



RESEARCH ARTICLE

# Modulation of tomato disease complex through sowing window and genotype interactions

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## Abstract

To identify the most suitable combination of two components, viz., sowing window and genotype for minimising disease incidence and maximising yield and quality of tomato, the current study was conducted in Northern Tripura during the autumn–winter season. The overall findings of the trial revealed that the negative impacts of high and frequent occurrences of tomato diseases, including tomato yellow leaf curl virus (TYLCV), bacterial wilt, early and late blight, on the yield and quality characteristics of tomato. Delayed transplanting, particularly on 7<sup>th</sup> December, significantly increased the intensities of TYLCV, bacterial wilt, early and late blight of 18.69 %, 10.61 %, 5.55 % and 6.45 %, respectively, observed in the Local cultivar. In contrast, transplanting during 7<sup>th</sup> and 21<sup>st</sup> October recorded comparatively lower disease pressure and reduced yield loss. Among the genotypes, Arka Abhed, Arka Rakshak and Arka Samrat consistently exhibited superior performance with higher yield (66.25 t ha<sup>-1</sup>), lower yield loss (1.61 %) and improved quality attributes, including higher lycopene (56.43 mg 100 g<sup>-1</sup>) and carotenoid (104.00 mg 100 g<sup>-1</sup>) contents. The interaction between genotype and sowing window significantly influences disease dynamics, indicating that both genetic resistance and optimal planting time play a crucial role in disease management. From this, it can be inferred that growing tomatoes in these regions during the autumn–winter months would be most fruitful, if carried out between the second and last weeks of October, using varieties such as Arka Abhed, Arka Rakshak and Arka Samrat.

**Keywords:** Arka Abhed; disease management; sowing window; Tripura; yield loss

## Introduction

Tomato (*Solanum lycopersicum* L.) is widely used for culinary purposes, consumed raw as a salad, or processed into several by-products like juice, puree, ketchup, sauce and chutneys. Ripe tomatoes are rich sources nutritionally important compounds, especially carotenoids such as lycopene,  $\beta$ -carotene (provitamin A) and ascorbic acid besides minerals like calcium, phosphorus and iron (1). Tomato and its products, when consumed regularly, help in reduction of carcinogenesis, particularly, prostate and mouth cancer and also lower the risk of chronic degenerative diseases (2). The antioxidants in tomato, viz., carotenoids, particularly lycopene,  $\beta$ -carotene, ascorbic acid, vitamin E, phenolic compounds and flavonoids are the reason for the health benefits (3).

In India, the cultivation of this crop is widespread in West Bengal, Uttar Pradesh, Madhya Pradesh, Bihar, Gujarat, Odisha, Maharashtra, Tamil Nadu, Chhatisgarh and Karnataka, West Bengal being the leading producer (4). The commercial production of tomato particularly grown under open field conditions is severely affected by various weather parameters like temperature, rainfall and humidity etc. and ultimately affect the yield and quality of fruit (5). Temperature and relative humidity play a vital role in tomato growth, fruit setting, number of seeds and thereby the shape of fruits (6). Due to high temperature physiological disorders like flower and fruit abscission are seen in tomato (7). It becomes very essential to find out the best date of transplanting to expose the plants to most conducive atmosphere for growth, fruit setting and quality characters, with minimisation in outbreak of several diseases such as

tomato yellow leaf curl virus (TYLCV), bacterial wilt, early as well as late blight etc., which in turn leads to huge quantitative and qualitative loss to this crop.

Tomato production cannot be greatly improved by favourable growing circumstances alone; instead, yield stability relies on the interplay between cultivar-specific genetic resistance and suitable management approaches, such as optimal planting timing and disease-preventive strategies.

The production of tomatoes in a specific place is contingent upon the genotype employed and the prompt accessibility of resources (8). Some types may remain beneficial for many years, while others might be replaced by newer cultivars after a few seasons, especially since they are not resistant to or are more likely to get sick from certain diseases. It is also necessary to identify the most suited cultivars for specific regions in accordance with the existing circumstances (5). Recent studies have shown that the interaction between genotype and planting time is very important for determining the disease pressure, yield stability and fruit quality of tomatoes grown in open fields, especially in subtropical and tropical areas where temperature and humidity have a big effect on pathogen dynamics and crop performance (9, 10).

With a careful eye on the aforementioned facts and since research on the interactive influence between transplanting window and tomato genotype in the state of Tripura (especially in the northern part) is still lacking-particularly regarding the impact of treatment combinations on the incidence of various diseases and the simultaneous estimation of yield and quality loss, the current experiment has been designed to have a close investigation over these previously discussed issues with a clinical objective to find out the best times to plant tomatoes with respect to any specific genotype in these areas.

To keep diseases from spreading in tomatoes, farmers use a combination of genetically coded resistance and preventative agronomic practices. Some improved tomato genotypes include built-in tolerance or resistance to common diseases such TYLCV, bacterial wilt, early blight and late blight. This is frequently what makes them adaptable and perform well in different places. But genetic resistance is often not enough when disease pressure is great. This is why cultural behaviours like planting at the right time, keeping fields clean, rotating crops and using pesticides wisely are important. Chemical plant protection measures are still an important part of disease management, but they don't always work as well as they could because pathogens can develop resistance, environmental concerns, higher production costs and small and marginal farmers may not be able to get to them easily. So, finding the right combinations of genotype and planting window that

naturally lower the risk of disease can cut down on the need for chemical treatments and improve long-term tomato production in open fields.

## Materials and Methods

The present study was carried out in 2021–22 and 2022–23 as multilocation farmers' field trials in North Kachucherra (Latitude: 24.000012° E and Longitude: 91.853116° N) in the Dhalai District of Tripura State. The experiment was conducted at North Kachucherra, Dhalai district, Tripura, using three different farmers' fields as replications. Each field served as one replication and the treatments were laid out following a randomised block design under similar soil and management conditions. The investigation was carried out under the direct supervision of Krishi Vigyan Kendra Dhalai, Salema, Tripura, India, which provided the location-specific standard package of practices for tomato cultivation as an autumn–winter crop. The experiment was conducted on a 5 m × 5 m plot with a row-to-row spacing of 60 cm and a plant-to-plant spacing of 45 cm, following the recommended package of practices for tomato cultivation in the area.

The areas experience humid sub-tropical weather, with average daily low and maximum temperatures ranging from 11.1 to 33.7 °C and relative humidity ranging from 32.43 to 92.11 % during the years of experimental study (Table 1).

