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RESEARCH ARTICLE

Evaluation of Long-Day Onion (*Allium cepa* L.) Genotypes for Yield and Quality Traits Under Temperate Conditions of Kashmir Valley in India

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Abstract
Onion (*Allium cepa* L.) is an important vegetable crop consumed throughout the world. Diverse crop germplasm is a prerequisite for the long-term success of breeding programs. We evaluated 50 long-day onion germplasm lines and two check varieties for phenotypic variation in 16 yield and quality traits. The genotype CITH-O-40 recorded the highest total yield and marketable yield, which can be attributed to the lowest bolter production, highest ABW and its fairly good polar and equatorial bulb diameter. The PCA-based hierarchical clustering divided the whole germplasm into three major clusters. Seven principal components (PC1 to PC7) explained ~77.8% of the total phenotypic variation. Polar diameter, neck thickness, percent bolters, marketable yield and total yield, constitute the PC1, the first main factor. Marketable yield showed a negative correlation with percent bolters and doubles production but had a significantly positive correlation with TSS content. Our results suggest that for increasing total bulb yield and marketable yield, the genotypes that produce a high percentage of bolters and doubles should not be considered in crop improvement programs. The current work elucidates the morphological variability present in the examined germplasm collection, which can be used for onion improvement breeding.

Keywords: *Allium cepa* L., Cluster analysis, Germplasm, Long day onion, Morphological variation, PCA.

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Introduction

Allium cepa L. is a highly valuable vegetable and spice reported to have originated in central Asia. The economic value of this crop derives from its culinary uses, nutritional benefits, and health-promoting properties (Benkeblia, 2005). Domestic and export demand is rising continuously; thus, high-yielding varieties with better quality traits is one of the primary breeding objectives. Genetic variability is essential to meet the diversified goals of plant breeding, such as higher yield, wider adaptation, desirable quality parameters, and resilience to biotic and abiotic stresses (Kushwaha *et al.,* 2021). The selection of genetically diverse parents is of immense importance for successful recombination breeding (Arunachalam, 1981; Akter *et al.,* 2015). Parents identified on the basis of the divergence analysis would be more promising in onion (Mohanty and Prusty, 2002). Knowledge of local populations can be useful in breeding location-specific cultivars since they possess balanced trait complexes suited for specific climatic and edaphic factors (Ricciardi *et al.,* 2020). These landraces and local cultivars often possess vast variability for agronomically important traits and are readily available for breeding elite cultivars without undesirable linkage drag (Swarup *et al.,* 2021). Thus, conservation and precise estimation of genetic variability within landraces are basic and continuous processes for crop improvement (Mondal, 2003; Verma *et al.,* 2008). Thus, germplasm evaluation in onion and related *Allium spp.* is a preliminary and essential step for quantification of the potential value of germplasm line for breeding the specific trait as well for higher yield (Dhatt *et al.,* 2005; Khosa *et al.,* 2014).

Principal component analysis (PCA) is a multivariate analysis method that reduces complexity in multi-dimensional data while retaining trends and patterns and enabling an easier understanding of connections and impacts among different variables (Lever *et al.,* 2017). PCA identifies the key traits decisive for genotypic variation and differentiation (Kovacic, 1994).

The germplasm studied in this investigation belongs to the long-day category of onion, which is transplanted in November-December in the Kashmir region. Its bulbing starts in the month of April following dormancy during winters and growth resumption in March. The bulb growth and development enter well into the month of June when the day length reaches 14 hours and more. When tops wither or topple over, the bulbs are harvested by the end of June or the beginning of July. The bulb yield of long-day onions in Kashmir is higher than short-day/ intermediate day onions grown elsewhere. However, the storage life tends to be shorter due to high water content of large bulbs. To date, no public sector variety has been released/ recommended for the region, although an introduction, 'Brown Spanish' is increasingly becoming popular among onion growers due to consistent efforts by the Indian Council of Agricultural Research (ICAR)-Central Institute of Temperate Horticulture (CITH), Srinagar. ICAR-Directorate of Onion and Garlic Research (DOGR), Rajgurunagar, Pune, is also instrumental in intensifying research on long-day onion through its All-India Network Research Project on Onion and Garlic, which it operates in the region through ICAR-CITH, Srinagar. The project has tested many long-day onion entries from both the public and private sector at ICAR-CITH.

Keeping all the above facts in view, this study was undertaken to determine the nature and extent of variability in onion germplasm collection at ICAR-CITH, Srinagar, and to identify promising genotypes according to their genetic potential for their possible use in future improvement programs and the development of high-yielding cultivars of onion.

Materials and Methods

Plant material and Experimental design

The experimental material consisted of 50 germplasm collections of long-day onion (*Allium cepa* L.) along with two long-day check varieties *viz.,* Brown Spanish and Yellow Globe. The study was conducted for three consecutive years from 2016 to 2018 at ICAR-CITH, Srinagar, Jammu & Kashmir, India. The Research Farm is situated at a latitude of 34° 05′ N and a longitude of 74°50′ E, at an elevation of 1640 meters above mean sea level (MSL). The average monthly meteorological data during the three cropping seasons of experimentation is given in Table S1.

The experiment was laid out in a randomized complete block design (RCBD). The sowing was done in August and transplantation in November/December at a spacing of 20 cm x 10 cm in 2.5 square meter plots per replication. Recommended NPK and S fertilizers were applied and appropriate plant protection measures were adopted for raising a good crop. Soil macronutrient status and other quality parameters at the experimentation block is given in Table S2. The observations were recorded on ten randomly selected plants of each germplasm line in each replication for 16 yield and quality parameters *viz.,* plant height (cm), number of leaves/plant, neck thickness (cm), polar diameter (mm), equatorial diameter (mm), Polar diameter/Equatorial diameter (P:E ratio), percent 'A grade' bulbs, percent' B grade' bulbs, percent 'C grade' bulbs, percent bolters, percent doubles, percent unmarketable bulbs, marketable yield (q/ha), total yield (q/ha), average bulb weight (g) and total soluble solids (%).

