



RESEARCH ARTICLE

# Screening onion varieties for sodicity tolerance: Insights from physiological parameters and gene expression studies

Amutha R<sup>1</sup>, N Aananthi<sup>2\*</sup>, M Vetrivel<sup>3</sup>, C Parameswari<sup>4</sup>, M L Mini<sup>5</sup>, S Nithila<sup>6</sup>, C Rajababu<sup>7</sup>, C Tamilselvi<sup>8</sup>, P Prema<sup>9</sup> & S Sheeba<sup>10</sup>

<sup>1</sup>Department of Seed Science and Technology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

<sup>2</sup>Department of Plant Breeding and Genetics, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

<sup>3</sup>Thangapazham Agricultural College, Tenkasi 627 758, Tamil Nadu, India

<sup>4</sup>Agricultural Research Station, Vaigaidam 625 562, Tamil Nadu, India

<sup>5</sup>Department of Biotechnology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

<sup>6</sup>Department of Crop physiology, Horticultural College and Research Institute for Women (HC & RI), Tiruchirappalli 620 009, Tamil Nadu, India

<sup>7</sup>Department of Crop Physiology, Agricultural College and Research Institute (AC & RI), Kudumiyamalai 622 104, Pudukkottai, Tamil Nadu, India

<sup>8</sup>Krishi Vigyan Kendra (KVK), Tamil Nadu Agricultural University, Tirur 602 025, Thiruvallur, Tamil Nadu, India

<sup>9</sup>Department of Computer science, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

<sup>10</sup>Department of Soils and Environment, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

\*Correspondence email - [aananthi.n@tnau.ac.in](mailto:aananthi.n@tnau.ac.in)

Received: 01 August 2025; Accepted: 02 March 2026; Available online: Version 1.0: 15 June 2026

**Cite this article:** Amutha R, Aananthi N, Vetrivel M, Parameswari C, Sheeba S, Mini ML, Nithila S, Rajababu C, Tamilselvi C, Prema P, Sheeba S. Screening onion varieties for sodicity tolerance: Insights from physiological parameters and gene expression studies. Plant Science Today. 2026; 13(sp2): 1-12. <https://doi.org/10.14719/pst.11024>

## Abstract

Sodicity is an important abiotic stress that limits crop production by altering many physiological and biochemical processes in plants. Onion is very sensitive to sodicity, which affects germination, plant growth and productivity. The present study was undertaken to screen onion varieties for sodicity tolerance. Fourteen bulb and four aggregatum onion (two seeds and two bulbs propagated) varieties were subjected to different levels of sodicity under laboratory conditions and physiological parameters were observed. Extent of sodicity tolerance was tested by assessing vigour index, stress tolerance index (STI), membrane stability index (MSI) and total dry matter production (TDMP). The results revealed that with increasing concentration of salts, vigour index, MSI, STI and TDMP decreased drastically. All 18 varieties screened displayed differential responses. Based on the outcome of the laboratory studies in sodic conditions, the identified sodicity-tolerant varieties, viz., Bhima Safed, CO 6 and Thuraiyur and sodicity susceptible varieties, viz., Bhima Red, CO 5 and Perambalur, were further selected for RT-PCR to assess the expression of abiotic stress genes under sodic soil. From the molecular studies it was evident that the sodicity-tolerant onion varieties Bhima Safed, CO 6 and Thuraiyur show stable expression of Glyceraldehyde-3-phosphate dehydrogenase (GAPDH), alternative oxidase (AOX) and Aquaporin (AQP) genes and are not affected by cultivation in sodic soil whereas the susceptible varieties viz., Bhima Red, CO 5, Perambalur showed downregulation of these genes. Investigating GAPDH, AOX and AQP signalling pathways will address the exact reason for the suppression of these genes under sodicity. Stable expression of the GAPDH gene may be used as a criterion for screening sodicity-tolerant onion varieties.

