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Flowering Behavior and Selection of Hybrid Potato Clones through LXT Breeding Approaches

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Abstract: Potato breeding in Bangladesh is very challenging because it is grown in the short winter season, and flowering does not occur naturally, explaining why artificial lighting and extra care are needed. In addition, the breeding scheme is mainly focused on improving potato yield, followed by tuber quality. The goal of this study was to choose male parents, as well as the effect of environment, on flowering and fruit (berry) setting and to estimate the combining ability among promising BARI-released potato varieties in the second filial generation. Lines of seven Bangladesh Agricultural Research Institute (BARI) varieties were crossed with two BARI variety potato parents as the tester (Line × tester). The BARI Alu-86, BARI Alu-72, BARI Alu-73, and BARI Alu-53 were selected as the best male parents based on the abundance of pollen and fruit set. In both years, flower initiation days varied among clones. For the majority of the traits, such as plant height, tuber number, and yield per plant, the variance of general combining ability (GCA) and specific combining ability (SCA) varied. The inheritance of the considered trait was predominant by non-additive gene action. Concerning general combining ability, for plant height, parents 'BARI Alu-41' and 'BARI Alu-53', for stem per hill, 'BARI Alu-79', for tuber number, 'BARI Alu-37', and for yield, 'BARI Alu-37' and 'BARI Alu-79' contributed complementary favorable alleles. The specific combining ability indicated 'BARI Alu-37' × 'BARI Alu-86' and 'BARI Alu-77' × 'BARI Alu-72' were the best potential hybrid families for the production of improved genotypes of tuber yield and tuber number. This study will help to design a breeding program following potato population development and the selection of progeny before their utilization as progenitors.

Keywords: flower; GCA; SCA; clone; tuber

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1. Introduction

After rice, wheat, and maize, potatoes are the 4th most significant food crop in Bangladesh [1]. In 2019, global potato production touched 370 million metric tons, where China is the world's biggest producer of potato, followed by India, Russia, the United States, Ukraine, Germany, and Bangladesh. Bangladesh took the top seven position in terms of production [2]. In Bangladesh, the average yield of potato is 20.61 t/ha, and a total of 9.65 million tons (Mt) of potato was produced from 0.47 million hectares (M ha) of land [2]. The potato is high in nutritional content and has high yield potential per unit area, where the starch level is high and sugar and fat content are low. It is high in energy, vitamin C, vitamin B6, folate, niacin, and minerals like phosphorus, potassium, iron, and magnesium [3,4]. Additionally, it is a good source of dietary antioxidants, which are required to control blood cholesterol levels [5,6].

In Bangladesh, the maximum portion of potato is consumed as vegetables for table purposes, with a small portion for processing, such as chips, french fries, and flakes. An adequate supply of potatoes stabilizes the vegetable market all around the year [7]. Potato is grown all over the country during the winter season for three months, which is shorter than that in other potato-growing countries of the world. Previous research on potato variety development has been based on high starch content and table consumption only. As a result, there is a lack of particular varieties ideal for food processing with a good proportion of dry matter, protein, starch, antioxidant, or low polyphenol and stress tolerance. The development of final products as well as adaptation in unfavorable environments, such as salt, heat, and drought stress, are influenced by a variety [8]. Variation in the existing commercial cultivated tetraploid varieties of potatoes rarely occurs because it is a vegetatively propagated crop, and stable inheritance of a trait is challenging. Therefore, the introduction and creation of variability in potatoes are immediately required for potato improvement programs in Bangladesh. The presence of variability in a trait is a necessary condition for its genetically inherited advancement. [9]. It has been found that the best clones come from a small number of crossings because most crosses between parental lines will not result in seed and/or progeny with desirable traits [10]. Thus, which genotypes will be the best parents; if this information is known earlier, efforts can be focused on the creation and the assessment of the most suitable combinations [10]. The choice of the right type of parent for hybridization is crucial. An excellent parent generates a lot of genetic diversity around a high family mean for a particular trait [1]. In addition, knowledge of different types of gene action (the way by which genes show their effects), amount of gene action, and combining ability estimates is important for potato breeding programs. Further, knowing the genotype's combining ability status will give a sense of how effectively they mix with a specific genotype to form viable populations. Franco et al. [11] mentioned that a high GCA indicates that multiple good additive genes will be passed down from parents to offspring. High-GCA parents could be selected for further breeding to make specific crosses. General and specific combining abilities [12] help the breeder to choose parents for hybridization. GCA and SCA also assist in the identification of promising genotypes in a segregating population, as well as provide information on gene function that aids in the comprehension of character inheritance. Plant breeders can use this information from parents to select better parental pairings for future potato variety development [13]. Simmonds [14] and Muthoni et al. [15] recommended screening parents and crossing them before their utilization in any breeding program, and combining ability analysis (identify promising cross combination) is a good method for looking at quantitative traits in parents and crosses. Hybridization has been made possible in the field of breeder seed production centers using prolonged photoperiods and bloom induction techniques [9]. We hypothesized that the BARI-released potato varieties require the same flowering days in the same environmental condition and management, and the crossing progenies will have similar yield potential. Therefore, the present study was undertaken to generate information related to the magnitude of flowering of BARI-released potato varieties, combining the ability of a representative sample of BARI-released varieties and estimating the nature of gene action among those varieties with respect to tuber yields and other components (plant height, stem per hill, tuber of tuber per plant).

