cultivars with improved bulb characteristics such as size, shape, and weight (Gupta and Singh 2016; Khosa *et al.*, 2016). However, further evaluation of the F_1 hybrids under diverse environmental conditions and across multiple growing seasons would be necessary to assess their stability and suitability for commercial cultivation (Mushtaq *et al.*, 2013; Tignegre *et al.*, 2022).

The F_2 generations demonstrate significant variability in bulb morphology and yield, typical of segregating populations like F_2 generations (Table 2). While generally exhibiting a wider range of values compared to F_1, instances of strong hybrid vigor are observed, particularly in combinations involving BARI Piaz-4. This highlights the potential for identifying and selecting superior lines with enhanced traits for further cultivation and breeding efforts (Kopecký *et al.*, 2022; Gautham and Thangappan, 2018. The variability within each F_2 population combination underscores the importance of evaluating large populations to identify superior lines with desirable characteristics for commercial production (Kopecký *et al.*, 2022; (Kopecký *et al.*, 2022; Gautham and Thangappan, 2018). Careful selection and evaluation are essential to advance promising lines and develop improved onion cultivars (Gupta *et al.*, 2021). Therefore, the F_2 generations represent a diverse population with the potential for the development of improved onion cultivars through selective breeding and further evaluation (Khosa *et al.*, 2016; Mitrova *et al.*, 2015).

Bulb yield in different generations

The bulb yield for different crosses in different generations is presented in Table 3. Variation was observed in the yielding behavior for different cross combinations. The higher mean bulb yield was recorded in F_1 than in the parental genotypes as expected. While most of the cases in F_2 , a reduction in mean bulb yield was observed compared to F_1's. At the same time, wider ranges are also observed in F_2's for the yielding performances. The cross combination (BARI piaz1 × BARI piaz4) produced the maximum yield (21.39 t/ha) in F_1 whereas the combination (BARI piaz6 × BARI piaz1) produced the minimum bulb yield (14.39 t/ha). Overall, crossing between BARI piaz1 and BARI piaz6 had the least production ability compared to other combinations. Comparison of different generation's yielding abilities were depicted in figures 1, 2, and 3 for different cross combinations.

The range of fresh yield values within each cell indicates the variability observed in yield performance within that specific cross combination and generation. A wider range suggests greater variability in yield performance within the population (Amir *et al.*, 2023). Comparing the mean fresh yield values across different generations within the same cross combination allows for the assessment of changes in yield performance over generations (Abdalla *et al.*, 2022; Alemu *et al.*, 2022). For instance, comparing the mean fresh yield of the F_1 and F_2 generations resulting from the same cross combination revealed potential differences in yield stability or improvement. Additionally, comparing mean fresh yield values across different cross combinations provides perceptions of the influence of parental genetics on yield performance (Khaki *et al.*, 2020; Patil and Subramaniam, 2020). Though the yielding ability was a little superior in F_1 it was not reduced much in F_2 as of BARI piaz1, so if the trend continues in further subsequent generations as F_3, $F_{4,}$ etc. then mass selection will be advantageous from those cross combinations involving BARI piaz4 as the female parent (Pike 1986; Shokrgozar *et al.*, 2021; Singh 1997).

Table 3. Performance of F_1 and F_2 generations along with parents for fresh yield (t/ha) of onion

Cross combinations	Mean (μ) ± Standard Deviation (σ)				Range			
	P_1	P_2	F_1	F_2	P_1	P_2	F_1	F_2
BARI piaz1xBARI piaz4	11.07±3.63	18.2±4.77	21.39±1.94	13.04±2.9	10.11-16.05	13.17-25.94	19.44-23.33	9.98-16.2
BARI piaz1xBARI piaz1	18.2±4.77	11.07±3.63	19.64±0.19	18.82±3.04	13.17-25.94	10.11-16.05	19.21-19.83	15.6-22.84
BARI piaz1xBARI piaz6	11.07±3.63	15.47±4.4	15.56±0.38	13.4±0.91	10.11-16.05	13.61-19.52	14.8-16.17	12.89-15.17
BARI piaz6xBARI piaz1	15.47±4.4	11.07±3.63	14.39±2.33	11.36±1.95	13.61-19.52	10.11-16.05	12.06-16.72	8.95-13.74
BARI piaz4xBARI piaz6	18.2±4.77	15.47±4.4	17.98±2.33	17.89±5.95	13.17-25.94	13.61-19.52	15.56-20.22	12.71-25.64
BARI piaz6xBARI piaz4	15.47±4.4	18.2±4.77	17.11±0.78	16.44±7.64	13.61-19.52	13.17-25.94	16.33-17.89	6.2-26.13