**Keywords:** gene expression; membrane stability index; onion; sodicity tolerance; stress tolerance index; total dry matter production; vigour index

## Introduction

Globally, onions are a significantly valuable crop cultivated in 140 countries with an area of 7.1 million hectares and production of 136 million tonnes, making onions the third most important vegetable after tomatoes and potatoes (1). India is the second largest producer of onions, contributing to 22 % of world onion production next to China, with an annual production of 31.69 million metric tonnes from an area of 1.94 million hectares. In Tamil Nadu, onion is cultivated in 28000 hectares with a total production of 0.03 million

tonnes, accounting for 1.7 % of share to all India production, as against Maharashtra with a share of 42.73 %. Plants are subjected to a multitude of stresses throughout their life cycle, among which drought and salt stress are the most important environmental factors reducing plant productivity considerably. These two stresses create similar reactions in plants by inducing water deficit. Sodicity is a major factor which affects crop growth and productivity at the global level. At the global level, 23 % of cultivable land is affected by salinity and 37 % land is affected by sodicity. In Tamil Nadu, 0.469 million hectares area has been affected by different levels of

salinity and sodicity. In Tiruchirappalli district, 11165 hectares of land are affected by salinity and sodicity and the Manikandam block of Tiruchirappalli district is severely affected due to sodicity, with an area of around 2000 hectare affected by sodicity (2).

In sodic soils, the alkalinity, exchangeable sodium, presence of  $\text{CaCO}_3$  and poor air-water relations affect the availability of nutrients. In addition, these areas often have high evaporation rates, which can encourage an increase in salt concentration at the soil surface. Salt-affected soils such as saline, saline-sodic and sodic usually have low biological activity because of both osmotic and ionic effects of salts and also due to limitations of carbonaceous substrates (3). Sodic soils are hard setting when dry, sticky when wet and are also prone to water erosion (4). High salinity and sodicity in onions adversely affect the crop growth and biomass yield. It hampers the onion plants' membrane stability index (MSI), relative water content, total chlorophyll and carotenoids. The firmness, pH, concentration of soluble solids, vitamins and minerals are very much reduced under saline and sodic soil conditions (5).

In onions, seedling emergence, bulb establishment and growth can be affected due to hard setting and crusting of soil or frequent waterlogging due to poor drainage under sodic soil conditions. Root growth is restricted due to the soil being dry, containing little air (6). If the exchangeable Na is large, less Ca, K and Mg are available in the soil and taken up by plants; some of these cations, especially K, are replaced by Na in plants (7). Sodium and chloride may be directly toxic and cause characteristic leaf burn in susceptible species. The tan or brown necrotic lesions are usually sharply separated from the adjacent healthy green tissue, with no symptoms of progressive deterioration in cells adjacent to the lesion. Duration of exposure to the accumulated toxic ions may be a factor in the development of injury. Onion is sensitive to sodicity stress during its earlier and later growth stages by exhibiting leaf burning symptoms and yield is drastically reduced due to premature senescence of leaves (8).

Plant growth and development under saline conditions in the field is often influenced by cumulative effects, multiple environmental stresses and genetic factors. Adoption of appropriate screening techniques and selection criteria may lead to the identification of varieties that are tolerant to sodicity. Genomic approaches play a significant role in encoding, cloning

and characterisation of important genes (9). A huge number of salt-responsive transcription factors and genes, which are either upregulated or downregulated in response to salinity stress, have been identified and characterised using transcriptomic and genomic approaches. Some RNA-binding proteins are known to regulate the expression of genes responsible for various abiotic stresses. In onion, drought stress-associated genes, NINJA, MalSyn, 21kDa, NAC29, ABCTrG, STYGRN, Chape, AOX, GAPDH, SOD, WRKY and AQP have been shown to have significant relevance in imparting stress tolerance (10).

A better understanding of the mechanisms by which plants respond to sodicity stress may help in identifying more tolerant varieties. Based on these backgrounds, the present study was formulated with the objectives, viz., to screen the *Allium cepa* var. *cepa* and *Allium cepa* var. *aggregatum* varieties for sodicity tolerance and to assess the alterations of stress-associated gene expression under sodicity conditions in the early growth stages of onion.

## Materials and Methods

Studies were taken up at the Department of Vegetable Science, Horticultural College and Research Institute, Tiruchirappalli, Tamil Nadu. Seeds of 14 bulb onion and 4 aggregatum onion varieties obtained from the Directorate of Onion and Garlic Research - Nashik, Indian Institute of Horticulture Research, Bengaluru, National Horticultural Research and Developmental Foundation-Janakpuri, New Delhi, Department of Vegetable Science, Tamil Nadu Agricultural University, Coimbatore, were used for the study and the details of the varieties screened are listed in Table 1.