Plant height was measured with a scale from ground level to the top of the plant just before the crop ripeness. The number of leaves per plant was counted along with the plant height measurements. Neck thickness and polar and equatorial diameters were measured with the Vernier Caliper. Percent bolters and percent doubles were calculated on a count basis in the field and average bulb weight was calculated by dividing the total yield of the plot by a total number of bulbs. Total and marketable bulb yields (q/ha) were determined on the basis of plot yield. Based on the recommendations of ICAR-DOGR, Pune, onion bulbs were categorized into three grades on the basis of bulb size, *i.e.,* A grade (>4.5 cm), B grade (3.5–4.5 cm) and C grade (2.5–3.5 cm). Total soluble solids (TSS) readings were taken 15-20 days after bulb harvesting by 'Hand-held Digital Refractometer' (ATAGO®, Japan). Harvesting was done in the third to fourth week of June.

Statistical analysis

The data of three years was pooled, and mean descriptive statistics were carried out using SAS statistical analysis software (SAS Institute Inc., 2017). The significant differences were detected using one-way analysis of variance (ANOVA) between the mean values of all characters recorded among the studied genotypes. The least significance difference (LSD) was calculated at 5% level of significance to test the differences between the means of tested genotypes. Pearson's correlation coefficient was calculated to analyze the correlations between the studied traits.

PCA and cluster analysis

Principal components analysis (PCA) was done to identify major traits accounting for the variation among the studied onion genotypes. The PCA was based on the correlation matrix, and the number of significant principal components was determined based on the Kaiser criterion, retaining any component with an Eigenvalue greater than 1 (Kaiser, 1960). Following PCA, the squared cosine (cos^2) was computed, which gave the quality of representation of the variables on the factor map and the total contribution of individual traits. Cos^2 demonstrates the importance of a component for a given observation and is important in identifying which component to make an inference on (Adu *et al.,* 2018). For a given trait, the sum of the cos^2 on all dimensions is equal to 1, whereupon if the trait is perfectly represented by only two dimensions (PC1 and PC2), the sum of the cos^2 on these two dimensions is 1 (Kassambara, 2017). The contribution, explaining the variations retained by two PCs (PC1 and PC2), is given by the formula (Kassambara, 2017):

$$[(C1 \times Eig1) + (C2 \times Eig2)] / (Eig1 + Eig2)$$

Where C1 and C2 are the contributions of the variable on PC1 and PC2, respectively, and Eig1 and Eig2 are the Eigenvalues of PC1 and PC2, respectively. To identify groups of genotypes with similar key quantitative traits, cluster analysis was performed using traits identified by the PCA as key contributing variables to genetic variation. PCA and Hierarchical Clustering on Principal Components (HCPC) were performed using R software v3.6.3 (2020).

Results and Discussion

The mean values and range of 16 yield and quality traits of 50 long-day onion genotypes and two check varieties from pooled data of the three years (2016-18) in presented in Table 1. The bulb diameter (polar and equatorial) and the P:E ratio determines the shape of the bulb and its storability. The maximum polar diameter (85.78 mm) was found in the genotype CITH-O-11, while the minimum (41.64 mm) was found in CITH-O-33. The equatorial diameter ranged from 46.11 mm to 84.53 mm. The highest equatorial diameter (84.53 mm) was recorded in CITH-O-33, while the smallest (41.64 mm) in CITH-O-13. The average P:E ratio ranged from 0.60 to 1.72 cm and the highest P:E ratio (1.72) was recorded in CITH-O-13, while the smallest (0.60) in CITH-O-2. Neck thickness has a significant effect on bulb storability and quality. The onion genotype showed a wide range in neck thickness ranging from 0.69 to 3.59 cm. The highest neck thickness (3.59 cm) was observed in CITH-O-24, whereas the lowest (0.69 cm) was observed in CITH-O-5.

Marketable yield depends upon the number and weight of A, B, and C grade bulbs and will determine the value of the produce. The yield of 'A grade' bulbs during three years ranged from 18.55 to 41.55%. The maximum 'A grade' bulbs (41.55%) were found in genotype CITH-O-15, while the lowest (18.55%) was found in check variety Yellow Globe. Similarly, the yield of 'B grade' bulbs ranged between 13.94 to 37.95% and 'C grade' bulbs ranged between 9.26 to 42.43%. In onions, the production of doubles and bolter bulbs are genetically determined parameters that deteriorate marketable bulb yield and quality (Abdalla and El Hassan, 1975; Rabinowitch, 1979). Bolted bulbs show poor shelf life and cannot be stored for a longer period of time. Thus, the identification of genotypes with minimum bolting is desirable. Double bulb production in the onion crop is undesirable for the processing industry and leads to lower market value.

In our study, the percent bolters production ranged from 2.05 to 18%. The maximum percent bolters were recorded in CITH-O-20 (18%), while the minimum was recorded in CITH-O-31 (2.05%). The percent doubles ranged from 1.04 to 7.35%. The maximum percent doubles (7.35%) were recorded for genotype CITH-O-1, while minimum percent doubles were found in CITH-O-44 (1.04%). The maximum percent of unmarketable bulbs was found in CITH-O-48 (62.75%), while the minimum percent of unmarketable bulbs was recorded in genotype CITH-O-40 (11.85%). Average bulb weight (ABW) determines the marketable yield and total yield of the crop. The ABW ranged from 90.07 to 365.74 g. The maximum average bulb weight (365.74 g) was found in CITH-O-40, while the lowest (90.07 g) was found in CITH-O-11. The average marketable yield ranged from 290.47 to 1582.46 q/ha. The maximum average marketable yield (1582.46 q/ha) was recorded in CITH-O-40, while the lowest (290.47 q/ha) in CITH-O-10. The average total yield ranged from 329.05 to 1642.38 q/ha. The maximum average total yield (1642.38 q/ha) was recorded in CITH-O-40, while the lowest (329.05 q/ha) in CITH-O-10. Trivedi *et al.* (2006) have indicated that onion yield improvement could be possible by increasing the equatorial and polar diameters of bulbs, average bulb weight and percent of 'A' grade bulbs. This is evident from the data that genotype CITH-O-40 topped the list of several desirable traits analyzed in our study, such as the highest total yield and highest marketable yield, which can be attributed to the lowest bolter production, highest ABW and fairly good polar and equatorial diameter of bulb. The genotype CITH-O-45 recorded the highest total soluble solids (TSS) content, *i.e.,* 14.54%. Genotypes CITH-O-36 (14.26%) and CITH-O-44 (14.06%) also recorded very high TSS content. Thus, these three genotypes *viz.,* CITH-O-36, CITH-O-44 and CITH-O-45, can serve as breeding material for high TSS content.