μ=Mean value; σ=Standard deviation; P_1=Parent one; P_2=Parent two; F_1=First filial generation; F_2=Second filial generation/segregating generation

Impact of parental selection

The choice of mother had a significant effect on the performance of progeny and segregating generation (Fig. 1, 2, 3). For instance, if BARI piaz1 is used as a mother the fresh bulb yield will be superior in F_1 in comparison to using as pollen donor (father) of the same parents' combination (i.e., BP1 x BP4 is superior to BP4 x BP1 in F_1). But in F_2, the performance became reversed, i.e., the fresh yield drastically reduced in F_2 when BARI piaz1 was used as a mother. In contrast, when BARI piaz4 was used as the mother plant then the F_1 performance was slightly superior to parents but not as high as BARI piaz1. Though the superior yield ability in $F_{1,}$ it was not reduced much in F_2 as of BARI piaz1, so if the trend continues in further subsequent generations as F_3, $F_{4,}$ etc., then mass selection will be advantageous from those cross combinations involving BARI piaz4 as female parent. When it comes to BARI piaz6, it showed better heterosis with BARI piaz4 rather than with BARI piaz1. Even in the case of the cross-combination BARI piaz6 × BARI piaz4, it showed an elevated yielding ability in F_2 which is superior to F_1. The choice of the mother plant significantly influences the yield performance of the progeny (Baskin and Carol, 2019; Mazer & David, 1996). For example, when BARI Piaz1 was used as the mother, the F_1 generation generally showed superior fresh bulb yield compared to using it as the donor in the same cross combination. Interestingly, while BARI piaz4 may not yield as high as BARI piaz1 in the F_1 generation, its performance does not decrease drastically in the subsequent F_2 generations. This suggests that BARI piaz4 may offer more stable and consistent yield performance over generations, making it a favorable choice for breeding programs (Pike 1986; Shokrgozar *et al.*, 2021; Singh 1997).

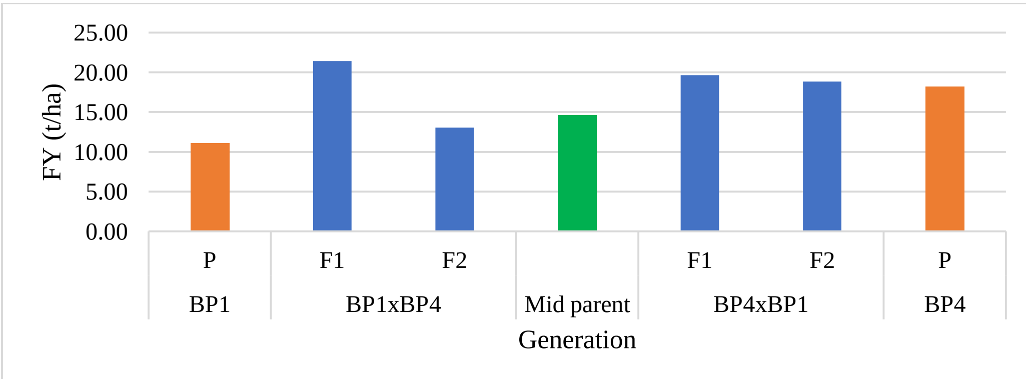

Fig. 1. Comparison of different generation's fresh yielding ability of the crosses between BARI piaz1 and BARI piaz4

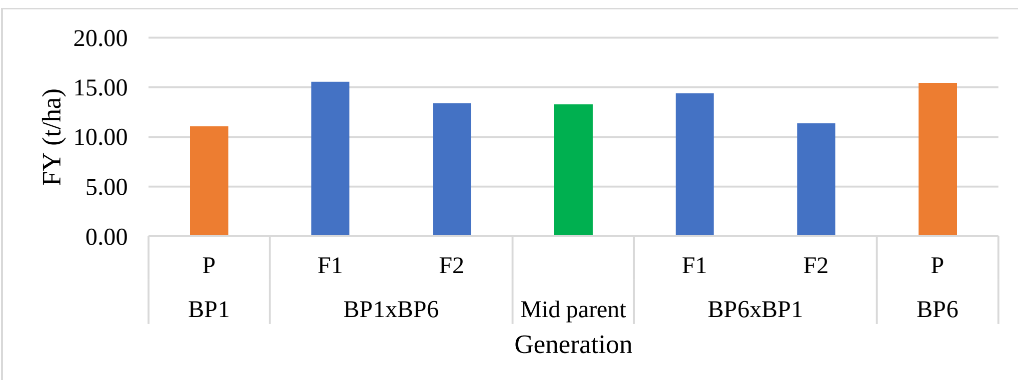

Fig. 2. Comparison of different generation's fresh yielding ability of the crosses between BARI piaz1 and BARI piaz6

