Effect of interannual rainfall variability and distribution on growth and yield of *kharif* onion cultivars in India

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Four-year field experiments were conducted to assess the effect of interannual rainfall variability and distribution on the plant growth parameters and yield five *kharif* onion cultivars, viz. Bhima Super, Bhima Dark Red, Agrifound Dark Red, Arka Kalyan and Phule Samarth. Each cultivar was replicated six times. The plant growth parameters and yield were recorded during the plant growth period. The results showed that rainfall received 30–60 days after transplanting substantially and negatively affected the plant growth parameters and bulb yield of all the cultivars during the high-rainfall years while increasing onion bulb rotting losses. Bhima Super and Bhima Dark Red produced significantly higher marketable bulb yields throughout the experimental period. Hence these two cultivars can be successfully cultivated during the *kharif* season. However, they produced 44.5–63.6% lower yield during the high-rainfall than the low-rainfall years. This indicates that the yield of *kharif* onion cultivars could be further increased through improved management practices.

Keywords: Bulb yield, *kharif* onion cultivars, leaf area index, plant growth period, rainfall intensity.

ONION (*Allium cepa* L.) is grown worldwide for vegetable, spice and culinary purposes. Most households need onions daily. It offers numerous nutritional and nutraceutical benefits. Globally, onion is cultivated in 5.47 m ha area, producing a total crop yield of 104.6 mt (ref. 1). India is the second largest onion-producing country in the world. In India, onion is cultivated during three seasons, namely *kharif* (monsoon), late *kharif* (late monsoon) and *rabi* (winter), contributing approximately 20%, 20% and 60% of the total production respectively. Once harvested, *rabi* onions could be stored up to October to meet the consumer demand until the arrival of *kharif* onions in the market. Although onion is a cool-season crop, to meet domestic requirements, it has also been adapted to *kharif* and late *kharif* seasons through varietal selection and improved cultivation practices. *Kharif* onions are supplied from October to January to stabilize the market prices[2].

However, genetic, environmental and cultivation practices affect *kharif* onion production[3]. Precipitation and temperature extremes severely damage onion production under changing climatic conditions[4,5]. Drought and excessive rainfall caused by rainfall extremes are the top two climatic factors that cause crop loss[6,7]. Being an irrigated crop, the effect of drought could easily be managed for onion through supplemental irrigation. However, excessive rainfall substantially damages *kharif* onion production[5]. Waterlogging caused by excessive rainfall negatively affects plant growth[8]. Due to shallow root growth, the onion crop is extremely sensitive to waterlogging-induced stress. The flooding damage level is determined by the season, soil quality, variety, crop-growth stage, rainfall intensity and duration. These factors also predict bulb yield and survival potential of a particular onion variety. Excessive rainfall can reduce crop yield by up to 34%, which is comparable to the reduction in crop yield with extreme heat and drought[6]. However, the loss caused by excessive rainfall fluctuates with the duration, frequency and intensity of rainfall, and the growth stage of the crop at which rainfall occurs[9].

According to Samra *et al.*[5], excessive rainfall at the maturity stage results in approximately 50–70% crop loss and affects bulb quality. Excessive rainfall during active growing stages hinders root growth, nutrient uptake, nutrient translocation and photosynthesis, thereby reducing crop growth and development[10]. Furthermore, information, particularly quantitative knowledge, available regarding the impact of excessive rainfall received during the growing period on plant growth and yield of *kharif* onion is limited and therefore leaves a critical knowledge gap. Thus, determining the effect of the interannual variability of monsoon rainfall and its distribution on plant growth and yield-contributing characteristics at different stages of *kharif* onion is crucial. Hence, the present study assessed the effect of interannual rainfall variability and distribution on *kharif* onion production to address this knowledge gap.

Materials and methods

Experimental site

The field experiment was conducted at the Research Farm of the Indian Council of Agricultural Research-Directorate

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of Onion and Garlic Research from 2015 to 2018. The experimental site is located near Pune, Maharashtra (18.32°N, 73.51°E; elevation 645 m amsl). The study area has a hot semi-arid climate with tropical wet and dry periods. The long-term average rainfall of the area is 820 mm year^{-1}, and is predominantly received during the southwest monsoon season (June–September, approximately 98.5%). The mean maximum and minimum air temperatures of the area are 27.0–39.5°C and 9.3–22.3°C respectively. The soil is *Typic Haplustepts* having a clay loam texture with slightly alkaline pH, and low concentration of organic carbon and available nitrogen (Supplementary Table 1).