2. Materials and Methods

2.1. Experimental Site and Climatic Details

The research was carried out for three consecutive years (2018–2021) during the *rabi* season (October to April) at the research field of the Breeder seed production center

(26°7′12″ N latitude and 88°45′33″ E longitude) Bangladesh Agricultural Research Institute (BARI) Debiganj, Panchagarh-5020. The area is under Himalayan Piedmont Soil (AEZ 1) located in the Panchagarh district and is characterized by higher elevation (36 m) and acidic soil (pH 5.8), with organic matter ranging from 1 to 1.8%. On the other hand, % nitrogen ranges from 0.068 to 0.081, phosphorus varies from 28.42 to 95.64 ug/g, and potassium ranges from 0.093 to 0.137 meq/100 g. A high-pressure sodium bulb (HPS) was used to extend the photoperiod after 4 PM to 11 PM to 16 h during the potato-growing season. Monthly average temperature (maximum and minimum) and rainfall variation are presented in Figure 1.

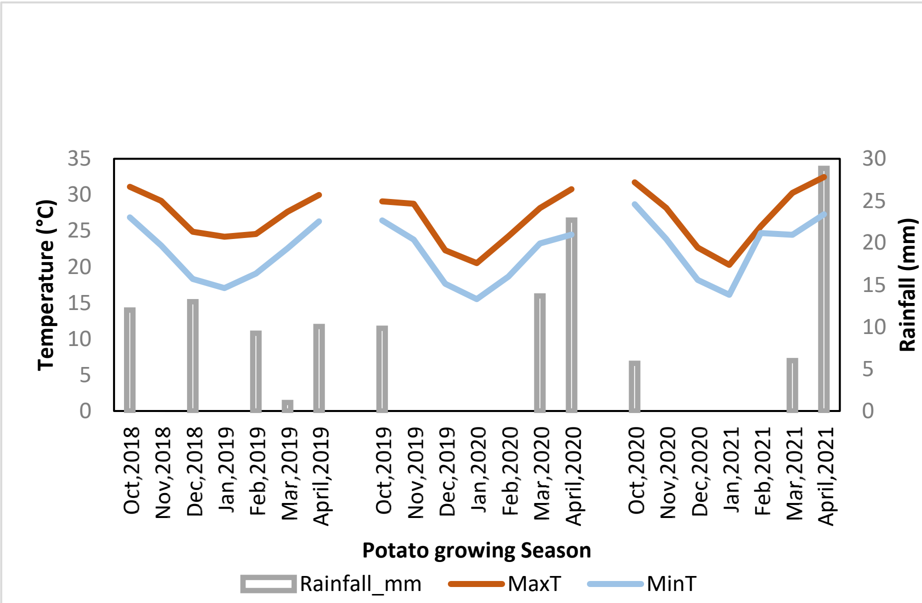

Figure 1. Monthly average temperature (maximum and minimum) and rainfall variation in Debiganj during the potato-growing season in 2018/2019, 2019/2020, and 2020/2021.

2.2. Plant Material and Generation of Hybrid Lines

During the first year in 2018, a large number of crosses between BARI released varieties and "test" lines (BARI Alu-72 & BARI Alu-86) were done to identify which Bari varieties set the most berries. BARI-released varieties were planted on 7th November and 17th November using the whole Brick's method [10] in non-replicated rows of five meters long, and earthing up was done just after planting. Seven genetically diverse promising varieties, BARI Alu-25, BARI Alu-37, BARI Alu-41, BARI Alu-53, BARI Alu-56, BARI Alu-77 and BARI Alu-79, were chosen as lines and were crossed with two testers BARI Alu-72, a salt-tolerant variety [1], and BARI Alu-86 (clonal variety) in a line × tester (LxT) design.