Fourteen bulb onion varieties and four aggregatum onion varieties were screened for tolerance to various levels of sodicity stress, based on vigour index, STI, MSI and TDMP. The onion varieties were screened using an osmotic solution of sodium bicarbonate ( $\text{NaHCO}_3$ ) in the roll towel method and the details are mentioned in Table 2. All the 14 varieties of bulb onion and aggregatum onion varieties, viz., CO 5 and CO 6, are propagated by seed; while the aggregatum onion varieties viz., Perambalur local and Thuraiyur local, were propagated by bulb. Different concentrations of  $\text{NaHCO}_3$ , viz., 10, 20, 30, 40 and 50 mM were used for screening the 14 bulb onion varieties and bulb propagated

**Table 1.** List of varieties used

| Sl.No | Bulb onion          | Bulb onion |              |
|-------|---------------------|------------|--------------|
| 1.    | Arka Kirthiman      | 10.        | Arka Yojith  |
| 2.    | Bhima Safed         | 11.        | Bhima Super  |
| 3.    | Bhima Shweta        | 12.        | Bhima Shubra |
| 4.    | Arka Kalyan         | 13.        | Bhima Raj    |
| 5.    | Bhima Shakti        | 14.        | Bhima Red    |
| 6.    | Agri Found Dark Red |            |              |
| 7.    | Bhima Light red     | 15.        | CO 5         |
| 8.    | Bhima Dark red      | 16.        | CO 6         |
| 9.    | Bhima Kiran         | 17.        | Perambalur   |
|       |                     | 18.        | Thuraiyur    |

**Table 2.** pH and EC of the salt solution used for the screening experiment

| Sl. No | Sodic solution | pH    | EC ( $\text{dS m}^{-1}$ ) |
|--------|----------------|-------|---------------------------|
| 1      | 0 mM           | 7.10  | 0.00                      |
| 2      | 10 mM          | 8.60  | 2.18                      |
| 3      | 20 mM          | 9.20  | 2.31                      |
| 4      | 25 mM          | 9.27  | 2.58                      |
| 5      | 30 mM          | 9.34  | 2.91                      |
| 6      | 40 mM          | 9.41  | 3.30                      |
| 7      | 50 mM          | 9.50  | 3.52                      |
| 8      | 75 mM          | 9.80  | 4.51                      |
| 9      | 100 mM         | 10.71 | 4.88                      |

aggregatum onion varieties viz., CO 5, CO 6. Higher concentrations of  $\text{NaHCO}_3$ , 25, 50, 75 and 100 mM were used for screening seed propagated aggregatum onion varieties viz., Perambalur local and Thuraiyur local. Onion seeds are more sensitive to  $\text{NaHCO}_3$  compared to the bulb and hence the concentration up to 50 mM  $\text{NaHCO}_3$  was used for screening bulb-propagated onion varieties, while a higher  $\text{NaHCO}_3$  concentration up to 100 mM was used for bulb-propagated aggregatum onion varieties.

Twenty seeds of each variety, soaked in water for 12 hr, were used for screening. Seeds were distributed over two layers of paper towel ( $21 \times 21$  cm) previously moistened with water equivalent to 3 times the dry weight of the paper, tied at both ends with a rubber band and kept in plastic beakers containing different concentrations (Control, 10, 20, 30, 40 and 50 mM) of  $\text{NaHCO}_3$ . For screening aggregatum bulb propagated onion varieties (Perambalur, Thuraiyur), equally sized bulbs were selected and the bulbs were directly sown in 6 beakers containing 1.5 kg of sand per beaker. Different concentrations (Control, 25, 50, 75 and 100 mM) of  $\text{NaHCO}_3$  solution were poured into beakers. The beakers were kept in laboratory conditions at room temperature for 21 days. At the end of the 21<sup>st</sup> day, vigour index, stress tolerance index (STI), membrane stability index (MSI) and total dry matter production (TDMP) were recorded. The experiment was designed as a completely randomised design with two factors. The first factor was the varieties and the second one, external sodicity stress levels.