Six distinct sowing windows, or transplanting dates, were used in the experiment as the first factor: S<sub>1</sub> - 21<sup>st</sup> September, S<sub>2</sub> - 7<sup>th</sup> October, S<sub>3</sub> - 21<sup>st</sup> October, S<sub>4</sub> - 7<sup>th</sup> November, S<sub>5</sub> - 21<sup>st</sup> November and S<sub>6</sub> - 7<sup>th</sup> December. Ten tomato varieties, with high yield potentiality and the varieties were selected based on (i) their documented resistance/tolerance to major diseases (Tomato leaf curl virus, bacterial wilt, early and late blight), (ii) adaptability to North Eastern Region conditions and (iii) recommended by ICAR for regional cultivation for higher yield, were also used as the second factor, which included - V<sub>1</sub> - Arka Abhed, V<sub>2</sub> - Arka Rakshak, V<sub>3</sub> - Arka Samrat, V<sub>4</sub> - Kashi Aman, V<sub>5</sub> - Arka Apeksha, V<sub>6</sub> - Arka Alok, V<sub>7</sub> - Arka Ananya, V<sub>8</sub> - Arka Abha, V<sub>9</sub> - Chiranjeevi and V<sub>10</sub> - Local, during the two study years. According to these two factors, the 60 numbers of treatment combinations were obtained as follows:

### Treatment combinations (S × V; 60 combinations)

S1V1, S1V2, S1V3, S1V4, S1V5, S1V6, S1V7, S1V8, S1V9, S1V10  
S2V1, S2V2, S2V3, S2V4, S2V5, S2V6, S2V7, S2V8, S2V9, S2V10  
S3V1, S3V2, S3V3, S3V4, S3V5, S3V6, S3V7, S3V8, S3V9, S3V10  
S4V1, S4V2, S4V3, S4V4, S4V5, S4V6, S4V7, S4V8, S4V9, S4V10  
S5V1, S5V2, S5V3, S5V4, S5V5, S5V6, S5V7, S5V8, S5V9, S5V10  
S6V1, S6V2, S6V3, S6V4, S6V5, S6V6, S6V7, S6V8, S6V9, S6V10

**Table 1.** Weather parameters of experimental sites during the period of investigation with special reference to maximum and minimum temperature along with maximum and minimum relative humidity

| Weather Parameter | Month | Average maximum temperature (°C) |       | Average minimum temperature (°C) |       | Average maximum relative humidity (%) |       | Average minimum relative humidity (%) |       |
|-------------------|-------|----------------------------------|-------|----------------------------------|-------|---------------------------------------|-------|---------------------------------------|-------|
|                   |       | 21–22                            | 22–23 | 21–22                            | 22–23 | 21–22                                 | 22–23 | 21–22                                 | 22–23 |
| September         |       | 33.7                             | 33.3  | 24.8                             | 25.0  | 92.11                                 | 91.70 | 70.39                                 | 71.43 |
| October           |       | 31.4                             | 31.0  | 22.3                             | 22.2  | 88.91                                 | 88.84 | 70.05                                 | 68.03 |
| November          |       | 29.2                             | 29.4  | 17.2                             | 17.5  | 87.75                                 | 88.87 | 56.12                                 | 54.00 |
| December          |       | 26.6                             | 26.9  | 13.8                             | 13.7  | 90.61                                 | 89.55 | 51.61                                 | 54.23 |
| January           |       | 25.6                             | 25.2  | 11.4                             | 11.1  | 86.06                                 | 86.65 | 45.29                                 | 47.20 |
| February          |       | 29.5                             | 29.2  | 14.8                             | 14.6  | 90.17                                 | 89.21 | 31.69                                 | 32.43 |

For the intensity of disease incidence (%), namely, TYLCV, bacterial wilt, early and late blight, the calculation was followed by the formula which was used by previous researchers (11):

Disease Incidence (%) =

$$\frac{\text{Number of diseased plant /leaves}}{\text{Number of total plants/leaves observed}} \times 100$$

Disease incidence observations for TYLCV, bacterial wilt, early blight and late blight were recorded at regular intervals of 10 days, starting from 30 days after transplanting and continued up to final harvest. Disease assessments were made on all plants within each plot following visual symptom-based scoring and the mean values were used for statistical analysis. Viral infections were identified based on characteristic field symptoms. Fruit yield was recorded from 10 randomly selected, healthy plants from the central area of each plot to avoid border effects. Harvesting was carried out at regular intervals of 4–5 days, starting from the onset of physiological maturity and continued until the final harvest. Fruits were considered mature when they reached the breaker to red-ripe stage, as indicated by uniform surface coloration characteristic of each genotype. The cumulative yield from all harvests was summed to obtain total yield per plot, which was subsequently used for yield and yield loss estimation. Statistical analysis was performed on plot-level data prior to extrapolation, ensuring that treatment effects were evaluated independently of scale transformation

Yield attributes such as yield and yield loss on account of disease infestation were estimated in t ha<sup>-1</sup> and %, respectively. The calculated yield loss values thus reflect the relative reduction in yield attributable to disease incidence under different sowing window–genotype combinations.

$$\text{Yield loss (\%)} = \frac{Y_{\text{max}} - Y_t}{Y_{\text{max}}} \times 100$$

As bio-chemical parameters, lycopene (mg 100 g<sup>-1</sup>) and carotenoids (mg 100 g<sup>-1</sup>) contents of the mature ripe tomato fruits were estimated by the spectrophotometric method at the District Level Soil, Plant and Water Testing Laboratory at Krishi Vigyan Kendra Dhalai. Lycopene and carotenoids were extracted using acetone: hexane (4 : 6) solvent mixture. Absorbance was recorded at 503 nm for lycopene and 450 nm for total carotenoids using a Ultraviolet–Visible (UV–Vis) spectrophotometer. Quantification was performed using standard equations as described by previous researchers (12).

The standard error of mean (S.E.m.(±)) and critical difference (CD) were calculated following (13).

$$\text{S.E.m. (\pm)} = \sqrt{\frac{\text{MSE}}{r}}$$

Where, MSE = mean error sum of square

r = Number of replications

S.E.(d) =  $\sqrt{\frac{2 \text{MSE}}{r}}$  To compare the effects of various treatments, a CD value was computed if the treatments involving any parameter were found to be significant.

$$\text{CD} = \sqrt{\frac{2 \text{MSE}}{r}} \times t_{0.025}$$

CD at 5 % = S.E.(d) × t<sub>0.05</sub>, e.d.f.

where MSE is the mean square error, r is the number of replications, t<sub>0.05, e.d.f.</sub> is the t-value at 5 % significance level with error degrees of freedom (e.d.f.) and e.d.f. denotes the error degrees of freedom

The experimental data were analysed using a randomised block design (RBD) with 3 replications. Analysis of variance (ANOVA) was performed to assess the significance of the main effects of sowing window, genotype and their interaction on disease incidence, yield, yield loss and quality parameters. Treatment means were compared using the CD test at the 5 % level of significance, wherever the F-test was found to be significant.