Due to the short photoperiod during the potato growing season in Bangladesh, potato plants rarely blossom [16]. Therefore, with the help of high-pressure sodium lights, the daylight was lengthened to 16 h. Stolons and tubers formed on bricks when the plant's stolons were set to ground, and the soil over bricks were removed to inhibit tuber formation and accelerate flowering [17]. Emasculation was done one day before crossing, in some cases. Seven selected lines were crossed with each of two testers in a half diallel fashion to test full sib progeny. No selfs or reciprocal crosses were considered. At maturity, berries were harvested when the color of the berries changed from deep green to light green 50–55 days after crossing. Finally, the seeds from the berries were extracted, processed, and stored for next year′s use. In the second year 2019, we planted the true potato seed (TPS) (the F1 seeds of previous year's crosses) and collected tubers from each family. Before cultivation, the TPS seeds were treated with 15 ppm GA3 for 24 h and then washed several times to accelerate germination. To facilitate field sowing, we used the "plug mix" method where the seed is pre-germinated in a prepared soil mix and sown in-tray, which results in good germination and seedling establishment [18]. To achieve good plant emergence of TPS within less time, freeing the land for other uses and reducing weed competition and simplifying agronomic practices, TPS was sown into trays. We mixed soil with sand, coconut dust, and ashes from rice husk in the proportion of 1:1:2:2, respectively, and sterilized the mixture with 60% formaldehyde and covered it with a polythene sheet for 7 days before putting it into the tray as the growing medium. TPS seeds were sown into the tray on 20 September 2019. All germinated seedlings were transplanted into a five-meter-long nursery bed with a spacing of 40 cm × 25 cm on 19 November 2019. In addition, this experimental area was covered by an 80-mesh net, and standard cultural practices were followed. Plants were selected at the green stage and at the harvesting stage, considering plant type, disease resistance, tuber size, shape, color, and tuber yield. Harvesting was done 16 days later after haulm cutting. The best clones were selected based on consumers′ preferences (long-oval, early bulker, short-statured plant height).

During the third year in 2020, five tubers of each selected best clone from the second year harvest (lines of seven BARI varieties, two testers and the hybrids from the crossing) were planted following a randomized complete block design (RCBD) with three replications at the research field of the Breeder seed production center during 2020–2021. Planting was done with a planting distance of 60 (between rows) × 30 (within rows) cm^2 in mid-November and the harvesting was made after 90 days of planting. Intercultural operations, application of fertilizer, and spraying of chemicals were applied when necessary to provide optimal crop conditions. The list of male and female parents used in this Line × Tester study is presented in Table 1.

Table 1. Pedigree and characteristics of male and female parents used in this LXT study.

Clone/Variety	Source	Origin	Skin Colour	Tuber Shape	Flesh Colour
BARI Alu-25 (Line 1)	Exotic	Netherlands	Red	long oval	Light yellow
BARI Alu-37 (Line 2)	Clone-4.4	Bangladesh	Yellow	oval	Light yellow
BARI Alu-41 (Line 3)	Clone-5.183	Bangladesh	Red	Short-oval	Light yellow
BARI Alu-53 (Line 4)	LB-6	CIP	Red	Round	Light yellow
BARI Alu-77 (Line 5)	Exotic	Denmark	Red	Round	Light yellow
BARI Alu-79 (Line 6)	CIP-126	CIP	Purplish Red	Long oval	Light yellow
BARI Alu-56 (Line 7)	Clone-8.46	Bangladesh	Red	Short-oval	Light yellow
BARI Alu-86 (Tester 1)	Clone-12.13	Bangladesh	Red	Long oval	Light yellow
BARI Alu-72 (Tester 2)	CIP-139	CIP	Red	Short-oval	Light yellow

2.3. Data Collection on Flowering Days and Plant Characteristics

The days to first flowering/flower initiation were counted for the year 2018–2019 and 2019–2020. Performance for yield, tuber number, average tuber weight, plant height, and stem per hill was measured in the seedling and maturity stage of 2019–2020). Plant height (PH), number of tubers/plant (NT), number of stems/plant (NS), and tuber yield/plant (TW) were all measured and calculated from 10 randomly selected plants of each plot from 2020–2021.

2.4. Statistical Analysis

Line into tester analysis was done to perform analysis of variance according to Randomized complete block design (RCBD), and the significance of differences was tested among the genotypes, including crosses and parents. To test the significance of genotypic differences, the treatment mean sum of square/Error mean sum of square was compared with the table value of F at a 5% level of significance. General combining ability (GCA) and specific combining ability (SCA) were estimated according to the method given by [19]. The Agricolae package was used for descriptive statistics, and variance estimates of specific combining ability (SCA) and general combining ability (GCA) in computer software R × 64-program version 1.4.1106 [20].