Correlation analysis

Pearson's correlation between different parameters evaluated is presented in Table 2. Several studies have shown that significant genetic variation exists for yield and yield-related traits *viz.,* polar diameter, equatorial diameter, neck thickness and ABW in onion (Trivedi *et al.,* 2006; Santra *et al.,* 2017; Barakat *et al.,* 2021). In our study, total bulb yield showed a significant positive correlation with marketable yield (r = 0.986) and TSS (r = 0.339) and

Table 1: Mean values and range of 16 yield and quality traits of 50 onion genotypes and two check varieties evaluated under temperate conditions of Kashmir, India

Genotypes	*Plant height (cm)*	*Range*	*No. of leaves/ plant*	*Range*	*Polar diameter (mm)*	*Range*	*Equatorial diameter (mm)*	*Range*	*P:E ratio*	*Range*	*Neck thickness (cm)*	*Range*	*AGB (%)*	*Range*	*BGB (%)*	*Range*
CITH-O-1	38	14-71	9	7-12	44	35-60	63	58-72	1	1	1	1-2	23	18-30	34	28-44
CITH-O-2	41	17-73	9	7-10	47	36-66	77	73-83	1	1	1	1-2	26	19-37	33	21-43
CITH-O-3	60	43-73	9	7-10	68	61-73	76	71-80	1	1	1	1-4	26	17-32	32	25-38
CITH-O-4	49	34-59	9	7-11	52	42-58	75	73-77	1	1	1	0-3	26	12-33	25	22-29
CITH-O-5	58	33-73	9	7-11	67	57-73	69	59-74	1	1	1	1-2	30	11-50	22	18-30
CITH-O-6	55	35-64	8	7-11	61	61-62	55	54-56	1	1	1	1-3	29	15-37	21	15-28
CITH-O-7	52	33-63	9	7-12	68	58-86	76	74-78	1	1	3	1-7	30	26-32	21	13-31
CITH-O-8	60	35-81	9	7-10	53	51-57	75	68-78	1	1	3	1-7	32	23-40	19	13-29
CITH-O-9	63	35-87	9	7-10	59	47-66	82	76-86	1	1	1	1-3	32	12-53	22	20-24
CITH-O-10	57	37-73	8	7-9	62	54-78	64	62-67	1	1	1	1-2	30	23-37	19	13-25
CITH-O-11	62	39-86	8	7-9	86	83-90	65	48-83	1	1	2	1-6	30	25-34	24	7-42
CITH-O-12	54	36-74	8	7-8	56	52-61	73	69-76	1	1	2	1-4	34	32-35	22	10-29
CITH-O-13	59	37-76	8	7-9	79	73-89	46	42-54	2	2	2	1-5	31	28-36	23	19-25
CITH-O-14	55	34-76	8	7-10	56	54-57	64	61-67	1	1	2	1-5	33	29-40	26	25-29
CITH-O-15	58	35-72	9	7-10	59	52-64	68	65-73	1	1	1	1-2	42	10-50	27	24-30
CITH-O-16	50	35-60	9	7-11	71	69-73	81	79-84	1	1	3	1-8	29	22-34	20	17-25
CITH-O-17	52	34-68	10	7-16	62	59-64	76	73-80	1	1	1	1-3	28	22-35	25	22-28
CITH-O-18	55	36-75	8	7-11	68	67-68	77	76-80	1	1	3	1-9	37	28-47	29	24-32
CITH-O-19	59	35-76	9	7-10	54	50-57	82	80-84	1	1	3	1-9	31	29-36	28	23-36
CITH-O-20	58	35-76	9	7-11	62	58-64	63	61-65	1	1	2	1-6	26	18-39	26	11-47
CITH-O-21	55	36-77	8	7-11	65	64-66	81	71-87	1	1	3	1-9	34	26-40	23	20-25
CITH-O-22	48	35-55	8	7-9	63	62-63	69	67-72	1	1	1	1-2	27	17-39	26	21-30
CITH-O-23	51	35-68	11	7-17	51	51-52	67	67-68	1	1	1	1-3	33	35-38	14	6-23
CITH-O-24	54	35-74	9	7-8	51	52-52	75	74-76	1	1	4	1-10	24	15-35	22	15-32
CITH-O-25	50	41-56	7	7-9	70	56-90	57	48-65	1	1	1	1-2	28	18-36	38	9-59
CITH-O-26	55	40-81	9	7-10	63	62-63	81	77-84	1	1	3	1-6	28	13-36	20	15-25
CITH-O-27	60	33-84	9	7-12	68	64-74	64	61-68	1	1	1	1-3	34	23-44	30	26-36
CITH-O-28	54	33-70	10	7-14	64	64-65	77	61-82	1	1	1	1-3	39	34-43	30	23-43