Experimental details

The experiments were performed in a randomized block design with six replications. Among them, three replicates were used for destructive plant sampling and the remaining for plant growth and yield observations. We evaluated five *kharif* cultivars, viz. Bhima Super (BS), Bhima Dark Red (BDR), Agrifound Dark Red (ADR), Arka Kalyan (AK) and Phule Samarth (PS). They are widely cultivated in *kharif* onion-growing areas of India. Approximately 40–45-days-old onion seedlings were transplanted on raised beds having a width of 1.2 m, height of 45 cm and length of 60 m, separated by a spacing of 15 cm × 10 cm, during July–August of each year (8 August 2015, 10 August 2016, 30 July 2017 and 2 August 2018). Each treatment plot had an area of 14 sq. m and was occupied by 933 onion plants. All recommended cultural practices, including fertilizer and weed management practices, and pest and disease control measures were followed throughout the experimental period. The onion crop was harvested every year during November (20 November 2015, 22 November 2016, 11 November 2017 and 14 November 2018), and the data on yield and rotting losses were recorded.

Number of leaves and leaf area index

From each treatment, 20 plants were labelled in the plot allotted for recording plant height, the number of leaves, and yield parameters. The number of leaves was recorded from 15 to 105 days after transplanting (DAT). At each sampling time point, 20 plants were collected from two rows (12 plants row^{-1}) from each cultivar at an interval of 15 days from 15 DAT to until harvest. The third fully matured leaf from the top of each plant was detached and used for measuring the leaf area using a leaf area meter. Leaf area index (LAI) was estimated using the formula

$$\text{LAI} = \frac{\text{Total leaf area of a plant (m}^2\text{)}}{\text{Ground area occupied by the plant (m}^2\text{)}}.$$

Equatorial bulb diameter

The bulb samples were separated from the aboveground portions to measure the equatorial diameter (ED; in millimetres) of the bulbs using a digital vernier caliper.

Dry matter accumulation and crop growth rate

Twenty plants collected from each plot were washed, air-dried and separated into aboveground portions and bulbs. Air-dried plant parts were chopped into pieces and dried in a hot-air oven at 58°C until a constant weight was attained. Aboveground biomass accumulation, biomass accumulation in the bulbs and total dry matter (TDM) accumulation were estimated (kg ha^{-1}). Based on TDM accumulation, the crop growth rate (CGR) was determined using the formula

$$\text{CGR} = W_2 - W_1/t_2 - t_1,$$

where W_1 is the dry weight per unit area at t_1, W_2 the dry weight per unit area at t_2, t_1 is the first sampling and t_2 is the second sampling.

Statistical analysis

Two-way analysis of variance (ANOVA) was performed using PROC MIXED of SAS ver. 9.3 to determine the effect of cultivars, years and their interactions on total onion yield and rotting losses. Moreover, the number of leaves, plant height, dry matter accumulation, LAI and CGR were also statistically analysed to study the effect of stage, cultivar, year and their interactions using three-way ANOVA. Tukey's honestly significant difference test was used for multiple comparisons among cultivars, years, stages and their interactions at $P < 0.05$. The Pearson correlation coefficient and a two-tailed test were used to determine the degree of correlation between rainfall, yield, plant height, the number of leaves, dry matter accumulation and LAI. Stepwise multiple regression analysis was also performed between the explanatory variables, namely T_{max}, T_{min}, RH_{max}, RH_{min} and rainfall, and the dependent variable, namely yield, using SAS software ver. 9.3.

Results

Rainfall change

Total rainfall varied from 468.0 to 1041.4 mm during 2015–18. Rainfall received during the growing season (July–November) was higher in 2015 (563.2 mm) and 2017 (561.8 mm) than in 2016 (204.2 mm) and 2018 (203.2 mm) (Figure 1). In addition to total rainfall, the number of rainy days with rainfall intensity of >30 mm was higher during 2015 and 2017 (high-rainfall years) than during