3. Results

3.1. Flower Initiation (Days) and the Choice of Male Parents'

BARI-released varieties required 43 to 128 days to flower initiation (Table 2). Considering both years, BARI Alu-47 required minimal days to flower (43 days and 44 days, respectively). BARI Alu-41 requires a maximum of 94 days to flower in 2019–2020, while BARI Alu-25 required the most days (128) to flower in 2020–2021 (Supplementary Table S1). In our study, 34 successful crosses were made during 2018–2019, and 4152 crosses were successful during 2019–2020 (Supplementary Tables S2 and S3). BARI Alu-72 was used as a male parent 5 times and 22 times in 2018–2019 and 2019–2020, respectively, with other parents. BARI Alu-86 was used as a male parent 6 times and 39 times in 2018–2019 and 2019–2020, respectively, with other parents (Figure 2). BARI Alu-86, BARI Alu-72, BARI Alu-73, and BARI Alu-53 were crossed as male parents based on the proportion of successful crosses over total crosses (Supplementary Table S4). The BARI Alu-86, BARI Alu-72, BARI Alu-73, and BARI Alu-53 were chosen as the best male parents based on their diversity and capacity to produce abundant fertile pollen within a short season and less flower drop. The consumers of northern Bangladesh choose BARI Alu-86, which has red skin and a long oval shape, while those in Bangladesh's southern region prefer BARI Alu-72, which has white skin and is salt tolerant. Though several of the male parents outperformed their female counterparts, we only considered two of the male parents for this study: BARI Alu-86 and BARI Alu-72. The proportion of crossing success as a female is also presented in Supplementary Table S5.

Table 2. Descriptive statistics of days to flowering among BARI potato collections.

Accessions	2019–2020				Accessions	2020–2021			
	Mean	Max	Min	SE		Mean	Max	Min	SE
BARI Alu-25	71.5	76	67	4.5	BARI Alu-25	122	128	116	6
BARI Alu-31	52	54	50	2.3	BARI Alu-31	75	86	64	11
BARI Alu-32	66	79	53	13	BARI Alu-32	67.5	82	53	14.5
BARI Alu-34	65.5	69	62	3.5	BARI Alu-34	69.5	79	60	9.5
BARI Alu-36	73.5	77	70	3.5	BARI Alu-36	67	78	56	11
BARI Alu-37	61	69	53	8	BARI Alu-37	70	80	60	10
BARI Alu-38	63	67	59	4	BARI Alu-38	71	74	68	3
BARI Alu-41	86.5	94	79	7.5	BARI Alu-41	76	87	65	11
BARI Alu-47	50.5	57	44	6.5	BARI Alu-47	58	73	43	15
BARI Alu-48	54.5	58	51	3.5	BARI Alu-48	85.5	110	61	24.5
BARI Alu-49	76.5	87	66	10.5	BARI Alu-49	80	100	60	20
BARI Alu-53	63	67	58	2.65	BARI Alu-53	82	99	65	17
BARI Alu-7	69.75	72	67	1.11	BARI Alu-7	75.50	83	68	7.5
BARI Alu-71	75	83	67	8	BARI Alu-71	71.5	86	57	14.5
BARI Alu-72	60.5	63	58	2.5	BARI Alu-72	70	78	62	8
BARI Alu-73	58	63	53	5	BARI Alu-73	70	79	61	9
BARI Alu-75	72	76	68	4	BARI Alu-75	73.5	82	65	8.50
BARI Alu-79	83.5	90	77	6.5	BARI Alu-79	83.5	101	66	17.5
BARI Alu-8	80.33	93	69	6.96	BARI Alu-8	100.5	122	79	21.5
BARI Alu-82	78	83	73	5	BARI Alu-82	98	103	93	5
BARI Alu-83	54	52	56	2.3	BARI Alu-83	83	86	80	6
BARI Alu-86	63	69	57	6	BARI Alu-86	71.5	74	69	2.50
BARI Alu-88	77	81	73	4	BARI Alu-88	92.5	118	67	25.5