### Observations recorded

#### Vigour index

The vigour index of the seedlings was calculated using the following formula and expressed as a percentage (11).

$$\text{Vigour Index} = (\text{Shoot length} + \text{Root length}) \times \text{Germination percentage} \quad (\text{Eqn. 1})$$

#### Stress tolerance index (STI)

Stress tolerance index was calculated using the following formula and expressed as percentage (12).

Stress Tolerance Index =

$$\left( \frac{\text{Vigour index of the treated seedling}}{\text{Vigour index of the control seedling}} \right) \times 100 \quad (\text{Eqn. 2})$$

#### Membrane stability index (MSI)

The MSI was estimated as per the standard protocol (13). This experiment was carried out to determine the extent of membrane damage in tissues subjected to sodicity stress. In MSI, the total inorganic ions (mainly  $\text{K}^+$ ) leaked out is measured in terms of electrical conductivity (EC) of the bathing medium before and after

$$\text{Percent leakage} = \left( \text{Ecb} - \frac{\text{Eca}}{\text{Ecc}} \right) \times 100 \quad (\text{Eqn. 3})$$

**Table 3.** List of primers used

| S.No. | Gene name                                 | Primer name                | Sequence (5'-3')                              | Product length (bp) |
|-------|-------------------------------------------|----------------------------|-----------------------------------------------|---------------------|
| 1     | Ninja-family protein AFP3-like            | Ac NINJA-F<br>Ac NINJA-R   | ACTCCGCCCTCCATACTCATTT<br>TTTCGCTCTCCAGGGTCAT | 179                 |
| 2     | Malate synthase, glyoxysomal              | Ac MalSyn-F<br>Ac MalSyn-R | TCGCCGTCTAACTCTACACC<br>ACCTGCTTCAAAGACCGAGA  | 202                 |
| 3     | 21 kDa protein                            | Ac 21kDa-F<br>Ac 21kDa-R   | TAGATGGATGGCGAACTCGG<br>TCTTCTTCTTCGCACTCGCT  | 191                 |
| 4     | NAC transcription factor 29-like, partial | Ac NAC29-F<br>Ac NAC29-R   | ATAAAGCCATGTTTCGGCGAC<br>GCCTTTTTCACCCGATGTT  | 172                 |
| 5     | ABC transporter G family member 9         | Ac ABCTrG-F<br>Ac ABCTrG-R | GGTCGAACCATGTTGTTGCC<br>GGCGTATCAACCAACGAACA  | 181                 |

the treatment, using a conductivity bridge. Leaf discs (about 20) of the test sample were taken in a test tube with about 10 mL of deionised water. The test tubes were covered and subjected to a high-temperature regime of 55 °C for 30 min in a water bath. Initial EC (Eca), just before transfer to the high temperature treatment and the EC after 30 min of high temperature treatment (Ecb), were recorded. The tubes were then boiled at 100 °C for 10 min and the EC was again recorded (Ecc) and MSI was expressed in percentage.

#### Total dry matter production (TDMP)

Twenty-one-day-old seedlings were first shade dried and then oven dried at 80 °C for 48 hr. The dry weight of the whole seedlings was recorded and expressed as mg per ten plants.

### Comparison of gene expression by RT-PCR

The expression of stress-associated genes Ac NINJA, Ac MalSyn, Ac 21kDa, Ac NAC29, Ac ABCTrG, Ac STYGRN, Ac Chape, Ac AOX, Ac GAPDH, Ac SOD, Ac WRKY, Ac AQP and Ac Ubiquitin K599 was studied using gene-specific primers (Table 3). Based on the results of laboratory studies in sodic conditions, one sodicity-tolerant bulb and aggregatum onion variety and one sodicity-sensitive bulb and aggregatum onion varieties were grown in normal and sodic soil conditions. Leaf samples were collected 25 days after sowing to study the relative gene expression by reverse transcription PCR. DNA was extracted from the leaf samples, which were further used for generating cDNA. The cDNA was uniformly diluted 25-fold; 5  $\mu\text{L}$  of diluted cDNA was used for PCR amplification with gene-specific primers and the gene expression of the PCR product was estimated by agarose gel electrophoresis. Finally, the variation in gene expression was compared.