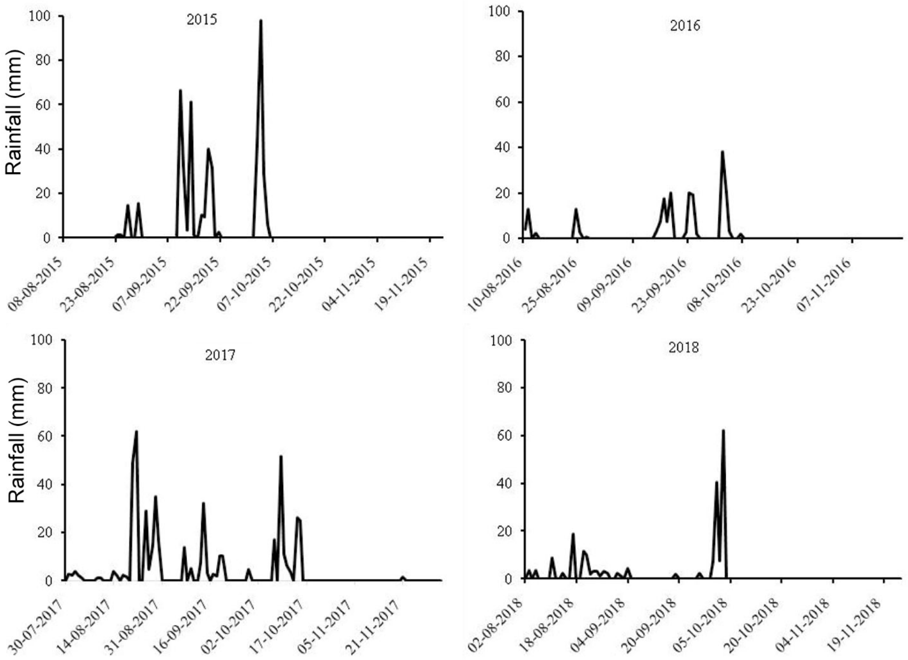

Figure 1. Rainfall received during the growing period (July–November) in the experiment site.

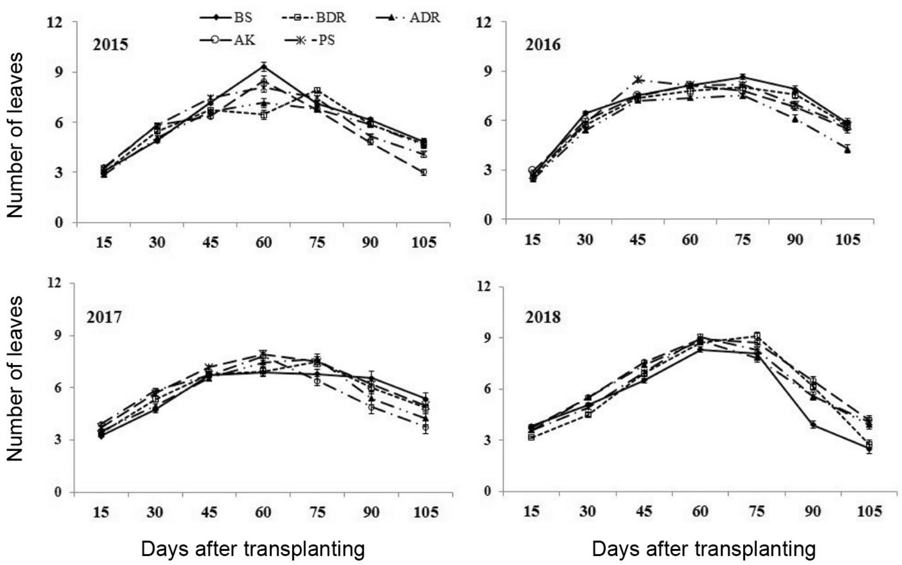

Figure 2. Effect of monsoon rainfall on the number of leaves at different growth stages of *kharif* onion cultivars during the experimental period.

2016 and 2018 (low-rainfall years). Furthermore, in all the years, rainfall was mostly received during 15–75 DAT (Figure 1). Overall, rainfall received was higher in September than during August, October and November in all four years of study.

Leaf area index

In all experimental years, except 2018, the number of leaves was higher in BS and BDR than in the other cultivars at 90 DAT (Figure 2). The stage, cultivar, year and their interactions significantly affected LAI (Supplementary Table 2). In general, LAI of all the cultivars varied between 0.23 and 3.84. It was lower across all cultivars in the high-rainfall years than in the low-rainfall years (Figure 3). In all the experimental years, LAI did not differ significantly between cultivars until 60 DAT. However, it varied significantly at 75 and 90 DAT in all experimental years. At these stages, a higher LAI was observed in BS and BDR than in the other cultivars. LAI was significantly and positively correlated with ED, the number of leaves and TDM accumulation (Table 1).