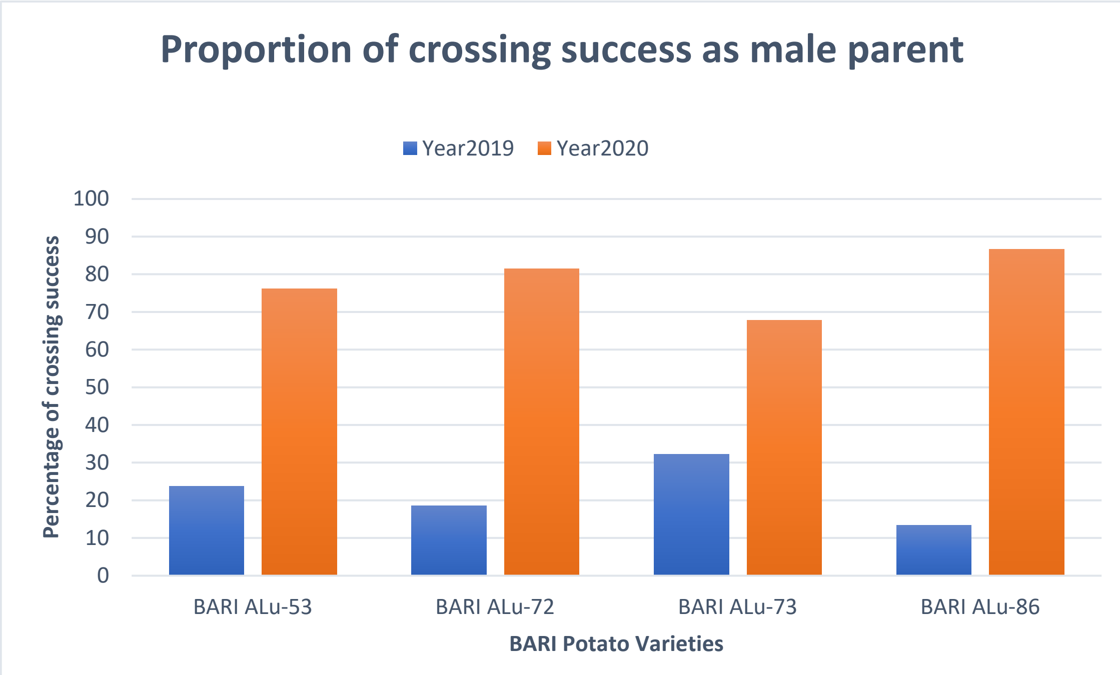

Figure 2. Proportion of successful crosses of each male parent used in potato breeding during 2019 and 2020.

3.2. Mean Performance

The descriptive statistics of morphological characteristics across cross-families of potato are presented in Table 3, and the ANOVA is presented in Table 4. BA 53 × BA 86 cross-families had the highest plant height (132 cm), and BA 37 × BA-86 cross-families had the highest tuber weight per plant (982 gm) (Table 3). Short plant height, more stems per hill, more tubers per hill, and maximum yield per plant, as well as a long oval form and white skin, are all desirable traits in a hybrid clone. Based on mean performance, BARI Alu-53 (98.33 cm) followed by BARI Alu-86 (90.38 cm) had the highest plant height, which was not the desired plant height. Between the testers, BARI Alu-86 recorded a higher plant height of 90.38 cm, followed by BARI Alu-72 (83.90 cm) (Table 5). Further, BARI Alu-37 had the highest yield per plant (492 gm), followed by BARI Alu-79 (463 gm). BARI Alu-79 had the highest number of stems per hill (7.50). BARI Alu-37 produced the highest number of tubers (12.50), followed by BARI Alu-41 (10.00). In the current study, the average performance of seven lines and two testers utilized as parents demonstrated that no single hybrids were superior in all the attributes evaluated. The cross BARI Alu-37 × BARI Alu-72, and BARI Alu-37 × BARI Alu-86 had the highest tuber number among the other hybrid families (Table 6).

Table 3. Average agronomic performance and morphological characteristics of Cross/families grown in BSPC during 2019–2020 season.

Cross Families	Plant Height (cm)	Stem/Hill	No of Tuber/pl	Yield Per Plant (gm)	Shape	Skin Color
BA 37 × BA-86	113 ± 3.28	1.6 ± 0.15	20 ± 2.33	982 ± 7.84	Oval	Red
BA 37 × BA-72	95 ± 3.61	1.6 ± 0.06	23 ± 2.65	742 ± 2.57	Round	Red
BA 25 × BA-86	87 ± 4.36	1.2 ± 0.15	5 ± 2.85	302 ± 13.53	Oval	Red
BA 25 × BA-72	115 ± 3.48	1.4 ± 0.1	13 ± 2.4	346 ± 7.72	Oval	Red
BA 41 × BA-86	94 ± 3.84	1.4 ± 0.06	19 ± 3.06	542 ± 4.91	oval	red
BA 41 × BA-72	104 ± 2.03	1.3 ± 0.15	14 ± 1.76	495 ± 7.51	oval	red