CITH-O-29	48	35-63	8	7-10	56	46-72	70	67-72	1	1	3	1-7	24	7-42	23	18-28
CITH-O-30	50	37-62	8	7-8	56	56-57	71	70-72	1	1	1	1-2	31	31-34	21	18-25
CITH-O-31	49	41-58	9	7-10	61	59-62	70	68-73	1	1	3	1-9	27	16-32	20	16-23
CITH-O-32	42	31-51	8	7-8	48	43-52	67	65-71	1	1	2	1-6	23	14-35	29	23-35
CITH-O-33	60	39-87	8	7-10	42	41-42	85	84-86	0	0	2	1-6	33	35-36	19	11-25
CITH-O-34	48	35-55	7	6-8	58	51-62	81	76-83	1	1	1	1-2	30	23-37	28	22-38
CITH-O-35	51	37-61	8	7-10	56	52-61	74	72-77	1	1	2	1-6	33	24-40	30	9-55
CITH-O-36	53	31-65	8	7-8	54	53-56	76	61-83	1	1	1	1-3	36	10-44	22	15-35
CITH-O-37	53	34-72	8	7-8	51	46-55	68	67-70	1	1	1	1-2	32	9-40	22	19-25
CITH-O-38	47	32-63	7	7-8	67	52-82	66	58-71	1	1	1	1-2	33	30-37	25	20-31
CITH-O-39	54	35-69	7	7-8	65	53-72	72	69-75	1	1	1	1-2	41	28-61	18	4-25
CITH-O-40	55	35-71	9	7-11	65	52-72	83	64-92	1	1	1	1-2	27	19-36	35	25-43
CITH-O-41	58	38-79	9	8-12	62	61-63	73	71-75	1	1	1	1-2	21	11-29	34	30-41
CITH-O-42	57	36-74	7	6-9	63	51-70	78	68-83	1	1	1	1-3	29	22-33	28	19-34
CITH-O-43	59	39-84	8	8-8	50	49-52	67	59-72	1	1	2	1-4	32	28-34	19	14-22
CITH-O-44	51	38-60	8	7-8	68	58-74	84	71-92	1	1	1	1-3	33	21-44	26	22-30
CITH-O-45	55	37-66	8	7-9	61	52-79	69	63-73	1	1	3	1-7	37	31-45	26	18-32
CITH-O-46	53	37-71	10	7-13	52	50-54	57	53-64	1	1	1	1-2	29	20-304	18	14-22
CITH-O-47	49	33-71	8	7-10	66	65-67	76	75-77	1	1	1	1-2	28	13-37	18	13-19
CITH-O-48	48	38-53	8	7-9	56	55-57	79	71-84	1	1	2	1-5	20	4-28	26	16-35
CITH-O-49	45	42-53	7	6-8	79	56-126	59	54-66	1	1-2	1	1-23	20	13-28	36	26-48
CITH-O-50	61	61-64	8	8-8	54	53-56	67	58-74	1	1	1	1-24	21	5-30	17	15-17
Yellow Globe	57	29-68	8	5-9	57	52-60	67	73-83	1	1	1	1-2	19	18-19	29	27-34
Brown Spanish	34	28-45	7	4-7	57	67-73	63	57-86	1	1	1	1-2	24	8-37	26	25-47
Minimum	**34**		7		42		46		0		1		19		14	
Maximum	63		11		86		85		2		4		42		38	
L.S.D. (at 5%)	30		3		5		11		0		1		16		14	

To be continued …

Abbrev.: P:E ratio (Polar: Equatorial diameter ratio); ABG (A grade bulb); BGB (B grade bulb); CGB (C grade bulb); ABW (Average bulb weight); TSS (Total soluble solids).
Footnote: All the values are presented up to one place of decimal to the nearest integer of the actual value.

Genotypes	*CGB (%)*	*Range*	*Bolters (%)*	*Range*	*Doubles (%)*	*Range*	*Unmarketable bulbs (%)*	*Range*	*Marketable yield*	*Range*	*Total yield (q/ha)*	*Range*	*ABW (g)*	*Range*	*TSS (%)*	*Range*
CITH-O-1	28	8-35	6	2-15	7	2-10	28	13-70	558	192-775	742	683-814	141	129-163	8	7-10
CITH-O-2	31	19-38	6	3-11	3	2-3	27	9-14	796	192-1071	1007	683-1102	148	129-163	11	10-13
CITH-O-3	23	23-31	6	0-17	1	0-2	25	8-21	1072	494-1418	1117	548-1453	151	131-164	14	13-15
CITH-O-4	24	24-42	6	0-17	3	0-5	26	24-76	923	502-1196	964	555-1226	115	102-133	10	7-15
CITH-O-5	26	23-40	4	0-13	3	0-5	26	9-19	788	428-993	855	470-1061	214	113-279	10	6-16
CITH-O-6	29	28-33	7	1-22	2	0-5	32	28-28	761	745-763	808	790-817	191	188-196	6	6-6
CITH-O-7	32	11-38	11	2-31	4	0-7	39	10-43	556	525-629	630	629-688	125	116-136	11	7-12
CITH-O-8	31	19-32	6	3-19	5	0-5	35	16-28	811	401-1057	864	476-1083	111	106-115	12	9-15
CITH-O-9	21	20-39	4	0-10	6	3-8	31	7-25	580	523-629	630	554-687	217	136-267	13	12-14
CITH-O-10	27	0-19	12	2-30	5	2-9	40	10-45	290	97-389	329	112-454	180	134-259	13	5-20
CITH-O-11	18	6-22	13	0-39	6	2-9	31	17-54	480	303-586	516	332-610	90	80-96	9	6-14
CITH-O-12	25	7-29	11	1-33	3	0-7	30	6-50	639	580-686	665	605-714	149	141-161	9	7-12
CITH-O-13	27	15-32	10	0-26	3	1-7	32	20-36	719	592-937	765	647-1010	92	81-154	12	8-9
CITH-O-14	23	11-26	7	0-22	5	0-8	25	17-33	613	473-685	652	529-717	114	105-126	13	9-19
CITH-O-15	13	12-20	13	0-32	2	1-6	31	15-40	635	432-971	464	324-540	158	96-196	11	10-12
CITH-O-16	35	12-44	9	0-27	2	0-4	40	17-39	889	677-1015	938	726-1051	195	166-216	10	9-12
CITH-O-17	29	13-36	10	0-29	3	0-5	29	15-35	589	573-601	630	605-647	200	154-274	8	7-9
CITH-O-18	9	5-17	6	0-19	4	0-6	25	12-32	749	592-854	797	674-882	210	160-295	9	8-13