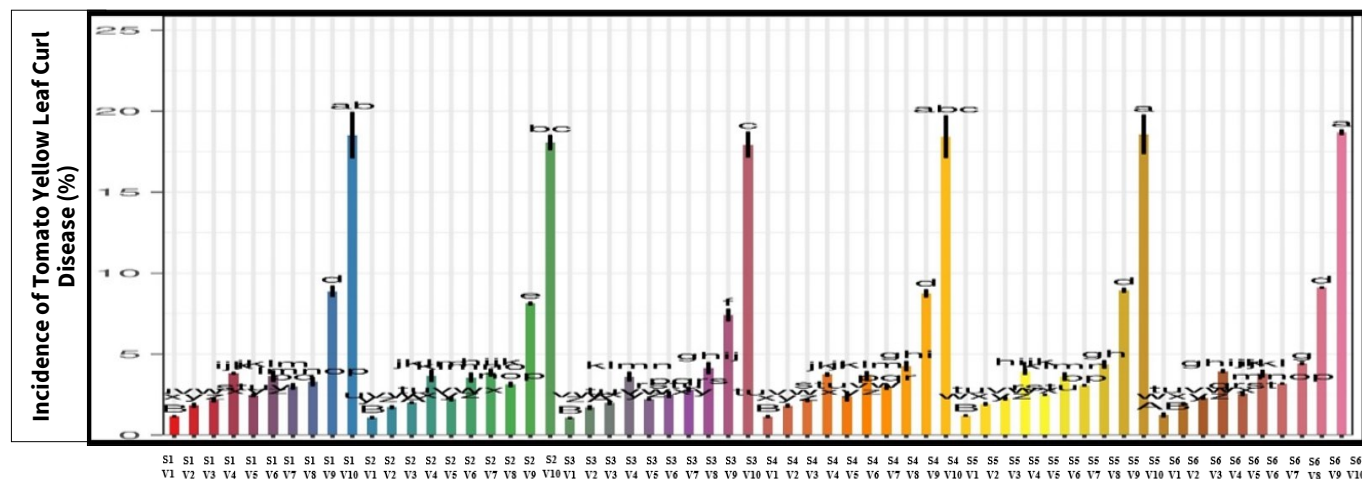
Statistical analysis was carried out using GRAPES (Generalised Regression Analysis and Power Evaluation System) online statistical software, a validated and widely used statistical package for agricultural research. Pooled analysis over two years was performed after testing the homogeneity of error variances.

## Results and Discussion

As per the pooled data, the study findings showed that the conjugal influences of transplanting window and genotype of tomato had a significant effect on the degree of occurrence of out-break of various diseases and its' concomitant effects over important yield as well as quality parameters of tomato. Higher disease incidence under late transplanting may be attributed to prolonged leaf wetness duration and favourable temperature regimes that enhance pathogen sporulation and infections and may also be associated with increased vector activity (whiteflies for TYLCV) and enhanced pathogen under cool, humid conditions. Additionally, delayed plating exposes crops to prolonged favourable conditions for pathogen multiplication, thereby increasing infection pressure. Data are presented through Fig. 1 to Fig. 8 and the results of the current investigation are addressed below.

### Interactive influences of sowing windows and genotypes over the intensity of out-break of tomato yellow leaf curl virus

As far as the interaction of transplanting date and cultivars of tomato is concerned, it could produce statistical variation over degree of occurrence of tomato TYLCV (Fig. 1). This parameter gave the highest intensity of out-break, when seedling was transplanted on 7<sup>th</sup> December with respect to variety Local cultivar (S<sub>6</sub>V<sub>10</sub>), with a value of 18.69 %. This was found as the minimum of 1.06 % under combination of commencement of transplanting on 21<sup>st</sup> October with variety Arka Abhed (S<sub>3</sub>V<sub>1</sub>). In general, acceptably favourable results in this aspect also had been revealed by genotype Arka Abhed, Arka Rakshak and Arka Samrat in combination with sowing windows of 21<sup>st</sup> September, 7<sup>th</sup> October, 21<sup>st</sup> October, 7<sup>th</sup> November, 21<sup>st</sup> November and 7<sup>th</sup> December with having values of 1.08 % (S<sub>2</sub>V<sub>1</sub>), 1.14 % (S<sub>4</sub>V<sub>1</sub>), 1.15 % (S<sub>1</sub>V<sub>1</sub>), 1.19 % (S<sub>5</sub>V<sub>1</sub>), 1.23 % (S<sub>6</sub>V<sub>1</sub>), 1.70 % (S<sub>3</sub>V<sub>2</sub>), 1.72 % (S<sub>2</sub>V<sub>2</sub>), 1.81 % (S<sub>4</sub>V<sub>1</sub>), 1.83 % (S<sub>1</sub>V<sub>2</sub>), 1.91 % (S<sub>5</sub>V<sub>2</sub>), 1.93 % (S<sub>6</sub>V<sub>2</sub>) and 1.98 % (S<sub>3</sub>V<sub>3</sub>), respectively. All these values showed considerable variations from genotypes Local, Chiranjeevi, Arka Abha and Arka Ananya, irrespective of dates of transplanting.



**Fig. 1.** Incidence of tomato yellow leaf curl disease (%) of tomato as influenced under the conjugal interaction between sowing window and genotype expressed through bar-chart with standard error.

Treatments with same letters are not significantly different at 5 % level.

### Interactive influences of sowing windows and genotypes over the intensity of out-break of bacterial blight

The intensity of occurrence of bacterial blight of tomato showed significant variations under the conjugal interaction of sowing window (S) and genotype (V) at constant levels of other cultural practices (Fig. 2). The highest intensity of 10.61 % was obtained from the treatment combination  $S_6V_{10}$ , viz., under the interaction between transplanting on 7<sup>th</sup> December along with cultivar Local. This was followed very closely by the interactive effect of cultivars Arka Apeksha, Arka Abha, Kashi Amnan, Arka Rakshak and Arka Samrat with same sowing window (i.e.,  $S_5V_{10}$ ,  $S_1V_{10}$ ,  $S_4V_{10}$ ,  $S_2V_{10}$  and  $S_3V_{10}$ , respectively) with values of 10.44, 10.21, 10.08, 10.02 and 9.56 %, respectively. On the other hand, no sign of out-break of bacterial wilt had been visualised when conjugal influences were judged as date of transplanting on 21<sup>st</sup> October with all the genotypes, except those of Local and Chiranjeevi (viz.,  $S_3V_{10}$  and  $S_3V_9$ , respectively).