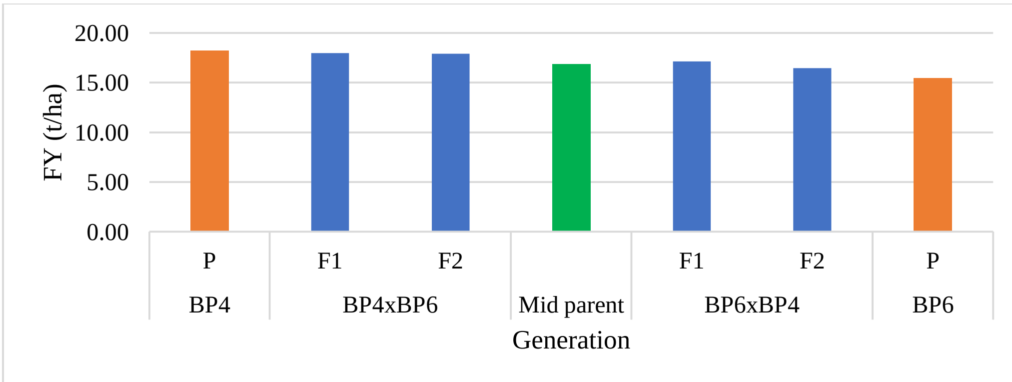

Fig. 3. Comparison of different generation's fresh yielding ability of the crosses between BARI piaz4 and BARI piaz6

Heterosis and inbreeding depression

Table 4 presents data on heterosis and inbreeding depression in F_1 and F_2 generations of onion hybrids involving BARI piaz1, BARI piaz4, and BARI piaz6. In terms of heterosis over mid-parent, F_1 hybrids frequently show positive heterosis for neck diameter (ND) and individual bulb weight (IBW), meaning these traits exceed the mid-parent average. For instance, the BARI piaz1 x BARI piaz6 hybrid exhibits high heterosis in ND (75.76%) and IBW (30.26%). Conversely, many hybrids show negative heterosis in the bulbing index (BI), indicating a lower BI than the mid-parent, which could result in more elongated bulb shapes. Regarding heterosis over a better parent, some F_1 hybrids, such as BARI piaz1 x BARI piaz6, outperform the superior parent in ND (71.93%), indicating an improved neck diameter compared to both parents. For individual bulb weight (IBW), certain hybrids (e.g., BARI piaz6 x BARI piaz1) do not exceed the better parent, showing any additional benefit in bulb weight.

In contrast, inbreeding depression generally leads to decreased performance in F_2 generation, with notable negative values in traits like field yield (FY). This reduction suggests that yield and bulb quality are adversely affected by inbreeding. In summary, some F_1 hybrids exhibit strong heterosis for neck diameter and bulb weight, which are valuable traits for commercial onion production. However, inbreeding depression negatively impacts yield and bulb quality in F_2 generations. These findings can guide parent selection in breeding programs aimed at improving yield, bulb shape, and quality.

Table 4. Heterosis and inbreeding depression analysis in F_1 and F_2 generations of onion