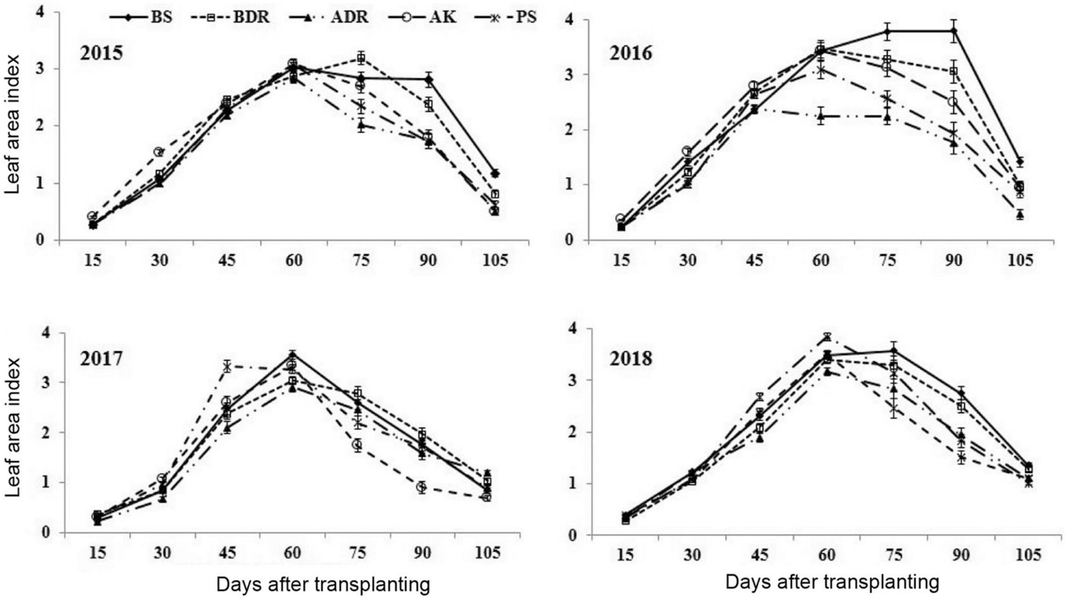

Figure 3. Leaf area index recorded at different growth stages of *kharif* onion cultivars during experimental period.

Table 1. Pearson correlation coefficient between plant growth and yield parameters

	Pearson correlation coefficient, $N = 360$						
	LAI	Number of leaves	Plant height	BMB	ED	Neck thickness	TDM
LAI	1	0.82842	0.8019	0.41628	0.56913	0.7479	0.53961
$P < 0.05$		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Number of leaves		1	0.70847	0.2801	0.45184	0.63667	0.38518
$P < 0.05$			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Plant height			1	0.26065	0.38338	0.60129	0.35375
$P < 0.05$				<0.0001	<0.0001	<0.0001	<0.0001
BMB				1	0.8895	0.54544	0.96865
$P < 0.05$					<0.0001	<0.0001	<0.0001
ED					1	0.76352	0.93044
$P < 0.05$						<0.0001	<0.0001
Neck thickness						1	0.67151
$P < 0.05$							<0.0001
TDM							1

LAI, Leaf area index; BMB, Biomass accumulation in bulbs; ED, Equatorial diameter; TDM, Total dry matter.

Bulb size

The crop growth stage, cultivar, year and their interactions significantly affected ED or bulb size. Compared with the high-rainfall years, the highest ED of bulbs (>45 mm diameter) at harvest was recorded in the low-rainfall years (Figure 4). The ED values of all the cultivars were approximately 30 mm till 60 days during the course of this study. During the high-rainfall years, the ED values increased by 16.7–41.3% from 60 days till harvest, while they increased by 49.1–69.2% in the low-rainfall years during the same period. In all experimental years, BS and BDR exhibited higher ED values than the other cultivars at harvest. ED was significantly and positively related to TDM accumulation ($r = 0.93$***).

Dry matter accumulation

Accumulation of aboveground biomass and TDM was significantly influenced by crop growth stage, cultivar, year and their interactions. TDM accumulation varied between 4,500 and 11,000 kg ha^{-1} (Figure 5). It was significantly higher during the low-rainfall years than the high-rainfall years. The accumulation increased from the value recorded in 2015 and 2017 by 38.5–107.5% and 28.1–79.7% in 2016 and 2018, respectively (low rainfall years). Irrespective of the cultivar and experimental year, TDM accumulation increased from 15 to 90 DAT and reached a plateau after 90 DAT. At 90 and 105 DAT, BS exhibited significantly higher TDM accumulation than the other cultivars in all years, followed by BDR. In the high-rainfall years, aboveground