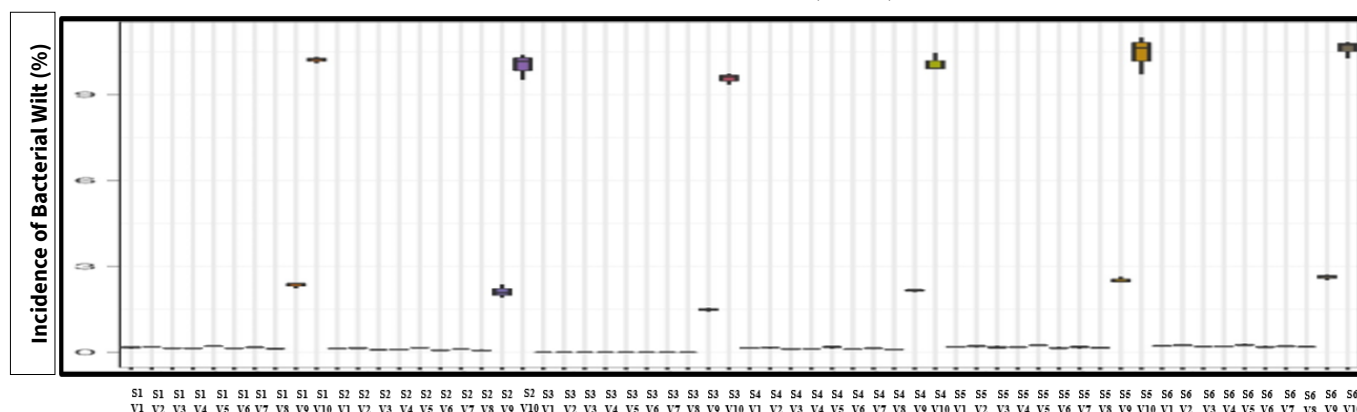
### Interactive influences of sowing windows and genotypes over the intensity of out-break of early blight

The conjugal effects of date of commencement of transplanting and genotype of tomato proved effective to create tangible variations for incidence of occurrence of early blight (Fig. 3). The maximum intensity for this was found as 5.55 % in case of Local cultivar, when it was transplanted on 21<sup>st</sup> November (viz.,  $S_5V_{10}$ ). Significantly higher incidence of early blight also found as 5.41, 5.32, 5.29, 5.18 and 5.15 % with same genotype with sowing windows of 7<sup>th</sup> December, 21<sup>st</sup> September, 7<sup>th</sup> November, 7<sup>th</sup> October and 21<sup>st</sup> October (i.e.,  $S_6V_{10}$ ,

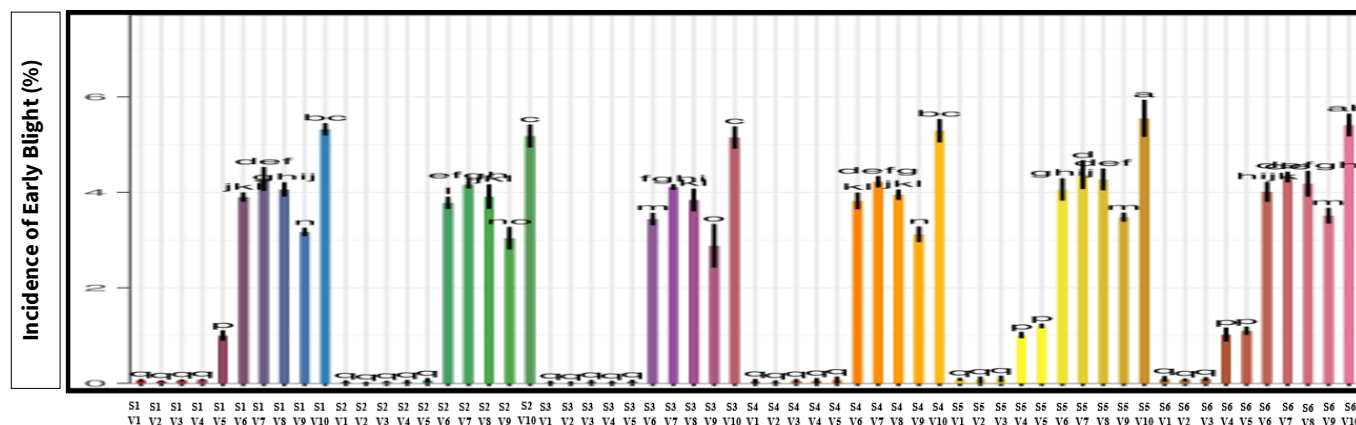
$S_1V_{10}$ ,  $S_4V_{10}$ ,  $S_2V_{10}$  and  $S_3V_{10}$ , respectively). All these values showed significant variations from all the other treatment combinations. Commencement of cultivation of tomato genotypes during 21<sup>st</sup> October, 7<sup>th</sup> November, 21<sup>st</sup> October, 21<sup>st</sup> November and 21<sup>st</sup> September with accessions namely, Arka Rakshak, Kashi Aman, Arka Samrat, Arka Abhed and Arka Samrat, revealed relatively meagre values for the same as 0.01 % ( $S_3V_2$ ), 0.01 % ( $S_2V_2$ ), 0.02 % ( $S_4V_2$ ), 0.02 % ( $S_3V_4$ ), 0.02 % ( $S_3V_1$ ), 0.03 % ( $S_3V_3$ ), 0.03 % ( $S_2V_1$ ), 0.03 % ( $S_3V_3$ ), 0.03 % ( $S_2V_4$ ), 0.04 % ( $S_4V_1$ ), 0.04 % ( $S_3V_5$ ), 0.04 % ( $S_1V_2$ ), 0.05 % ( $S_4V_4$ ) and 0.05 % ( $S_4V_3$ ).

### Interactive influences of sowing windows and genotypes over the intensity of out-break of late blight

The highest percentage of occurrence late blight disease of tomato of 6.45 was registered under initiation of transplanting on 7<sup>th</sup> December as a result of influence of the interaction with genotype Local (i.e.  $S_6V_{10}$ ), followed by 6.31, 6.21, 6.15, 6.14 and 6.10 %, respectively found also from genotype Local under transplanting on 21<sup>st</sup> November, 7<sup>th</sup> November, 7<sup>th</sup> October, 21<sup>st</sup> September and 21<sup>st</sup> October (viz.,  $S_5V_{10}$ ,  $S_4V_{10}$ ,  $S_2V_{10}$ ,  $S_1V_{10}$  and  $S_3V_{10}$ , respectively) (Fig. 4). Remarkable variations were found for the same with all these treatment combinations from the remaining ones. Practically no symptom of late blight had been visualised with sowing windows of 7<sup>th</sup> October and 21<sup>st</sup> October in combination with variety Arka Abhed (i.e.,  $S_2V_1$  and  $S_3V_1$ , respectively). Equally acceptable results for this parameter also had been seen for the same genotype with sowing windows 21<sup>st</sup> September ( $S_1V_1$ ), 7<sup>th</sup> November (i.e.  $S_4V_1$ ) and 21<sup>st</sup> November (i.e.  $S_5V_1$ ).