Table 3. *Cont.*

Cross Families	Plant Height (cm)	Stem/Hill	No of Tuber/pl	Yield Per Plant (gm)	Shape	Skin Color
BA 53 × BA 86	132 ± 2.03	2.4 ± 0.015	10 ± 2.73	724 ± 15.86	oblong	white
BA 53 × BA 72	115 ± 2.08	1.5 ± 0.15	11 ± 2.73	610 ± 7.37	oval	red
BA 77 × BA 86	97.6 ± 2.08	1.4 ± 0.12	9 ± 4.1	513 ± 2.33	oval	red
BA 77 × BA 72	102.4 ± 2.96	1.2 ± 0.12	8 ± 1.0	713 ± 5.46	oval	red
BA 79 × BA 86	80.2 ± 2.96	1.2 ± 0.06	5 ± 1.45	318 ± 9.84	long oval	red
BA 79 × BA 72	99 ± 5.04	1.6 ± 0.1	7 ± 2.03	612 ± 7.31	oval	red
BA 56 × BA 86	83 ± 3.38	1.5 ± 0.1	16 ± 2.4	510 ± 7.09	oval	red
BA 56 × BA 72	84 ± 3.18	1.6 ± 0.21	13 ± 1.45	625 ± 5.86	oval	red
Min	80.2	1.2	5	302		
Max	132	2.4	23	982		
Mean	100.09	1.49	12.36	573.86		

Table 4. Mean squares from line × tester analysis with parents of flowering and yield characteristics grown in BSPC during the 2020–2021 seasons.

Source of Variation	Df	Plant Height	Stem per Hill	Tuber Number per Plant	Yield per Plant (in Grams)
Replications	2	34.48	70.870	0.0580	278740 ***
Treatments (entries)	22	470.02 ***	47.062	103.518 ***	23034 ***
Parents	8	767.70 ***	17.315	116.667 ***	13368 **
Parents vs crosses	1	194.69	20.653	0.0010	54298 ***
Crosses (hybrids)	13	308.01 *	67.399	103.388 ***	26577 ***
Lines (female)	6	467.27 *	97.143	159.841 *	43176
Testers (male)	1	557.36.	115.238	173.571	8889
Lines x Testers	6	107.19	29.683	35.238	12926 **
Error	44	128.11	38.445	24.36	3851
σ^2g (L)		60.01	1.12	2.076	5041
σ^2g (T)		21.44	0.407	0.658	−192.23
σ^2gca		6.54	0.122	0.222	444.77
σ^2sca		76.51	1.285	3.061	5492.649
σ^2gca/σ^2sca		0.08	0.095	0.07	0.080
Contribution of line (%)		70.02	66.52	71.36	74.99
Contribution of tester (%)		13.92	13.15	12.91	2.57
Contribution of line × tester (%)		16.06	20.33	15.73	22.44

Df denotes degrees of freedom, σ^2gca denotes variance of general combining ability, σ^2sca variance of specific combining ability, * p = 0.05, ** p = 0.01 *** p = 0.001.

Table 5. Effects of General Combining Ability (GCA) for yield and yield characteristics grown in BSPC during the 2020–2021 season.

Source of Variation	Plant Height (Mean) (cm)	Stem per Hill (Mean)	No of Tuber per Plant (Mean)	Yield per Plant (in Grams) (Mean)
BARI Alu-25 (Line1)	−2.238 (84.50)	0.238 (5.33)	−1.047 ** (8.50)	−66.261 *** (309.00)
BARI Alu-37 (Line2)	3.595 (90.33)	0.738 (5.833)	2.952 *** (12.50)	117.404 *** (492.66)
BARI Alu-41 (Line3)	9.595 ** (96.33)	−0.428 (4.66)	0.4523 (10.00)	2.238 (377.50)
BARI Alu-53 (Line4)	11.595 *** (98.33)	−1.261 (3.833)	−0.8809 (8.66)	−90.928 *** (284.33)

Table 5. *Cont.*

Source of Variation	Plant Height (Mean) (cm)	Stem per Hill (Mean)	No of Tuber per Plant (Mean)	Yield per Plant (in Grams) (Mean)
BARI Alu-77 (Line5)	−10.071 ** (76.66)	−1.095 (4.00)	−2.214 *** (7.33)	−87.428 *** (287.833)
BARI Alu-79 (Line6)	−1.571 (85.166)	2.404 *** (7.50)	0.4523 (10.00)	87.738 *** (463.00)
BARI Alu-56 (Line7)	−10.904 ** (75.833)	−0.595 (4.50)	0.285 (9.833)	37.23 (412.50)
SE	4.62	0.80	0.64	25.33
BARI Alu-86 (Tester1)	3.642 (90.38)	0.523 (5.61)	0.642 (10.19)	14.547 (389.80)
BARI Alu-72 (Tester2)	−3.642 (83.09)	−0.523 (4.571)	−0.642 (8.90)	−14.54 (360.714)
SE	2.46995	0.42787	0.90	35.83

Values in parentheses are the corresponding means, (** designates $p \leq 0.01$; *** designates $p \leq 0.001$, highly significant).