Cross combinations	BL	BD	ND	BI	IBW	FY
Heterosis over mid-parent						
BARI piaz1 x BARI piaz4	9.44	0.00	26.39	-43.09	-11.95	46.16
BARI piaz 1 x BARI piaz6	44.31	-6.35	75.76	-40.22	30.26	17.26
BARI piaz4 x BARI piaz1	19.05	-10.00	73.32	-47.37	24.97	34.20
BARI piaz4 x BARI piaz6	-6.70	7.78	44.95	-48.30	25.16	6.80
BARI piaz6 x BARI piaz1	27.70	-13.98	60.51	-45.97	1.62	8.44
BARI piaz6 x BARI piaz4	-6.70	5.12	62.63	-43.56	9.43	1.63
Heterosis over better parent						
BARI piaz1 x BARI piaz4	-4.45	-7.22	17.43	-43.17	-35.28	17.53
BARI piaz 1 x BARI piaz6	34.15	-9.12	71.94	-40.71	11.55	0.58
BARI piaz4 x BARI piaz1	3.94	-16.50	61.03	-47.45	-8.14	7.91
BARI piaz4 x BARI piaz6	-12.83	2.90	37.51	-48.65	3.87	-1.21
BARI piaz6 x BARI piaz1	18.70	-16.53	57.02	-46.42	-12.97	-6.98
BARI piaz6 x BARI piaz4	-12.83	0.37	54.27	-43.93	-9.19	-5.99
Inbreeding depression						
BARI piaz1 x BARI piaz4	-10.75	5.93	-16.82	80.97	-9.65	-39.04
BARI piaz 1 x BARI piaz6	-24.64	17.50	-35.78	66.95	-12.76	-13.88
BARI piaz4 x BARI piaz1	-1.27	30.53	-41.93	125.84	-11.19	-4.18
BARI piaz4 x BARI piaz6	11.21	-1.30	-31.95	110.63	-25.75	-0.50
BARI piaz6 x BARI piaz1	-17.48	27.44	-33.96	94.44	2.21	-21.06
BARI piaz6 x BARI piaz4	14.40	0.30	-35.09	80.53	-3.74	-3.92

BL=Bulb length; BD=Bulb Diameter; ND=Neck Diameter; BI=Bulbing Index; IBW=Individual Bulb Weight; FY=Fresh Yield

The text also highlights instances of heterosis, particularly with BARI piaz4 as the female parent. The cross-combination involving BARI piaz6 and BARI piaz4 showed elevated yield ability in the F_2 generation compared to the F_1 generation, which is a different result from earlier studies (Engelen *et al.*, 2004; Gogas and Metaxia, 2014). Such observations suggest the potential for early generation selection of superior segregating lines with desirable yield characteristics for further cultivation and breeding efforts (Gogas & Metaxia, 2014).

Overall, the research underscores the significant genetic variability within onion populations resulting from diverse parental crosses, providing breeders with ample opportunities to develop superior cultivars tailored to specific needs (Bertan and Oliveira, 2007). Understanding the dynamics of parental selection and the cross combination is crucial for onion breeders to develop cultivars with improved yield and other desirable traits (Ochar and Seong, 2023; Swarup *et al.*, 2021). The presence of hybrid vigor and heterosis in F_1 generations indicates the potential for combining diverse parental lines to produce offspring with enhanced traits, including yield, quality, and resilience. The observed variability in trait expression within F_2 hybrid populations emphasizes the importance of evaluating large populations to identify individuals with desired trait combinations, enabling breeders to advance breeding objectives effectively. Continued evaluation and selection within populations are necessary to identify and advance superior lines for commercial cultivation and breeding programs (Santantonio *et al.*, 2020). Careful selection of parental lines, such as prioritizing varieties like BARI Piaz4 with consistent performance, is crucial for ensuring stability and success in hybrid progeny across generations.

Conclusion

This study, based on crosses between three onion varieties viz., BARI piaz1, BARI piaz4, and BARI piaz6 offers an understanding of effective onion breeding strategies. The significant genetic diversity observed within these populations provides ample opportunities for breeders to select and develop superior lines with enhanced traits. The F_1 generations consistently outperformed their parental lines, demonstrating the benefits of hybrid vigor and heterosis in boosting yield, quality, and resilience. Parental selection played a key role, with varieties like BARI piaz4 showing stable performance across multiple generations, making it ideal for breeding programs focused on high-yielding, stable cultivars. Furthermore, the trait segregation seen in F_2 populations highlights the importance of evaluating large populations to identify individuals with desirable combinations of traits. This study emphasizes the value of harnessing genetic diversity, hybrid vigor, and careful parental selection in developing resilient, high-performing onion varieties that thrive in diverse environments, thereby contributing to sustainable agricultural productivity.

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Author’s contribution

M.A.A: Conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing – original draft. M.S.N: Investigation, methodology, validation, writing – original draft. M.M.H: Methodology, resources, validation, supervision. reviewed, revised and edited the content. AHFF: Investigation, methodology, validation. M.A.A.K: Methodology, validation. snm: funding acquisition, project administration, resources, supervision, writing – review & editing. M.T.R.:Reviewed, revised and edited the content.

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