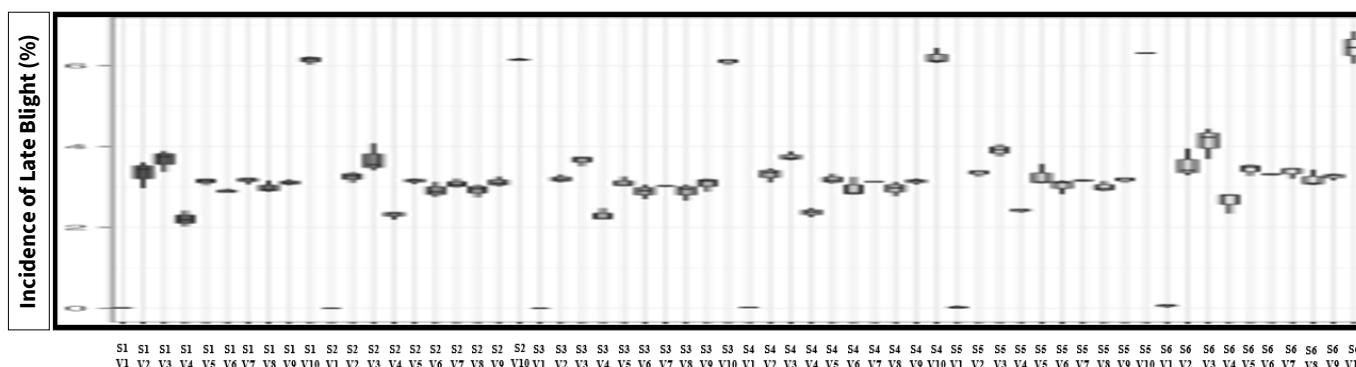


**Fig. 2.** Incidence of bacterial wilt (%) of tomato as influenced under the conjugal interaction between sowing window and genotype expressed through boxplot with standard error.



**Fig. 3.** Incidence of early blight (%) of tomato as influenced under the conjugal interaction between sowing window and genotype expressed through bar-chart with standard error.

Treatments with same letters are not significantly different at 5 % level



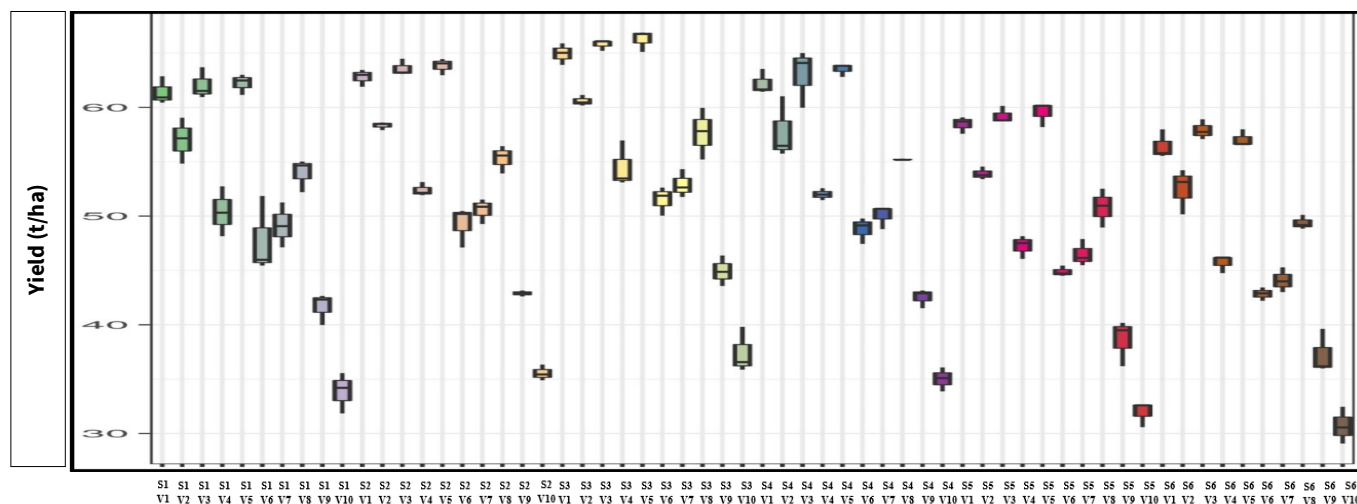
**Fig. 4.** Incidence of late blight (%) of tomato as influenced under the conjugal interaction between sowing window and genotype expressed through boxplot with standard error.

In the present investigation, the maximum infestation of TYLCV, bacterial wilt, early and late blight were visualised as 18.69 %, 10.61 %, 5.55 % and 6.45 %, respectively, when transplanting was done as late as on 7<sup>th</sup> December with conjugal influences of the Local cultivar. As a partial agreement to the aforesaid fact (14) has reported that tomato is susceptible to more than 200 diseases and losses of the yield due to the disease was as high as 71–95 %. By all, tobacco mosaic virus (TMV), tomato leaf curl virus (TLCV) and TYLCV caused 80, 90 and 100 % yield loss of tomato, respectively, as investigated by previous researchers (15). The bacterial wilt disease can cause upto 90 % yield losses in tomato (16). Keeping in close agreement with the present findings, previous researchers reported the incidence of bacterial wilt disease in tomato, brinjal and potato in West Bengal, with disease severity ranging from 9.86 % to 86.45 %, respectively (17). Persistence of high bacterial load within the plant xylem and accumulation of copious number of exo-polysaccharides (EPS) in the xylem is assumed to be the cause of the irreversible wilting of the infected plant culminating in plant death (18). Environmental factors play a key role in the development of the disease. Early blight develops more rapidly during periods, when environmental conditions alternate between humidity and drought (19). The disease effects on all foliar plant parts and causes a great reduction in quantity (20), causing fruit yield losses of up to 86 % in India (21, 22). Low temperature and high humidity prevailed from November to January favours late blight incidence (23). According to an estimate, 85–90 % yield losses recorded in Chittoor district (24). As per these similar types of earlier research finding and according to the wholesome outcomes of the present study this could be said here that very early (i.e., 21<sup>st</sup> September) and very late (i.e., 7<sup>th</sup> December) transplanting mostly might have exerted more conducive

atmospheric condition for break out of various diseases of tomato, especially while cultivating with susceptible genotypes. Recent research has shown analogous findings, indicating that delayed planting heightened the incidence of viral and fungal diseases due to extended exposure to favourable environmental circumstances (25). Conversely, genotypes like Arka Abhed, Arka Rakshak and Arka Samrat consistently exhibited reduced disease incidence during favourable sowing periods, underscoring the influence of genetically encoded resistance in mitigating disease manifestation under field circumstances. Recent findings underscore that host resistance is the most dependable and enduring strategy for managing intricate disease syndromes like TYLCV and bacterial wilt, particularly in open-field agriculture (26).