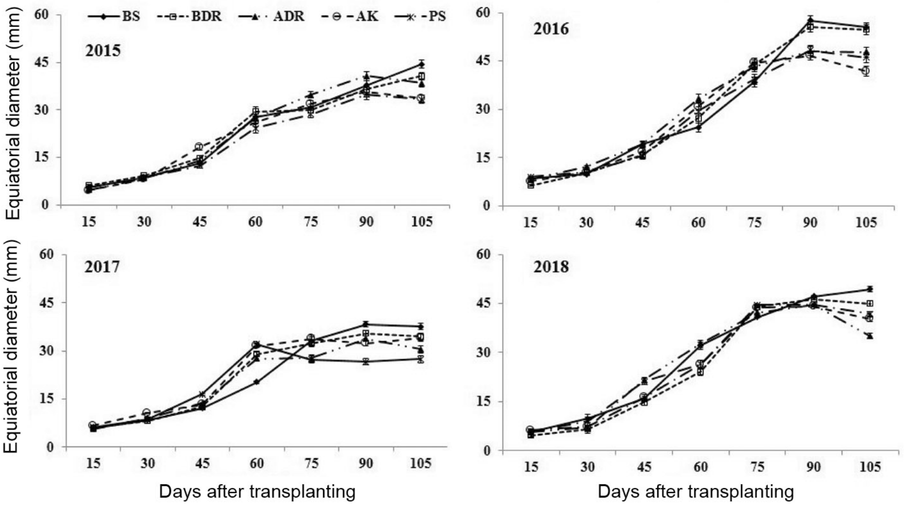

Figure 4. Equatorial diameter of onion bulbs recorded at different growth stages of *kharif* onion cultivars during the experimental period.

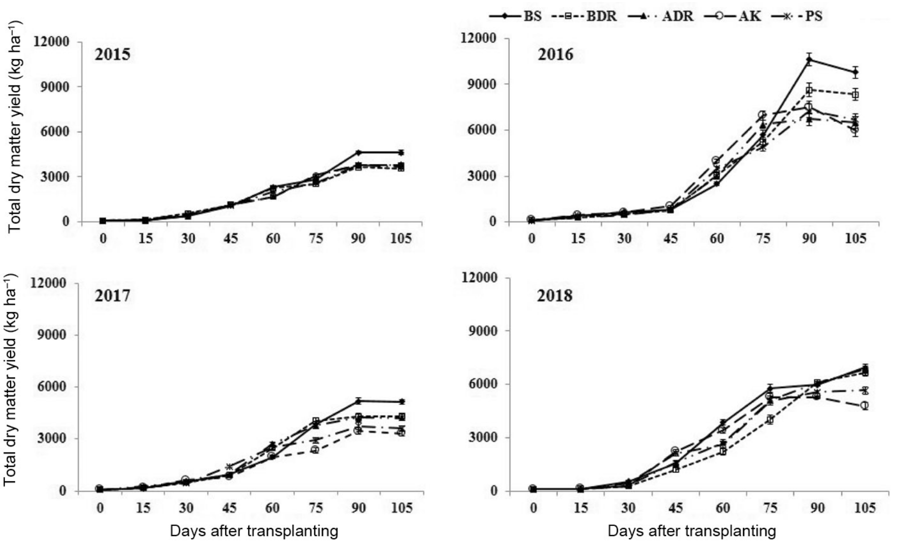

Figure 5. Effect of rainfall on total dry matter accumulation in *kharif* onion cultivars during the experimental period.

biomass accumulation increased to 105 DAT, while it increased to 90 DAT during the low-rainfall years and decreased thereafter. In all the cultivars, aboveground biomass accumulation was higher during the high-rainfall years than the low-rainfall years (Figure 6). BS accumulated higher aboveground dry matter over the years compared to the other cultivars. Furthermore, TDM accumulation exhibited a significant positive relationship with plant height and the number of leaves.

Crop growth rate

Cultivar, crop growth stage, year and their interactions significantly affected CGR. For all cultivars, CGR was lower in the high-rainfall years than in the low-rainfall years (Table 2). The rate increased up to 60 and 75 DAT in 2015 and 2017 respectively, and decreased thereafter until 75 and 90 DAT in those years. CGR again increased from 75 and 90 DAT until harvest. In contrast, during the low-rainfall years, CGR increased up to 75 DAT, and subsequently decreased after 75 days and reached a negative value at harvest. Except in 2018, CGR of BS and BDR increased up to 90 DAT in all years. In 2018, CGR of BS increased up to 60 DAT and then gradually decreased till 90 DAT.

Onion yield

Cultivar, year and their interactions significantly affected onion yield. The yield decreased by 55–65% during high-rainfall years compared to low-rainfall years (Figure 7).