CITH-O-19	28	18-32	7	0-22	2	0-5	26	0-30	719	516-856	750	489-900	126	118-136	14	12-15
CITH-O-20	24	5-26	18	0-54	3	0-8	47	5-66	467	410-568	507	451-580	118	105-137	13	10-16
CITH-O-21	22	17-24	6	0-17	2	0-7	24	12-31	599	436-698	637	491-726	111	105-118	11	8-16
CITH-O-22	21	5-22	16	0-45	4	0-9	44	22-57	606	470-707	665	559-759	208	133-263	11	7-17
CITH-O-23	29	11-15	10	1-29	4	0-11	46	37-48	461	424-544	513	454-596	176	175-178	11	11-11
CITH-O-24	29	13-28	10	0-30	2	1-7	49	33-42	634	629-661	697	689-711	170	163-172	9	8-9
CITH-O-25	12	8-14	14	0-41	2	0-6	44	14-53	522	470-564	556	541-631	143	128-160	12	11-13
CITH-O-26	16	15-16	17	1-44	5	0-8	42	28-56	483	422-594	507	452-653	228	156-289	11	10-12
CITH-O-27	19	7-29	3	2-9	4	0-3	27	13-23	1370	362-1918	1400	436-1962	152	105-176	12	8-19
CITH-O-28	20	14-19	3	0-6	2	0-5	22	0-20	715	604-797	735	622-826	191	147-259	11	9-15
CITH-O-29	23	17-34	9	0-26	4	0-11	32	14-43	361	255-518	383	282-600	110	82-144	12	8-17
CITH-O-30	23	18-23	5	1-15	4	0-12	30	14-34	344	297-357	375	329-383	174	170-176	8	8-9
CITH-O-31	23	22-62	2	0-5	3	1-3	48	7-24	1304	570-1722	1344	616-1758	148	140-156	8	7-10
CITH-O-32	35	19-45	8	0-23	1	0-4	20	5-31	740	366-963	758	388-994	131	92-150	11	8-16
CITH-O-33	19	18-20	6	0-18	3	1-8	48	23-34	491	458-532	529	477-596	126	124-128	8	7-8
CITH-O-34	28	10-31	4	0-11	3	0-8	31	22-23	1130	546-1479	1156	561-1509	250	133-322	12	11-13
CITH-O-35	15	12-18	4	0-11	5	0-13	24	9-34	564	513-589	584	543-619	142	137-149	11	10-12
CITH-O-36	31	21-47	3	1-7	4	1-6	35	20-28	418	278-495	446	337-539	117	81-151	14	13-16
CITH-O-37	31	5-41	13	0-31	6	0-9	33	27-44	491	309-587	594	413-865	160	99-191	8	6-10

CITH-O-38	24	20-30	7	0-14	2	2-4	28	12-20	1023	425-1375	1054	464-1413	192	111-241	14	13-14
CITH-O-39	23	5-25	5	0-16	2	0-5	29	25-31	878	320-1163	935	391-1283	176	94-239	8	7-8
CITH-O-40	20	19-36	3	0-7	3	0-5	12	5-11	1582	512-2124	1642	549-2255	366	132-514	13	12-13
CITH-O-41	23	5-25	15	0-44	2	0-7	41	13-53	743	598-820	787	659-909	244	158-292	13	13-14
CITH-O-42	26	12-27	6	0-17	5	1-10	24	10-32	562	533-590	595	494-655	316	142-405	13	11-14
CITH-O-43	26	15-28	12	1-19	6	1-12	30	4-38	340	240-430	404	369-537	152	119-194	10	8-13
CITH-O-44	19	15-22	8	0-24	1	0-3	27	11-34	688	507-782	758	560-959	155	134-170	14	13-16
CITH-O-45	22	13-27	5	0-13	4	0-6	17	10-27	518	402-578	550	518-643	123	107-138	15	14-15
CITH-O-46	16	4-20	18	3-45	4	0-7	43	22-57	518	454-641	549	499-670	218	160-499	13	8-20
CITH-O-47	23	24-29	9	0-28	3	0-9	42	34-44	514	510-524	557	553-573	202	201-209	13	13-13
CITH-O-48	31	25-42	4	0-11	4	0-12	63	19-31	501	478-543	556	505-620	144	127-159	11	7-13
CITH-O-49	22	20-23	8	0-23	5	4-10	27	19-39	344	291-430	395	381-570	126	117-132	9	6-7
CITH-O-50	42	8-60	9	0-27	4	0-12	34	4-45	412	282-526	446	406-555	106	119-141	14	13-14
Yellow Globe	37	35-39	3	1-5	2	2-5	27	13-44	758	561-963	914	537-1117	250	129-299	12	10-12
Brown Spanish	34	21-40	2	0-2	2	0-2	29	5-35	666	366-1480	698	372-1760	132	128-374	9	10-13
Minimum	9		2		1		12		290		329		90		6	
Maximum	42		18		7		63		1582		1642		366		15	
L.S.D. (at 5%)	12		23		6		32		493		507		93		5	

Table 2: Pearson's correlation between different yield and quality traits studied in onion germplasm under the temperate conditions of Kashmir, India