### Interactive influences of sowing windows and genotypes on yield

The concomitant effect of various dates of transplanting and genotypes of tomato in the present investigation exhibited highly considerable variations (Fig. 5). The highest yield had been found as 66.25 t ha<sup>-1</sup> under 21<sup>st</sup> October date of planting with variety Arka Apeksha (i.e., S<sub>3</sub>V<sub>5</sub>), followed by the Arka Samrat and Arka Abha, with same sowing window (viz., S<sub>3</sub>V<sub>3</sub> and S<sub>3</sub>V<sub>1</sub>), where these were obtained as 65.79 and 64.94 t ha<sup>-1</sup>, respectively. However, differences between S<sub>3</sub>V<sub>5</sub>, S<sub>3</sub>V<sub>3</sub> and S<sub>3</sub>V<sub>1</sub> were insignificant in nature. Genotypes Arka Apeksha, Arka Samrat and Arka Abha also revealed acceptable results with respect to yield of tomato with transplanting on 7<sup>th</sup> October and 7<sup>th</sup> November with values of 63.82 t ha<sup>-1</sup> (S<sub>2</sub>V<sub>5</sub>), 63.59 t ha<sup>-1</sup> (S<sub>2</sub>V<sub>3</sub>), 63.51 t ha<sup>-1</sup> (S<sub>4</sub>V<sub>5</sub>) and 63.02 t ha<sup>-1</sup> (S<sub>4</sub>V<sub>3</sub>). Irrespective of genotypes of tomato in majority of the cases commencement on cultivation on 7<sup>th</sup> December, 21<sup>st</sup> November



**Fig. 5.** Yield ( $\text{t ha}^{-1}$ ) of tomato as influenced under the conjugal interaction between sowing window and genotype expressed through boxplot with standard error.

and 21<sup>st</sup> September reduced the yield potentiality in the current study in a considerable manner. The continuously better-quality features discovered in Arka Samrat and Arka Abhed indicate their aptitude for both production maximisation and enhanced nutritional quality under optimal planting schedules. Recent studies conducted across multiple locations have demonstrated that cultivar performance is significantly influenced by seasonal planting times and local climatic circumstances, with ideal sowing windows improving both yield potential and yield stability (9, 10).

#### Interactive influences of sowing windows and genotypes on average yield loss on account of diseases incidence

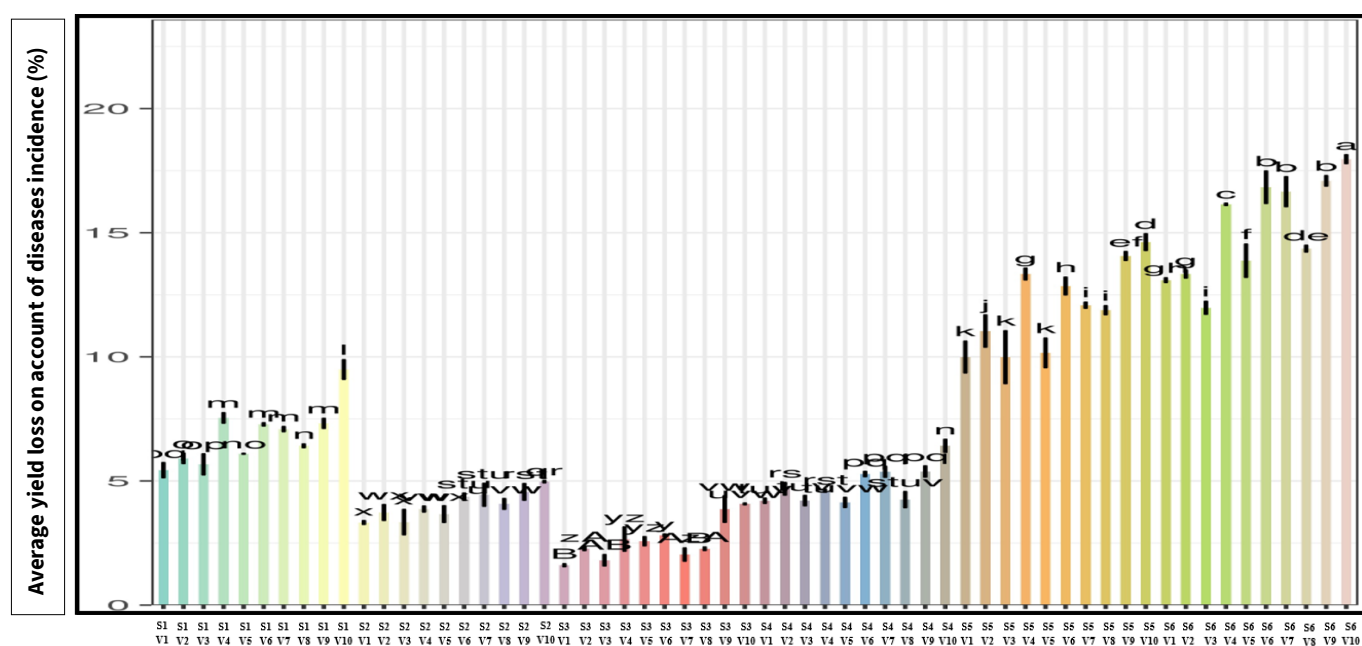
Interactions of transplanting date and genotype of tomato produced significant variation with respect to average yield loss on account of disease incidence (Fig. 6). The lowest value for this (1.61 %) was recorded from variety Arka Abhed, while transplanting was done on 21<sup>st</sup> October (i.e.  $S_3V_1$ ). Whereas the maximum average yield loss of 17.96 % was found with Local cultivar through 7<sup>th</sup> December sowing window ( $S_6V_{10}$ ). Considerably, better result for this also registered during transplanting on 21<sup>st</sup> October with genotypes Arka Samrat

( $S_3V_3$ ), Arka Ananya ( $S_3V_7$ ), Arka Abha ( $S_3V_8$ ), Arka Rakshak ( $S_3V_2$ ) and Kashi Aman ( $S_3V_5$ ) with values of 1.81 %, 2.04 %, 2.27 %, 2.27 % and 2.57 %, respectively. Equally good results in this context, irrespective of cultivars of tomato, used in the present investigation, with respect to average yield loss had been documented with sowing windows such as 21<sup>st</sup> October ( $S_3$ ), 7<sup>th</sup> October ( $S_2$ ) and 7<sup>th</sup> November ( $S_4$ ).

Keeping parity to the intensity of disease outbreak the fruit yield of tomato in the current study showed lower yield potentiality with too early and too late transplanting of seedlings as autumn-winter crop, with proportionate increase in average yield loss percentage. These outcomes showed partial agreement with the previous research studies of (5, 27, 28).