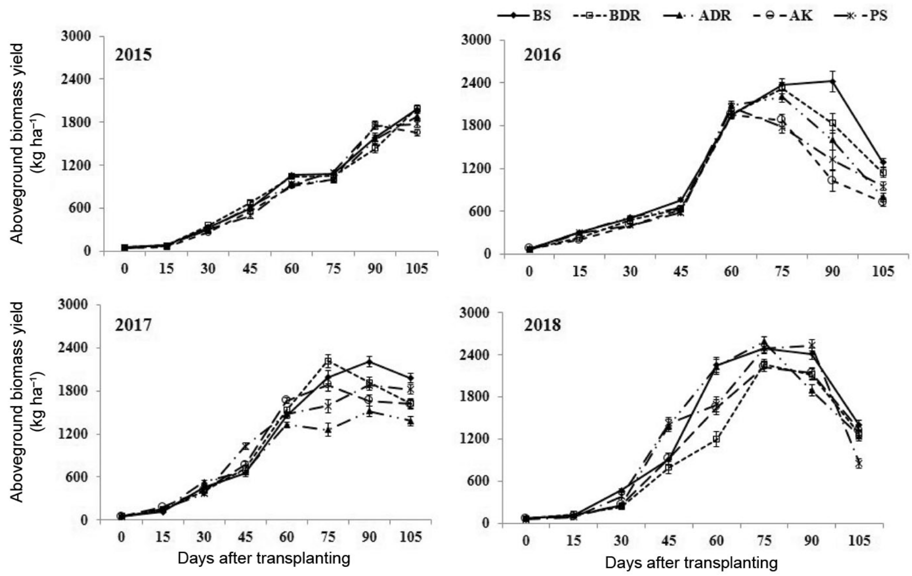

Figure 6. Effect of rainfall on aboveground biomass accumulation in *kharif* onion cultivars during the experimental period.

Table 2. Effect of interannual variability of monsoon rainfall and its distribution on crop growth rate of onion

Days after transplanting	Bhima Super	Bhima Dark Red	Agrifound Dark Red	Arka Kalyan	Phule Samarth
2015					
15	2.6	4.0	1.3	1.0	3.2
30	22.5	26.8	24.3	19.3	23.2
45	40.0	41.1	41.7	45.6	31.7
60	84.7	67.7	58.3	61.7	57.8
75	45.1	33.7	77.9	71.9	54.4
90	101.7	123.1	63.6	66.1	79.4
105	62.5	49.0	37.1	5.7	28.4
2016					
15	20.7	11.9	20.2	12.3	21.3
30	11.0	17.7	14.3	13.4	5.0
45	23.2	24.6	29.4	31.3	22.8
60	149.2	153.6	187.3	157.4	186.8
75	166.3	142.7	249.3	209.8	69.2
90	301.5	228.7	–36.4	–7.6	96.9
105	–45.3	–92.4	–43.7	–53.0	–17.5
2017					
15	5.1	7.6	7.4	11.0	7.9
30	26.1	18.9	28.7	19.3	16.6
45	18.3	26.8	14.6	26.5	59.8
60	75.3	107.4	74.3	119.3	88.4
75	119.6	103.6	41.8	79.3	23.8
90	96.0	16.4	47.3	1.3	39.3
105	6.2	54.0	57.3	63.3	105.3
2018					
15	1.6	2.8	3.0	0.6	0.7
30	26.9	7.7	10.0	12.4	22.0
45	64.2	67.7	128.1	76.5	112.3
60	158.1	66.6	80.0	80.8	37.7
75	126.9	120.8	168.8	168.9	148.8
90	124.9	144.0	36.0	71.9	63.1
105	70.2	23.8	–42.8	34.7	–20.7
HSD value (5%)	Year	3.8	Variety	4.1	
	Stage	13.5	Year ∗ variety	8.2	
	Year ∗ stage	25.2	Stage ∗ variety	28.2	
	Stage ∗ year ∗ variety	60.3			

Crop growth rate was influenced significantly by year, variety, stage and their interactions ($P < 0.0001$).

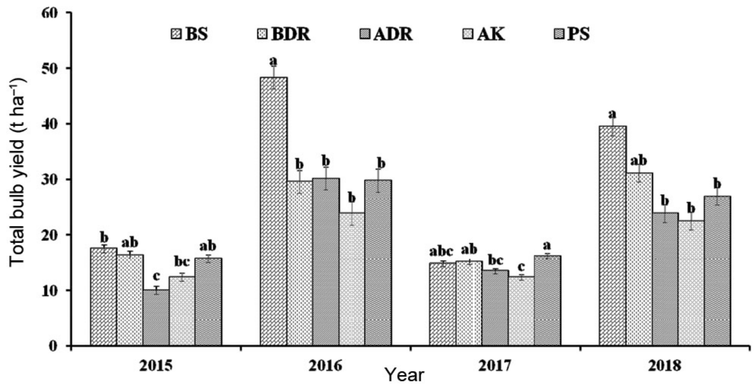

Figure 7. Effect of rainfall on yield of *kharif* onion cultivars during the experimental period.