## Results

The present investigation aimed to screen the bulb and aggregatum onion varieties for sodicity tolerance based on vigour index, STI, MSI and TDMP. After laboratory screening, three tolerant onion varieties, viz., Bhima Safed, CO 6 and Thuraiyur local and three susceptible varieties, viz., Bhima Red, CO 5 and Perambalur local, were taken for molecular studies (RT-PCR) to assess the expression of abiotic stress genes under sodicity. To achieve the objectives, a series of experiments was carried out in laboratory conditions. The results of the experiments were statistically analysed and the data were presented in appropriate tables.

### Effect of sodicity stress on seedling physiology of bulb onion

#### Vigour index

Vigour index is an important index for sodicity tolerance and significant varietal variations were observed due to stress treatments (Table 4). The vigour index of bulb onion varieties varied from 566–1329 with an average vigour index of 792 in the control. The vigour index decreased with an increase in sodicity

**Table 4.** Effect of sodium bicarbonate on the vigour index of bulb onion varieties

| Varieties       | Vigour index |       |       |       |       |       | Mean |
|-----------------|--------------|-------|-------|-------|-------|-------|------|
|                 | Control      | 10 mM | 20 mM | 30 mM | 40 mM | 50 mM |      |
| Arka Kirthiman  | 1056         | 833   | 736   | 569   | 448   | 110   | 625  |
| Bhima Super     | 766          | 719   | 593   | 438   | 309   | 61    | 481  |
| Bhima Shweta    | 1041         | 992   | 952   | 732   | 448   | 155   | 720  |
| Arka Kalyan     | 848          | 743   | 708   | 568   | 450   | 136   | 576  |
| Bhima Red       | 949          | 772   | 690   | 526   | 357   | 32    | 554  |
| Bhima Shakti    | 846          | 656   | 594   | 471   | 281   | 77    | 488  |
| AFDR            | 935          | 717   | 597   | 485   | 275   | 86    | 516  |
| Bhima Safed     | 1329         | 1284  | 1218  | 915   | 669   | 230   | 941  |
| Bhima Dark red  | 566          | 497   | 439   | 350   | 205   | 64    | 354  |
| Bhima Kiran     | 889          | 730   | 657   | 457   | 313   | 91    | 523  |
| Arka Yojith     | 570          | 379   | 334   | 274   | 175   | 52    | 297  |
| Bhima Shubra    | 734          | 554   | 518   | 408   | 261   | 54    | 422  |
| Bhima Raj       | 696          | 543   | 471   | 341   | 239   | 89    | 397  |
| Bhima Light red | 922          | 804   | 730   | 532   | 339   | 82    | 568  |
| Mean            | 792          | 723   | 660   | 505   | 341   | 75    | 531  |
|                 | V            |       | S     |       | V × S |       |      |
| SEd             | 18.0         |       | 11.82 |       | 44.23 |       |      |
| CD (0.05)       | 35.65        |       | 23.34 |       | 87.33 |       |      |

V: Variety, S: Sodidity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

stress imposed using  $\text{NaHCO}_3$  at 10, 20, 30, 40 and 50 mM levels. Treatment with 50 mM  $\text{NaHCO}_3$  showed the least vigour index. At this level of sodicity, the vigour index ranged from 32–230 with an average vigour index of 75, which was about 90 % reduction over the control. Comparing the performance of varieties at the highest sodicity levels of 50 mM  $\text{NaHCO}_3$ , it could be observed that the varieties Bhima Safed (82.7 %), Arka Kalyan (83.196 %) showed lesser reduction in vigour index, while the variety Bhima Red showed highest reduction in vigour index of 96.6 %, followed by Bhima Shubra (92.6 %) and Arka Yojith (90.87 %) over the control. The remaining varieties showed a higher reduction in vigour index, which varied from 85.10–90.53 %.

#### Stress tolerance index (STI)

The results revealed that with an increase in sodicity level, there was a decreasing trend in STI in all the bulb onion varieties (Table 5). The mean STI of varieties reduced from 100 (control) to 82.6, 74.9, 57.4, 38.4 and 10.5 due to 10, 20, 30, 40 and 50 mM sodicity levels respectively. Individual varieties differed significantly with respect to their STI at various levels of sodicity. At the highest sodicity level of 50 mM  $\text{NaHCO}_3$ , Bhima Safed, Arka Kalyan and Bhima Shweta recorded lower stress tolerance indices of 82.70, 84.00 and 85.10 % respectively, showing their tolerance to sodicity stress. The poor performing varieties, viz., Bhima Red,

Bhima Shubra and Bhima Super recorded significantly higher reduction in STI of 96.60, 92.60 and 92.00 % respectively, indicating their susceptibility to sodicity stress.