Table 6. Estimates of SCA effects of crosses for yield and yield characteristics grown in BSPC during the 2020–2021 season.

Crosses	Plant Height (cm)	Stem Per Hill	Tuber Per Plant (No.)	Yield Per Plant (in Grams)
BA-25 × BA-86	1.19 (89.33ab)	−0.19 (5.67a)	−1.142 (8.00ab)	−55.88 (267.66cde)
BA-25 × BA-72	−1.19 (79.667b)	0.19 (5.00a)	1.1428 (9.00ab)	55.88 (350.33abcde)
BA-37 × BA-86	9.976 (96.67ab)	1.69 (7.00a)	0.809 (12.67a)	63.88 ** (542.00a)
BA-37 × BA-72	−9.976 (84.00b)	−1.69 (4.67a)	−0.809 (12.33a)	−63.88 ** (443.33abcd)
BA-41 × BA-86	3.357 (103.33ab)	0.476 (5.67a)	0.3571 (11.00ab)	40.952 (433.00abcd)
BA-41 × BA-72	−3.357 89.33ab	−0.476 3.67a	−0.357 9.00ab	−40.952 322.00bcde
BA-53 × BA-86	−0.69 (94.00ab)	1.0238 (4.33a)	2.309 *** (10.33ab)	42.21 (312.00bcde)
BA-53 × BA-72	0.6904 (102.67ab)	−1.0238 (3.33a)	−2.3095 *** (7.00b)	−42.21 (256.66de)
BA-77 × BA-86	−3.309 (77.00b)	−0.19 (4.33a)	−0.642 (7.33b)	−69.71 ** (232.67e)
BA-77 × BA-72	3.3095 76.33b	0.19 3.67a	0.6428 7.33b	69.71 ** 343.00bcde
BA-79 × BA-86	10.8095 ** 92.33ab	−0.309 6.67a	1.64285 ** 11.00ab	22.88 471.33ab
BA-79 × BA-72	−10.8095 ** 78.00b	0.309 8.33a	−1.6428 ** 9.00ab	−22.88 454.67abc
BA-56 × BA-86	0.5238 80.00b	0.642 5.67a	0.5238 11.00ab	42.95 470.0ab
BA-56 × BA-72	−0.5238 71.67b	−0.642 3.34a	−0.5238 8.67ab	−42.95 355.0abcde
SE	6.534	1.13	0.9	35.82

Values in parentheses are the corresponding means, BA stands for BARI Alu (** $p = 0.01$ *** $p = 0.001$) Means with a similar letter (s) in the same column are statistically similar and values with different letters are significantly different.

3.3. Combining Ability

Choosing parents becomes simple based on general combining ability performance when a trait is regulated directionally by a set of alleles and additive effects. The GCA/SCA ratio determines the type of gene activity present. A high ratio indicates the presence of additive genetic impacts, while a low ratio (e.g., 1) indicates the presence of dominance and/or epistatic gene effects. The single degree of freedom comparison (parents vs. hybrids), which indicates average heterosis, was also significant in terms of yield per plant. As a result, the hybrids had a significant proportion of heterosis (Table 4). Lines (female parents) contributed more than 65% of the hybrid variation, while tester contribution had the smallest range from 2.57 to 13.92% (Table 4). GCA and SCA were not significant for any of the traits (Table 4). The ratio between GCA/SCA was found to be relatively low (0.08, 0.095, 0.07, and 0.08 for Plant height, Stem/hill, No of tuber/pl, and yield per plant, respectively), which defined the occurrence of dominance and/or epistatic gene action (Table 4). The specific combining ability variances were recorded higher than the general combining ability variance for plant height, stem per hill, number of tubers per plant, and yield per plant, which indicated that a greater amount of genetic variability was present (Table 5). Concerning the general combining ability for plant height, the parents BARI Alu-41 and BARI Alu-53 were good combiners. BARI Alu-79 for stem per hill and yield and BARI Alu-37 for tuber number and yield contributed complementary favorable alleles and had good general combining ability (Table 5). SCA performance in terms of yield per plant and number of tubers per plant is presented in Table 6. Seven of the 24 crosses crossed with BA-72 had a positive particular combining ability, while the others had a negative specific combining ability in terms of yield per plant (Table 6). On the other hand, seven crosses using BA-86 as a tester showed negative specific combining ability in terms of tuber number per plant (Table 6). The specific combining ability indicated ‘BARI Alu-37’ × ‘BARI Alu-86’ and ‘BARI Alu-77’ × ‘BARI Alu-72’ as the most promising hybrid with a higher tuber yield and tuber number (Table 6).