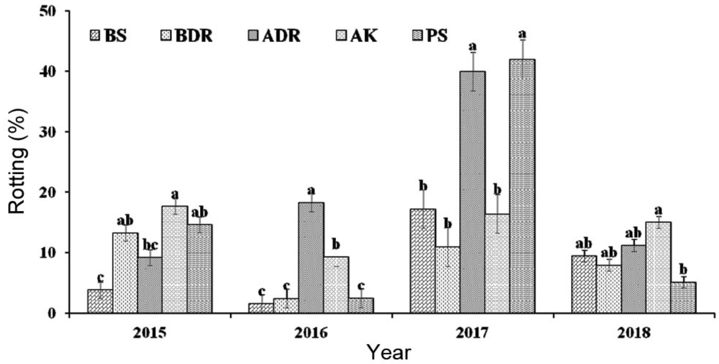

Figure 8. Effect of rainfall on rotting loss (%) of *kharif* onion cultivars during the experimental period.

Compared with other cultivars, the yield of BS was significantly higher during low-rainfall years (48.3 tonne ha^{-1} in 2016 and 39.5 tonne ha^{-1} in 2018). In 2018, the total bulb yield (31.1 tonne ha^{-1}) of BDR was comparable to that of BS. During high-rainfall years, the yield of BS, BDR and PS was higher than that of AK and ADR. However, the yield of BS decreased by 62.6–63.7% during the high-rainfall years (2015 and 2017) compared to the low rainfall years (2016 and 2018). During the same period, the reduction in BDR yield was 44.5–51.4%. The highest bulb rotting was observed in PS during the high-rainfall years (14.6% in 2015 and 41.0% in 2017) compared to the low-rainfall years (2.5% in 2016 and 5.1% in 2018) (Figure 8). However, the lowest bulb rotting was recorded in BS in 2015 and BDR in 2017. Furthermore, onion yield was significantly and negatively correlated with total rainfall ($r = -0.741$) and days above 30 mm ($r = -0.709$) and 40 mm ($r = -0.724$) rainfall.

Discussion

The main limiting factor for onion production is water. The onion crop requires approximately 350–550 mm of water during the growing season[11]. Frequent low/moderate intensity rainfall favours plant growth and development. However, frequent high seasonal rainfall (>850 mm) severely affects plant growth, reducing *kharif* yield[12]. Extreme precipitation event-induced waterlogging is a major contributor to yield losses[13]. The present study analysed the effect of interannual variation in precipitation and its distribution on the growth, development and yield of *kharif* onion.

Plant growth parameters

In the present study, the increase in plant height, the number of leaves and LAI recorded in 2016 and 2018 might be due to low rainfall coupled with supplemental irrigation during the dry period. Being an irrigated crop, onion can be successfully cultivated with supplemental irrigation during low/moderate rainfall years[14]. Furthermore, the lack of a statistically significant correlation between the growth parameters and rainfall received from transplantation to 30 DAT confirmed that rainfall during the initial 30 days of plant growth had less/no impact on it. Our previous study supported this result, which showed that waterlogging at an establishment and at the early vegetative stage (1–30 DAT) caused less damage[10]. Conversely, Ren *et al.*[15] reported that the effect of waterlogging varied with the plant growth stage at which it occurs. Excess rainfall received during 30–60 DAT in 2015 and 2017 might have led to decreased plant height, the number of leaves, and LAI in all cultivars after 30 DAT in those years. Excess rainfall-induced anoxic conditions may have resulted in oxidative damage to the root tissues and inhibited root respiration, energy generation and nutrient uptake[16]. Moreover, the strong negative correlation between the rainfall received during 30–60 DAT and plant growth parameters, namely LAI and plant height, explains the decreased plant growth during that period.

A higher number of green leaves were recorded at 90 DAT during the high-rainfall years than the low-rainfall years, possibly due to the inherent ability of the plants to recover from the excess moisture stress condition at a later growth stage. The plants may have maintained greenness during recovery by developing aerenchymatous root cells to withstand waterlogging. The presence of root aerenchyma facilitated tissue aeration and reduced the impact of excess moisture on plant growth and development in wheat and barley[17]. Although plants have more green leaves during recovery, LAI has decreased, possibly because of decreased leaf length and size. Malik *et al.*[18] also reported decreased leaf length and area during recovery. Moreover, the decreased number of leaves, LAI and plant height at maturity during low-rainfall years might be attributable to leaf abscission[19].