#### Membrane stability index (MSI)

Membrane stability index is an important index for sodicity tolerance and significant varietal variations in MSI were observed due to stress treatments (Table 6). The MSI of bulb onion varieties varied from 65.3–74.2. The average MSI of control was 71.48. While observing the effect of different sodicity stresses on MSI, a greater reduction was recorded at the sodicity of 50 mM. At this level of sodicity, the MSI ranged from 41.3–58.2 with an average MSI of 49.50 %, which was observed to be a 30.75 % reduction over the control. At 10, 20, 30 and 40 mM concentrations, the average MSI was 63.6, 60.4, 58.64 and 55.06 % respectively. Comparing the performance of varieties at the highest sodicity levels of 50 mM, it could be observed that the varieties Bhima Safed (20.7 %) and Bhima Shweta (21.6 %) showed less reduction in MSI and Bhima Red variety showed the highest reduction in MSI (40.5 %), followed by Bhima Raj (38 %) and Bhima Dark Red (36.2 %) over the control. The remaining varieties showed a higher reduction in MSI, which ranged from 25.1–36.2 %.

#### Total dry matter production (TDMP)

The TDMP of bulb onion varieties varied from 48–62 mg with an

**Table 5.** Effect of sodium bicarbonate on stress tolerance Index (STI) of bulb onion varieties

| Varieties       | STI     |       |       |       |       |       | Mean |
|-----------------|---------|-------|-------|-------|-------|-------|------|
|                 | Control | 10 mM | 20 mM | 30 mM | 40 mM | 50 mM |      |
| Arka Kirthiman  | 100     | 78.9  | 69.7  | 53.9  | 42.4  | 10.4  | 59.2 |
| Bhima Super     | 100     | 93.9  | 77.4  | 57.2  | 40.3  | 8.0   | 62.8 |
| Bhima Shweta    | 100     | 95.3  | 91.5  | 70.3  | 43.0  | 14.9  | 69.2 |
| Arka Kalyan     | 100     | 87.6  | 83.5  | 67.0  | 53.1  | 16.0  | 67.9 |
| Bhima Red       | 100     | 81.3  | 72.7  | 55.4  | 37.6  | 3.4   | 58.4 |
| Bhima Shakti    | 100     | 77.5  | 70.2  | 55.7  | 33.2  | 9.1   | 57.6 |
| AFDR            | 100     | 76.7  | 63.9  | 51.9  | 29.4  | 9.2   | 55.2 |
| Bhima Safed     | 100     | 96.6  | 91.6  | 68.8  | 50.3  | 17.3  | 70.8 |
| Bhima Dark red  | 100     | 87.8  | 77.6  | 61.8  | 36.2  | 11.3  | 62.5 |
| Bhima Kiran     | 100     | 82.1  | 73.9  | 51.4  | 35.2  | 10.2  | 58.8 |
| Arka Yojith     | 100     | 66.5  | 58.6  | 48.1  | 30.7  | 9.1   | 52.2 |
| Bhima Shubra    | 100     | 75.5  | 70.6  | 55.6  | 35.6  | 7.4   | 57.5 |
| Bhima Raj       | 100     | 78.0  | 67.7  | 49.0  | 34.3  | 12.8  | 57.0 |
| Bhima Light red | 100     | 87.2  | 79.2  | 57.7  | 36.8  | 8.9   | 61.6 |
| Mean            | 100.0   | 82.6  | 74.9  | 57.4  | 38.4  | 10.5  | 60.6 |
|                 | V       |       | S     |       | V × S |       |      |
| SEd             | 0.46    |       | 0.30  |       | 1.15  |       |      |
| CD (0.05)       | 0.92    |       | 0.60  |       | 2.27  |       |      |