Parameters	*Plant height (cm)*	*No. of leaves per plant*	*Polar diameter (mm)*	*Equatorial diameter (mm)*	*P:E ratio*	*Neck thickness (cm)*	*AGB (%)*	*BGB (%)*	*CGB (%)*	*Bolters (%)*	*Doubles (%)*	*Unmarke-table (%)*	*Marke-table yield*	*Total yield (q/ha)*	*TSS (%)*
No. of leaves per plant	ns	1													
Polar diameter (mm)	ns	ns	1												
Equatorial diameter (mm)	ns	ns	ns	1											
P:E ratio	ns	ns	0.806**	-0.684**	1										
Neck thickness (cm)	ns	ns	ns	0.241*	ns	1									
AGB (%)	0.327**	ns	ns	ns	ns	ns	1								
BGB (%)	-0.253**	ns	ns	ns	ns	ns	-0.265**	1							
CGB (%)	ns	ns	-0.305*	ns	-0.232*	ns	-0.460**	-0.239*	1						
Bolters (%)	ns	ns	ns	-0.285**	0.260**	ns	ns	ns	ns	1					
Doubles (%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	1				
Unmarketable (%)	ns	ns	ns	ns	ns	ns	-0.264*	ns	ns	0.423**	ns	1			
Marketable yield	ns	ns	ns	ns	ns	ns	ns	0.281*	ns	-0.438**	-0.391**	-0.286*	1		
Total yield (q/ha)	ns	ns	ns	ns	ns	ns	ns	0.298*	ns	-0.452**	-0.339**	-0.281*	0.986**	1	
TSS (%)	ns	ns	ns	0.292*	ns	-0.331**	ns	ns	ns	ns	ns	ns	0.344**	0.339**	1
ABW (g)	0.266*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Abbrev.: P:E ratio (Polar: Equatorial diameter ratio); ABG (A grade bulb); BGB (B grade bulb); CGB (C grade bulb); ABW (Average bulb weight); TSS (Total soluble solids).
* Correlation is significant at the 0.05 level. ** Correlation is significant at the 0.01 level. ns: non-significant

a significant negative correlation with percent bolters (r = -0.452) and percent doubles (r = -0.339**)**. Concurrently, marketable yield showed a significant negative correlation with percent bolters (r= -0.438) and percent doubles (r = -0.391). However, marketable yield showed a significant positive correlation with TSS (r = 0.344). Previously, Arya *et al*. (2017), while studying twenty-six onion accessions, found a significant negative correlation between percent doubles, percent bolters and marketable yield and a positive correlation with TSS. Therefore, for increasing total bulb yield and marketable yield, the genotypes that produce a high percentage of bolters and doubles should not be considered in crop improvement programs. Onion TSS content determines the suitability to storage and recovery of dehydrated onion. TSS content is affected by various factors such as nutrient application, row spacing, regional condition and storage conditions (Tekle, 2015; Lee *et al.,* 2016; Bekele *et al.,* 2018; Islam *et al.,* 2019). Studies regarding the association of plant height and biomass accumulation with TSS content are scanty. In our study, TSS content and neck thickness are negatively associated. This is obvious because the wider neck of onion bulbs is disadvantageous as it leads to post-harvest moisture loss and, thus, decreases the TSS content. TSS content was found to be positively correlated with equatorial diameter and interestingly, in turn, equatorial diameter is negatively associated with bolters production, which is an undesirable feature. Thus, the genetic basis of such associations needs to be investigated.

Principal Component Analysis (PCA)

The aim of factor analysis is to reduce the number of effective parameters to discriminate genotypes. PCA reduces the dimensionality of the data by transforming initial variables into a new small set of variables without losing the important information in the original variables. Seven principal components, PC1 to PC7, were extracted from the original data, which had latent roots >1, and accounted for nearly 77.8% of the total variation. Results of the PCA analysis. *i.e.,* Eigenvalues, the proportion of variance explained and the cumulative proportion for the extracted PCs, is presented in Table 3. PCA showed that 11 of the studied parameters accounted for 47.3% of the variance as the three main factors, with the other 5 parameters scattered within four factors determined as 77.8% of the total variance. PCA of quantitative traits in onion genotypes revealed maximum variation and the first seven PCs showed Eigenvalues >1, where PC1 possessed the highest Eigenvalue (3.12). Out of seven major PCs extracted, the PC1 showed significant factor loadings for morphological traits *viz.,* polar diameter (0.537), percent bolters (0.356), no. of leaves/plant (0.347) and neck thickness (0.275). Arya *et al.* (2017) observed that high positive loading from onion average bulb weight, bulb yield and high negative loading from leaf length, double/deformed bulb in PC1 contributed more towards differentiating the clusters. Similarly, Singh *et al.* (2013) observed that in the first principal component for onion plant height, marketable yield, bulb polar diameter and bulb neck thickness were the major contributors. These findings show that our results are in agreement with previous findings. Hanci and Gokce (2016) reported that the characters contributing more positively to PC1 were bulb weight and diameter of the pseudo stem.

The first two principal coordinates were used to create an outline of the differences and relationships between the genotypes by measuring the quality of representation (cos^2) of individuals on the factor map (Fig. 1). The first factor separated genotypes CITH-O-40, CITH-O-34, and CITH-O-27 and CITH-O-3 on the side of factor plot that has the highest number of traits like marketable yield, total yield and polar diameter and were the most prominent genotypes contributing towards PCA. Also, the genotypes CITH-O-11 and CITH-O-13 settled in the upside of factor plot that have lower amounts for these traits and were the least contributing individual factors. Dangi *et al.* (2018), on the basis of squared cosine value (cos^2) for individual factors on the first two principal coordinates, also found the most prominent genotypes contributing towards PCA as well as the least contributing individual factors.

Hierarchical clustering on principal components (HCPC)

In the present investigation, hierarchical clustering was performed by using Ward's criterion on the selected principal components. Ward's criterion is based on multi-dimensional variance like PCA. The PCA step is considered a denoising step, which can lead to a more stable clustering to identify groups (*i.e.,* clusters) of similar objects within a data set of interest. Our PCA results showed that PC1, PC2 and PC3 explained 19.56, 15.46, and 12.27% variability, respectively and contributed 47.3% of the total variation in the data sets, suggesting these PC scores might be used to summarize the original 16 variables in any further analysis of the data. Characters with the largest absolute value closer to unity within the first PC influence the clustering more than those with lower absolute value closer to zero. Therefore, in the present study, the first three principal components were taken because of the relatively high contribution of these components rather than the small contribution from each principal component. The cluster analysis performed on the PCA results suggested a three-cluster solution (Fig. 2). The partitioning into three clusters is represented on the factor map produced by the first two principal components and the individuals are colored according to their clusters (Fig. 3). The barycentre of each cluster is also represented by triangle, circle and square. The graph shows that the three clusters are well-separated on the first two principal components. Superimposing the individuals on the principal component map suggested that cluster