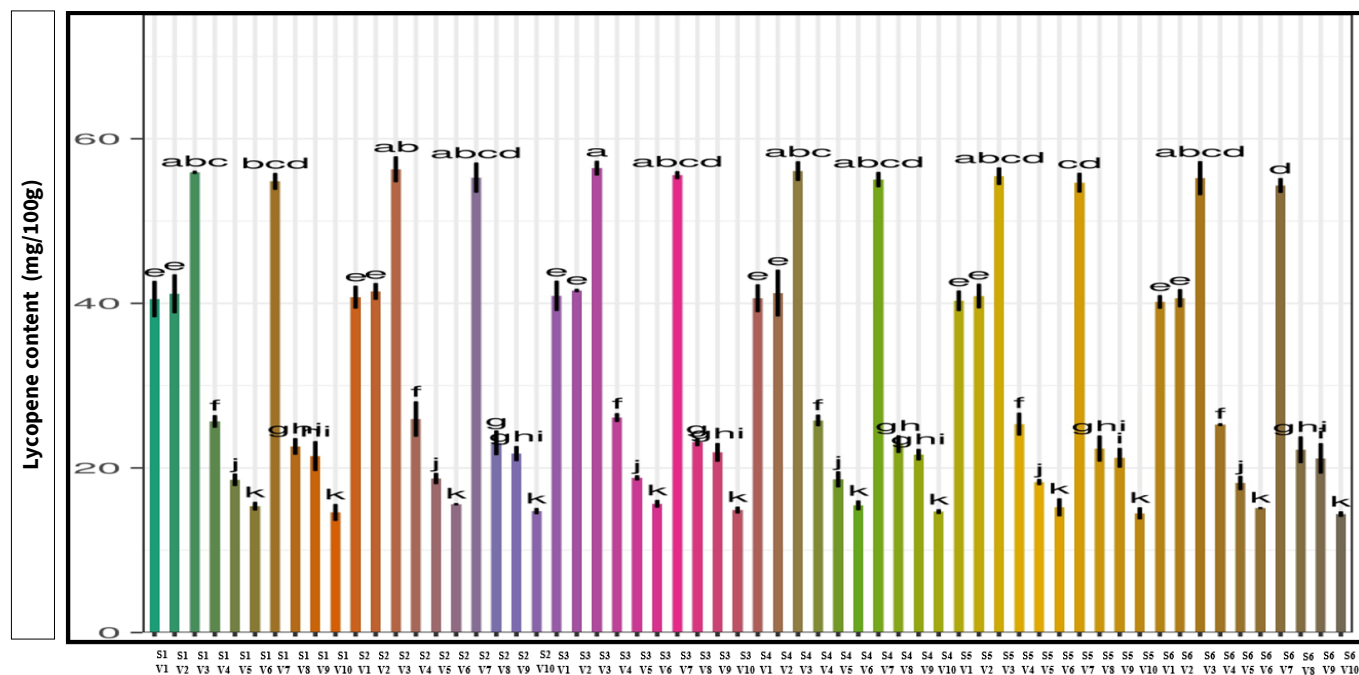
#### Interactive influences of sowing windows and genotypes on lycopene content

Under the influence of interaction of sowing window and cultivar of tomato lycopene content of mature ripe fruit showed statistical variations (Fig. 7). The highest values for this parameter had been seen under 21<sup>st</sup> October planting with variety Arka Samrat (i.e.,  $S_3V_3$ ), with a value of 56.43  $\text{mg } 100 \text{ g}^{-1}$ . In contrast to this, the lowest



**Fig. 6.** Average yield loss on account of diseases incidence (%) of tomato as influenced under the conjugal interaction between sowing window and genotype expressed through bar-chart with standard error.

Treatments with same letters are not significantly different at 5 % level.



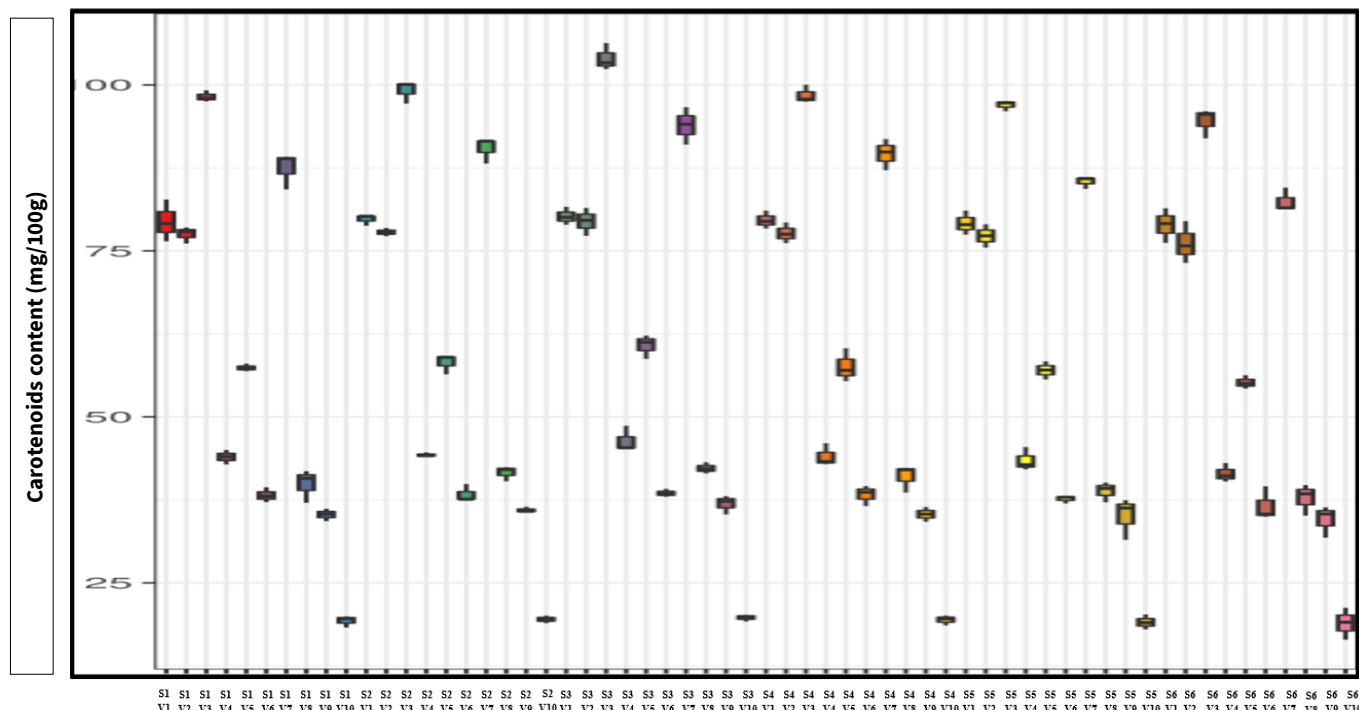
**Fig. 7.** Lycopene content ( $\text{mg } 100 \text{ g}^{-1}$ ) of tomato as influenced under the conjugal interaction between sowing window and genotype expressed through bar-chart with standard error.