V: Variety, S: Sodidity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

**Table 6.** Effect of sodium bicarbonate on the membrane stability index (MSI) of bulb onion varieties

| Varieties       | MSI (%) |       |       |       |       |       | Mean  |
|-----------------|---------|-------|-------|-------|-------|-------|-------|
|                 | Control | 10 mM | 20 mM | 30 mM | 40 mM | 50 mM |       |
| Arka Kirthiman  | 73.5    | 68.3  | 65.9  | 64.8  | 60.2  | 55.0  | 64.62 |
| Bhima Super     | 71.4    | 66.4  | 62.8  | 61.4  | 55.3  | 50.6  | 61.32 |
| Bhima Shweta    | 74.2    | 70.5  | 67.2  | 65.0  | 63.0  | 58.2  | 66.35 |
| Arka Kalyan     | 71.7    | 66.2  | 61.4  | 57.6  | 56.4  | 50.4  | 60.62 |
| Bhima Red       | 69.4    | 55.2  | 51.8  | 51.4  | 47.7  | 41.3  | 52.80 |
| Bhima Shakti    | 70.7    | 65.9  | 61.2  | 60.4  | 54.8  | 48.3  | 60.22 |
| AFDR            | 72.3    | 67.8  | 64.1  | 63.4  | 55.3  | 49.1  | 62.00 |
| Bhima Safed     | 71.1    | 68.8  | 65.0  | 64.1  | 61.9  | 56.4  | 64.55 |
| Bhima Dark red  | 70.9    | 56.9  | 53.5  | 52.0  | 49.6  | 45.2  | 54.68 |
| Bhima Kiran     | 73.8    | 68.2  | 65.8  | 65.8  | 56.7  | 51.2  | 63.58 |
| Arka Yojith     | 71.1    | 58.9  | 55.3  | 53.3  | 51.0  | 45.3  | 55.82 |
| Bhima Shubra    | 73.5    | 58.2  | 55.7  | 55.5  | 54.0  | 48.6  | 57.58 |
| Bhima Raj       | 71.8    | 58.6  | 55.2  | 52.3  | 50.6  | 44.5  | 55.50 |
| Bhima Light red | 65.3    | 61.1  | 60.9  | 54.0  | 54.4  | 48.9  | 57.43 |
| Mean            | 71.48   | 63.64 | 60.41 | 58.64 | 55.06 | 49.50 | 59.9  |
|                 | V       |       | S     |       | V × S |       |       |
| SEd             | 0.21    |       | 0.27  |       | 0.76  |       |       |
| CD (0.05)       | 0.46    |       | 0.37  |       | 1.20  |       |       |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

**Table 7.** Effect of sodium bicarbonate on Total dry matter production (TDMP) (mg) of bulb onion varieties

| Varieties       | TDMP (mg) |       |       |       |       |       | Mean |
|-----------------|-----------|-------|-------|-------|-------|-------|------|
|                 | Control   | 10 mM | 20 mM | 30 mM | 40 mM | 50 mM |      |
| Arka Kirthiman  | 62        | 56    | 50    | 44    | 30    | 21    | 44   |
| Bhima Super     | 54        | 32    | 29    | 28    | 22    | 12    | 30   |
| Bhima Shweta    | 58        | 56    | 52    | 47    | 38    | 23    | 46   |
| Arka Kalyan     | 61        | 56    | 51    | 42    | 36    | 17    | 44   |
| Bhima Red       | 57        | 27    | 26    | 20    | 15    | 8     | 26   |
| Bhima Shakti    | 48        | 44    | 39    | 44    | 26    | 12    | 36   |
| AFDR            | 53        | 50    | 42    | 38    | 35    | 18    | 39   |
| Bhima Safed     | 59        | 57    | 53    | 39    | 39    | 30    | 46   |
| Bhima Dark red  | 56        | 33    | 27    | 20    | 17    | 11    | 27   |
| Bhima Kiran     | 54        | 38    | 33    | 28    | 23    | 13    | 32   |
| Arka Yojith     | 57        | 42    | 33    | 29    | 17    | 12    | 32   |
| Bhima Shubra    | 53        | 36    | 29    | 24    | 21    | 11    | 29   |
| Bhima Raj       | 55        | 29    | 27    | 23    | 18    | 9     | 27   |
| Bhima Light red | 60        | 51    | 45    | 23    | 28    | 12    | 37   |
| Mean            | 56        | 43    | 38    | 32    | 26    | 15    | 35   |
|                 | V         |       | S     |       | V × S |       |      |
| SEd             | 0.38      |       | 0.25  |       | 0.93  |       |      |
| CD (0.05)       | 0.75      |       | 0.49  |       | 1.80  |       |      |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