4. Discussion

Many commercial varieties fail to flower, and the flowers fail to set berries [21]. In the right conditions, all potato plants can generate blooms. Several methods could be applied to induce flowering and stop the abscission of flowers [22]. The response to flower-inducing and berry-set methods varied from genotype to genotype [15]. In our study, the flowering period was influenced by genotype, as well as other environmental factors, including temperature and day length. In the middle of January, potato plants stopped flowering as the temperature fell, and the days became shorter. However, in late February, the temperature began to climb and the length of the days started to lengthen, allowing flowering but putting berry drop at risk due to a monsoon storm (Figure 1). Similar findings were published by Muthoni et al. [15], who found that genotype, temperature, and day length are determining factors in potato flowering and fruiting. Flower-inducing hormones might be another essential method for getting flowers and berries. Standardizing the conditions for flowering and fruiting for each clone may not be cost effective or practicable. However, in natural conditions, days to flower initiation will help to synchronize flowering among parents and help to make specific crosses. Similarly, Gopal [23] reported that flowering initiation fluctuated from 6 to 15 weeks after planting, while the flowering period was 1 to 10 weeks. In addition, the selection of male parents will reduce the failure of fertilization, increase the fertilization success rate, and save the cost and labor for this hybridization program. Due to limited resources, we evaluated 10 hybrid plants from each family. Instead of evaluating the limited number of plants, it is better to evaluate all the members of the families; otherwise, there is a chance of losing the diverse desirable clones. BARI Alu-41 and BARI Alu-53 for plant height, BARI Alu-79 for stem per hill, and BARI Alu-37 for tuber number and yield are good combiners regarding general combining ability (Table 5). The most potential hybrid families for developing improved genotypes for the trait tuber yield and tuber number are BARI Alu-37 × BARI Alu-86, and BARI

Alu-77 × BARI Alu-72, according to the specific combining ability (Table 6). Lv et al. [24] mentioned that future generations' GCA performances could be predicted by evaluating the GCA of a line in an earlier generation, saving time and money. We evaluated the GCA effect in the 2nd filial generation before seed multiplication for the preliminary yield trial, which also saves time and money. All plants of high SCA hybrid families would be evaluated precisely to get a promising hybrid based on other desirable characteristics. Christie and Shattuck [25] reported that which sort of gene activity is present is determined by the GCA/SCA ratio; the presence of additive genetic influences is indicated by a high ratio. Variation in additive gene action will be limited, allowing non-additive gene activity, such as epistasis, to contribute to relatively significant progeny variation [26]. In our investigation, we found that the GCA/SCA value was quite low, which characterized the prevalence of non-additive gene action and showed significant diversity among hybrid clones. The most commercially important characteristics, including yield, specific gravity (dry matter content), tuber size, and tuber number, have proven that non-additive genetic variance is important in tetraploid breeding [27]. In the inheritance of tuber yields in potatoes, SCA was found to be more important than GCA [28]. The line into tester analysis was shown to provide excellent opportunities for assessing the utility of potato clones as breeding parents.

Climate change has an impact on potato production in Bangladesh. The winter season is getting shorter, and potato growers are experiencing issues due to erratic rains in Bangladesh. Potato breeding should be concentrated on salt-tolerant varieties for saline areas, waterlogged tolerant varieties for Haor areas, high dry matter producing varieties for processing, and pest- and disease-resistant varieties. To develop varieties with a wide spectrum of adaptability and tolerance, new breeding materials will be required. In addition, potato breeding needs to be a targeted breeding strategy supported by marker-assisted breeding. Genetic markers linked to specific genes could speed up the breeding process in the future [21].

5. Conclusions

For a successful cross, the effect of environment and parent selection based on flowering and fruit (berry)-setting behavior must be considered. Selection between progeny (crosses/full-sib families) and within the most promising clones would be beneficial for breeding quality traits. Furthermore, potato breeding time will be reduced by selecting potato clones with desirable qualities in the first generation and selecting superior clones using a Line into Tester approach. The trait-specific selection of parents by population screening may also result in the delivery of promising clones. Rapid multiplication and multi-location evaluation, combined with modern approaches, such as marker-assisted selection, genomic selection, gene editing, and targeted hybridization, may help future potato breeding. The findings of the present study will serve as a guide for future potato breeding programs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12040501/s1, Table S1: Different varieties' days to flowering during the 2019 and 2020 seasons at the breeder seed production center; Table S2: List of BARI variety × BARI variety crossing successes during the 2019 season at the breeder seed production center; Table S3: List of BARI variety × BARI variety crossing successes during the 2020 season at the breeder seed production center; Table S4: Proportion of crossing successes as males during the 2019 and 2020 seasons at the breeder seed production center; Table S5: Proportion of crossing successes as females during the 2019 and 2020 season at the breeder seed production center.

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