Treatments with same letters are not significantly different at 5 % level.

lycopene content of  $14.39 \text{ mg } 100 \text{ g}^{-1}$  had been registered with treatment combinations  $S_6V_{10}$ , viz., cultivation of Local cultivar with transplanting at 7<sup>th</sup> December (i.e.,  $S_6V_{10}$ ). Considerably, better contents of lycopene were also found for the fruits of Arka Samrat and Arka Ananya upon sowing window of 7<sup>th</sup> October, 7<sup>th</sup> November and 21<sup>st</sup> September (viz.,  $S_2V_3$ ,  $S_4V_3$ ,  $S_1V_3$ ,  $S_3V_7$ ,  $S_5V_3$  and  $S_2V_7$ , as per the same order), with values for the same as 56.29, 56.07, 55.925, 55.58, 55.45 and 55.28  $\text{mg } 100 \text{ g}^{-1}$ , respectively. Notable fact here is that in the present experiment treatment combinations having inclusion of either Local cultivar ( $V_{10}$ ) or Arka Alok ( $V_6$ ) or Arka Apeksha ( $V_5$ ) under various dates of transplanting revealed relatively lower contents of lycopene for mature ripe fruits of tomato.

#### Interactive influences of sowing windows and genotypes on carotenoids content

The specific duration of transplanting in combination with genotype literally produced tangible differences with respect to carotenoids contents of tomato in the present study (Fig. 8). The highest content of carotenoids of  $104.00 \text{ mg kg}^{-1}$  was obtained from the treatment combination  $S_3V_3$ , viz., under the interaction between transplanting on 21<sup>st</sup> October along with cultivar Arka Samrat. This was followed very closely by the interaction effect of the same cultivar with sowing windows 7<sup>th</sup> October, 7<sup>th</sup> November, 21<sup>st</sup> September, 21<sup>st</sup> November and 7<sup>th</sup> December (viz.,  $S_2V_3$ ,  $S_4V_3$ ,  $S_1V_3$ ,  $S_5V_3$  and  $S_3V_3$ , as per the same order) with values of 99.15, 98.45, 98.23, 96.96 and 94.51  $\text{mg } 100 \text{ g}^{-1}$ ,



**Fig. 8.** Carotenoids content ( $\text{mg } 100 \text{ g}^{-1}$ ) of tomato as influenced under the conjugal interaction between sowing window and genotype expressed through boxplot with standard error.

respectively. On the other hand, comparatively lesser carotenoids contents of mature ripe tomato fruits had been visualised, when interactive influences were judged with genotype Local with dates of transplanting as 7<sup>th</sup> December (S<sub>6</sub>V<sub>10</sub>), 21<sup>st</sup> November (S<sub>5</sub>V<sub>10</sub>), 21<sup>st</sup> September (S<sub>1</sub>V<sub>10</sub>), 7<sup>th</sup> November (S<sub>4</sub>V<sub>10</sub>), 7<sup>th</sup> October (S<sub>2</sub>V<sub>10</sub>) and 21<sup>st</sup> October (S<sub>3</sub>V<sub>10</sub>) with values of 18.91, 19.07, 19.27, 19.41, 19.50 and 19.74 mg 100 g<sup>-1</sup>, respectively.

In majority of the cases in the current investigation better out turn with respect to lycopene and carotenoids contents had been found with variety Arka Abhed, Arka Rakshak and Arka Samrat, with sowing windows between second to third week of October. This might be attributed to the fact that most favourable climatic condition prevailed during these periods for improvement of quality parameters of tomato genotypes. Near similar experimental findings also had been documented by earlier researchers, according to them the inhibition of lycopene production in tomato took place at higher temperatures (38°C) (29). Lycopene constitutes 80–90 % of the total carotenoids in tomato fruits (30). So, in the present study the behaviour of fluctuation of carotenoids contents in tomato fruits might be due to the changes in the level of lycopene contents under various experimental conditions. Variations in tomato genotypes for fruit quality parameters at high temperature conditions was observed by previous researchers (31). Carotenoids and lycopene contents was also observed as low at temperature stress and at control condition (32). The current findings align with prior studies demonstrating that delayed transplantation increases the prevalence of viral and fungal infections in tomatoes due to optimal temperature-humidity conditions (33). Recent research has validated that both genetic factors and environmental variables during fruit ripening significantly influence carotenoid composition and overall fruit quality in tomatoes (34, 10)

## Conclusion

In the Dhalai district of northern Tripura, regardless of the genotypic configurations of tomato, the overall results of this investigation demonstrated unequivocally that higher disease intensities—specifically, tomato yellow leaf curl virus (TYLCV), bacterial blight, early and late blight—always had a positive impact on the average yield loss due to disease incidence, which in turn had negative effects on vital yield and quality parameters of tomato. The increased disease incidence brought about by very early as well as very less late transplanting led to a concurrent deterioration in the quality and yield potentiality of tomato. When it came to having the most positive effects on the tomato's quantitative as well as qualitative characteristics, transplanting windows 7<sup>th</sup> and 21<sup>st</sup> October out performed all the other dates of transplanting considered in the present investigation. The out-turns of this present investigation, more specifically pointed towards the fact that genotypes like Arka Abhed, Arka Rakshak and Arka Samrat could give more similar kinds of results in association with subjected sowing windows. It is therefore recommended that tomato production be attempted as an autumn-winter crop in the northern Tripura region most successfully during the first to third week of October, with a variety of options such as Arka Abhed, Arka Rakshak and Arka Samrat. However, among the other types Kashi Aman and Arka Apeksha also could be included and this period of transplanting time might, under any kind of variation, be prolonged all the way to the first week of November.

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## Authors' contributions

AKM, AKS and PKB provided overall scientific guidance, critical review and refinement of the technology, ensured rigorous assessment of results and contributed to manuscript revision and final approval. HV contributed senior-level technical inputs, critical evaluation of findings and revision of the manuscript. AD conceptualised the study, coordinated multilocation trials, developed the experimental methodology, supervised data collection, performed data analysis and interpretation and drafted the manuscript. RKR, VRS, CRS, NKE, PR, RD<sup>1</sup>, BD, RK, MP and SS contributed to technology formulation, experimental execution, data generation, statistical interpretation, comparability assessment of results across locations and manuscript revision. RD<sup>2</sup>, TB and SD were primarily responsible for field-level data collection, disease scoring, yield recording, laboratory analysis of quality parameters, drafting of initial sections and coordination with participating farmers. All authors have read, reviewed and approved the final manuscript [RD<sup>1</sup> stands for Rubin Debbarna and RD<sup>2</sup> stands for Ratan Das].

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflicts of interest to declare.

**Ethical issues:** None

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