Table 3: Principal components analysis for 16 traits in onion genotypes evaluated under temperate conditions of Kashmir, India

PCA	*PC1*	*PC2*	*PC3*	*PC4*	*PC5*	*PC6*	*PC7*
Eigenvalues	3.126	2.481	1.975	1.424	1.296	1.134	1.014
Proportion of variance	0.1956	0.1546	0.1227	0.0872	0.0829	0.072	0.063
Cumulative Proportion	0.196	0.350	0.473	0.560	0.643	0.715	0.778
Variables	PC 1	PC 2	PC 3	PC4	PC5	PC6	PC7
Plant height (cm)	0.198	0.489	0.28	0.251	0.253	0.158	0.411
No. of leaves/plant	0.347	0.449	-0.189	0.584	0.312	-0.41	-
Polar diameter (mm)	0.537	0.11	0.101	-0.347	0.229	-0.458	-
Equatorial diameter (mm)	-0.226	-0.333	0.334	-0.129	0.101	0.129	-0.29
P:E ratio	0.106	0.585	-0.124	0.112	-0.155	0.115	-
Neck thickness (cm)	0.275	-0.571	0.197	-0.455	0.24	0.111	0.246
%A grade bulb	0.135	0.458	-0.412	-0.26	0.227	-0.315	-0.161
%B grade bulb	-0.262	0.18	-0.31	0.192	-0.525	0.32	0.125
%C grade bulb	-0.317	-0.3	0.146	-0.184	0.371	0.467	0.145
%Bolters	0.356	0.158	0.122	0.337	0.254	-0.191	-0.115
%Doubles	0.257	-0.262	0.167	-0.158	0.795	0.132	-0.324
%Unmarketable	0.294	-0.137	0.495	-0.163	-0.317	-0.469	-0.187
Marketable yield(q/ha)	-0.499	0.226	-0.172	-0.279	0.127	-	-
Total yield (q/ha)	-0.496	0.231	-0.173	0.16	-0.285	-	-
TSS (%)	-0.271	0.191	0.565	-0.108	0.182	-0.395	0.175
ABW (g)	0.122	0.27	0.745	-0.132	0.234	-0.402	-0.192

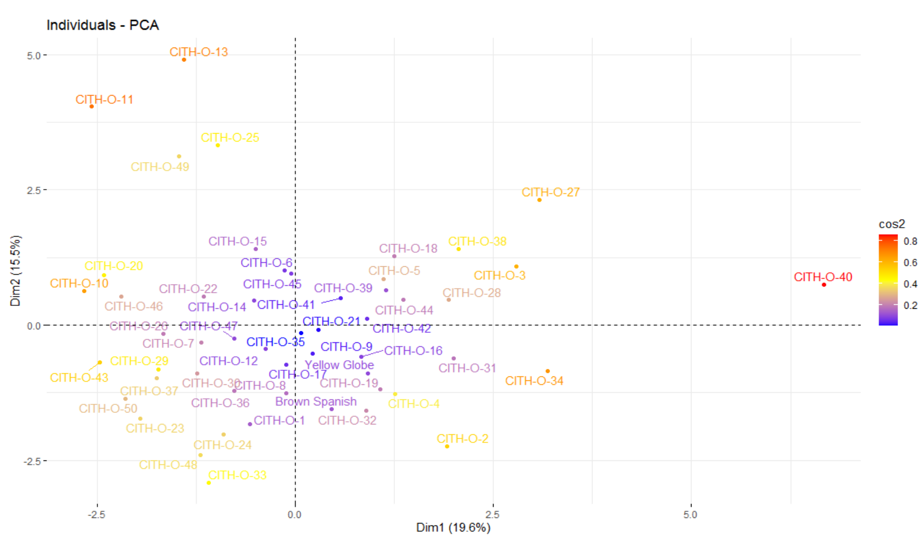

Fig. 1: Contribution of 52 onion accessions towards PCA based on cos^2 value

1 is largely negative to PC1; cluster 2 is largely negative to PC2 and cluster 3 is mainly positive to PC1. Therefore, individuals in clusters 1, 2 and 3 are associated with the variables that are mapped to the respective quadrants of the factor map. The variables P:E ratio, polar diameter, % B grade bulb, number of leaves/plant, ABW, and equatorial diameter were most significantly associated with cluster 1. Cluster 2 was significantly associated with variables such as percent unmarketable bulbs, C grade bulb, %doubles, P:E ratio, percent B grade bulb, total yield, marketable yield and polar diameter. Cluster 3 was significantly associated with variables such as unmarketable bulbs, %A grade bulb,

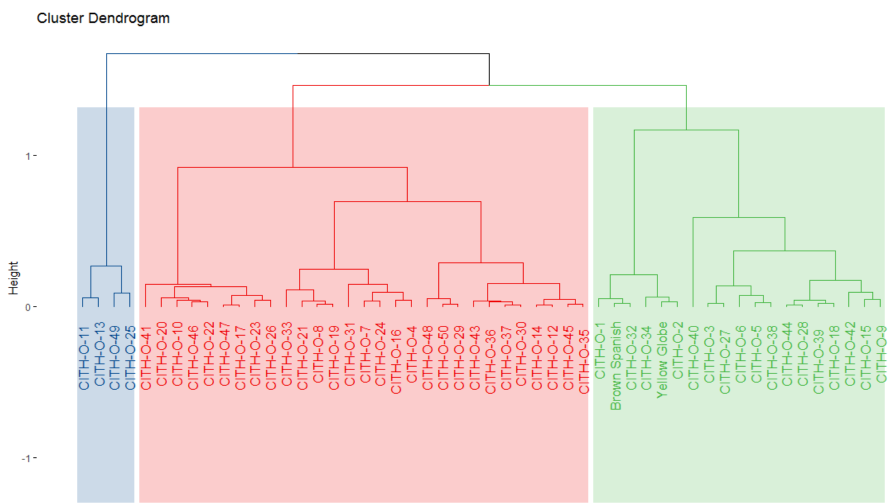

Fig. 2: Hierarchical clustering on principal components (HCPC) showing clustering patterns of 52 onion collections based on 16 parameters