Yield attributes

High accumulation of dry matter in the aboveground portions of the plants at maturity during the high-rainfall years is probably due to the reduced translocation of photosynthates from the aboveground portion to the bulbs. Moreover, the strong positive relationship between the number of leaves at 90 DAT and rainfall explains the increase in aboveground dry matter accumulation at crop maturity during the high-rainfall years. However, a decrease in TDM accumulation and a smaller bulb size observed in all cultivars during the high-rainfall years in the present study can be explained by the significant negative relationship between the yield attributes, namely TDM accumulation and bulb size, and rainfall received during the growing period. According to Kim *et al.*[20], the dry matter yield in maize decreased because of waterlogging-induced stomatal closure and reduced transpiration and photosynthesis. The decreased CGR recorded at the bulb development stage in 2015 and 2017 may be a result of excess rainfall received during the active growth stage in those years. Ploschuk *et al.*[17] reported a similar impact of waterlogging on the physiological parameters in field pea and rapeseed. They reported that a week after transplanting, the photosynthetic rate decreased and reached values close to zero. Bulb development and enlargement in onion occurs at 60 DAT. The photosynthates produced are translocated from the aboveground portions to the bulbs during this period. However, in the present study, excess rainfall received during the study period severely affected bulb development and translocation of the photosynthates.

Onion yield and bulb rotting

Yield is a function of plant growth parameters and their interactions with the environment[21]. In the present study, the decrease in yield in 2015 and 2017 may have been due to a waterlogging-induced reduction in plant height, the number of leaves, LAI and dry matter yield. Samra *et al.*[5] also reported yield loss of approximately 50–70% and 10–15% in onions due to excess rainfall received in 1998 and 2005 respectively. Abewoy[4] reported that waterlogging at the bulb development stage resulted in a 30–40% reduction in onion yield. In the present study, multiple regression analysis revealed that weather variables, namely T_{max}, T_{min}, RH_{max}, RH_{min} and rainfall recorded during the growing season accounted for a 68.6% variation in onion yield (Supplementary Table 3). Among these factors, rainfall alone contributed to 54.9% variation in bulb yield. Moreover, rainfall received during September alone accounted for 60.4% variation in onion yield (Supplementary Table 4). This confirms that excess rainfall received during the growing period leads to a reduction in plant growth parameters and yield of *kharif* onion. A strong negative relationship was observed between yield and rainfall intensity, which showed that year-to-year fluctuations in precipitation and its intensity strongly affected *kharif* onion production. Moreover, the yield loss observed in all five onion cultivars in 2015 and 2017 was possibly due to the direct effect of excess rainfall on plant growth and yield attributes and the indirect effect of fungal and bacterial pathogens[22].

Higher bulb rotting was observed during 2015, 2017 and 2018, possibly because of excess rainfall during the bulb development phase (60–75 DAT). Excess rainfall might have facilitated the growth of pathogenic fungi and bacteria. Gadge and Lawande[23] reported that excess rainfall favours incidences of *Stemphylium* blight and basal rot diseases in onions. Increased incidence of these diseases might lead to bulb rotting under waterlogged conditions, which is correlated to the reduced marketable quality of onion[24]. In 2019, heavy rainfall at crop maturity reduced onion yield in the Lasalgaon region of Maharashtra, mainly due to bulb rotting[2]. However, postharvest bulb rotting was the lowest in 2016, possibly because of the presence of fully mature bulbs with senescent leaves[25]. Overall, this result confirms that total rainfall received during the growing season, its seasonal distributions and intensity determine plant growth and development, bulb yield and quality of onion.

Conclusion

High rainfall variability and distribution severely damage onion crops, causing economic losses to farmers. The present study revealed that excess rainfall received at 30–60 DAT and high-intensity rainfall (>30 mm) severely affect plant growth and development, and the marketable bulb yield of *kharif* onion cultivars. However, cultivars such as BS, BDR and PS exhibited better plant growth and produced a higher yield during the high-rainfall years than other varieties. These cultivars can be successfully grown during the *kharif* season with improved management practices. Moreover, the reduction in the yield of these cultivars was higher during the high-rainfall years than the low-rainfall years. Hence, cultivars that tolerate waterlogging must be developed to increase *kharif* onion production.

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