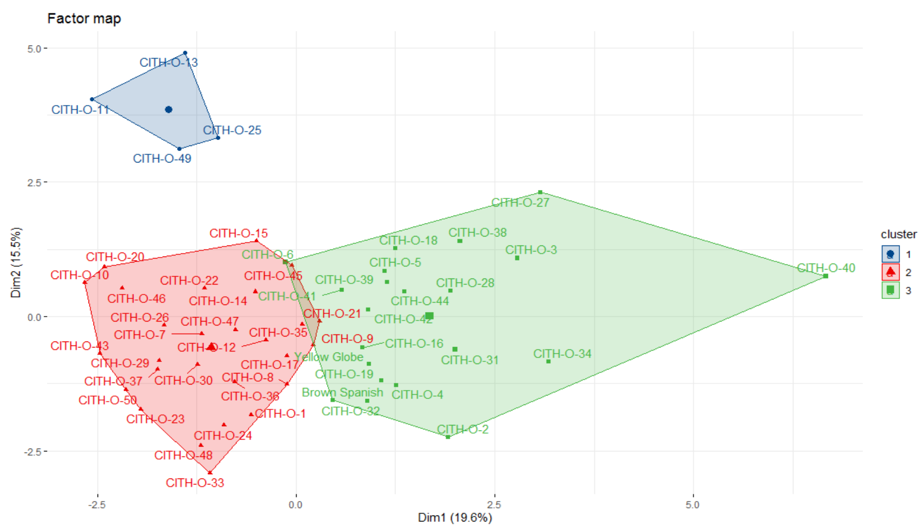

Fig. 3: Factor map representation of three clusters produced by the first two PCs (Individuals are coloured according to their cluster)

%doubles, %bolters, P:E ratio, A grade bulbs, total yield, marketable yield and equatorial diameter. For each cluster, the top 4 closest individuals to the cluster center are shown in Fig. 3. For example, representative individuals for cluster 1 include CITH-O-25, CITH-O-13, CITH-O-11 and CITH-O-49, representatives of cluster 2 include CITH-O-30, CITH-O-36, CITH-O-47 and CITH-O-29, and cluster 3 include CITH-O-44, CITH-O-39, CITH-O-5, CITH-O-31 and CITH-O-42. Although the 52 genotypes have the same geographic origin except for Yellow Globe and Brown Spanish still, they were grouped into different clusters, indicating the presence of significant phenotypic diversity. Nevertheless, the results in the present study highlighted genotype groups that have similar or contrasting features or contribute strongly to the quality of representation on the factor map or to variation and could accordingly be explored to identify the genetic basis of specific traits.

Conclusion

In a nutshell, the most important traits contributing to variation in the onion genotypes included plant height, number of leaves, polar diameter, equatorial diameter and neck thickness. Besides this, traits like average bulb weight, total yield and marketable yield could be used to select onion genotypes for a notable improvement in cultivation in changing environments. The PCA-based hierarchical clustering divided the whole germplasm into three major clusters. The first seven principal components explained ~77.8%, and the first three principal components explained 47.3% of the total phenotypic variation. Polar diameter, neck thickness, percent bolters, marketable yield and total yield, constitute the PC1, the first main factor. This study also offers a path to rapid screening of large onion genotypes in field experiments for crop improvement purposes like crossing the genotypes from different clusters. For example, Cluster I and Cluster II could result in heterotic expression and bring large variability in the segregating generation. Identification of key phenotypic parameters will reduce the costs associated with phenotyping of all traits. For instance, the genotype CITH-O-40 recorded the highest total yield and marketable yield, which can be attributed to the lowest bolter production, highest ABW and its fairly good polar and equatorial bulb diameter. In fact, we observed that marketable yield showed a significant negative correlation with percent bolters and doubles production, but it had a significantly positive correlation with TSS content. Furthermore, the quantitative approach employed here can underpin further well-targeted and in-depth field-based studies of traits to support onion breeding programs.

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Declarations of interest

There is no conflict of interest.

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Table S1: Monthly average meteorological data for crop seasons of the year 2016-2018 at Srinagar

Day	*Average temperature (°C)*		*Average rainfall (mm)*
	Max.	*Min.*	
Year 2016			
January	11	-2	64
February	15	1	28
March	16	4	140
April	20	8	82
May	26	12	44
June	30	17	18
July	30	18	55
August	28	17	44
September	28	14	2
October	25	6	1
November	17	0	0
December	11	-3	0
Year 2017			
January	4.7	-1.1	134
February	10.9	1.4	87
March	15.6	4.1	58
April	21.2	7.8	169
May	24.7	12.4	23
June	27.7	15	66
July	29.9	18.8	31
August	30.1	17.6	22
September	28.9	13.2	11
October	24.8	6	0
November	16.3	1.1	10
December	11.3	-2.1	30
Year 2018			
January	7.0	-2.0	60
February	8.2	-0.7	70
March	14.1	3.4	100
April	20.5	7.9	80
May	24.5	10.8	80
June	29.6	14.9	50
July	30.1	18.1	70
August	29.6	17.5	60
September	27.4	12.1	30
October	22.4	5.8	20
November	15.1	0.9	20
December	8.2	-1.5	50

Table S2: Soil status and available macronutrients at Vegetable block, ICAR-CITH before transplanting of Onion crop.

Soil parameters	*2016*	*2017*	*2018*
Soil texture	*Silt Loam*		
Soil pH	7.89	7.58	7.1
Electrical conductivity (ds/m)	1.11	0.525	0.823
Soil organic Carbon (%)	0.50	0.47	0.48
Available N (kg/ha)	313.6	324.1	329.7
Available P (kg/ha)	11.72	11.92	13.01
Available K (kg/ha)	254.35	259.2	258.71
Available Ca (Cmol/kg)	3.8	4.2	3.7
Available Mg (Cmol/kg)	2.1	2.4	2.5
Available S (ppm)	12	13.9	15.1