average of 56 mg in the control (Table 7). While observing the effect of different sodicity stresses imposed using  $\text{NaHCO}_3$  at 10, 20, 30, 40 and 50 mM levels, greater reduction in TDMP was recorded at the sodicity level of 50 mM. At this level of sodicity, the TDMP ranged from 8–30 mg with an average TDMP of 15 mg and an average of about 73 % reduction over the control was observed. At 10, 20, 30 and 40 mM concentrations, average TDMP was 0.43, 0.38, 0.32 and 0.26 mg respectively. Comparing the performance of varieties at the highest sodicity level of 50 mM, it could be observed that the varieties Bhima Safed (49.20 %) and Bhima Shweta (60.34 %) showed less reduction in TDMP, whereas

the variety Bhima Red showed the highest reduction (85.96 %) and followed by Bhima Raj (83.64 %) over the control. The remaining varieties showed a higher reduction in TDMP, which ranged from 66.00–80.30 %.

#### Effect of sodicity stress on seedling physiology of aggregatum onion (seed propagation) varieties

##### Vigour index

Vigour index is an important parameter for sodicity tolerance and significant varietal variations in vigour index were observed due to stress treatments (Table 8). The vigour index of aggregatum onion

**Table 8.** Effect of sodium bicarbonate on the vigour index of aggregatum onion (Seed propagation)

| Varieties | Vigour Index |       |       |       |       |       | Mean  |
|-----------|--------------|-------|-------|-------|-------|-------|-------|
|           | Control      | 10 mM | 20 mM | 30 mM | 40 mM | 50 mM |       |
| CO 5      | 1109         | 978   | 842   | 694   | 524   | 399   | 757.6 |
| CO 6      | 1137         | 1056  | 1005  | 910   | 777   | 616   | 916.8 |
| Mean      | 1123         | 1016  | 923   | 802   | 650   | 507   | 837   |
|           | V            | V     | S     | V × S | V × S |       |       |
| SEd       | 7.34         | 7.34  | 12.72 | 17.9  | 17.9  |       |       |
| CD (0.05) | 15.16        | 15.16 | 26.26 | 37.14 | 37.14 |       |       |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

varieties CO 5 and CO 6 was 1109 and 1137, with an average vigour index of 1123 under control. While observing the effect of different sodicity stresses imposed using 10, 20, 30, 40 and 50 mM levels of  $\text{NaHCO}_3$  on vigour index, the highest reduction of 54.85 % was recorded at the sodicity of 50 mM compared to the control. At 10, 20, 30, 40 and 50 mM concentrations, the average vigour index varied from 507–1016. Comparing the performance of varieties at the highest sodicity levels of 50 mM, it could be observed that variety CO 6 showed less reduction in vigour index (45.8 %) and CO 5 showed the highest reduction in vigour index (64.02 %) over the control.

#### Stress tolerance index (STI)

Stress tolerance index was calculated based on the vigour index of the seedlings as percentage ratio between the values under different sodicity stress treatment and control. The results revealed that with an increase in sodicity levels, there was a decreasing trend in STI in the two aggregatum onion varieties CO 5 and CO 6 (Table 9). The mean STI of varieties reduced from 100 (control) to 90.4, 82.0, 71.2, 57.6 and 44.9 due to 10, 20, 30, 40 and 50 mM sodicity levels. The highest reduction in STI of 55.10 % was recorded at the sodicity level of 50 mM compared to the control. At the highest sodicity level of 50 mM, CO 6 showed less reduction in STI (45.9 %), the poor-performing variety, CO 5, showed the highest reduction in STI (64.1 %) over the control.

#### Membrane stability index (MSI)

Membrane stability index is an important index for sodicity tolerance and significant varietal variations in MSI were observed due to stress treatments (Table 10). The MSI of aggregatum onion varieties was 73.0 and 74.2, with an average MSI of 73.6 under control. While observing the effect of different sodicity stresses imposed using  $\text{NaHCO}_3$  at 10, 20, 30, 40 and 50 mM levels on MSI, the highest reduction of 25.68 % was recorded at the sodicity of 50 mM

compared to the control. At 10, 20, 30, 40 and 50 mM concentrations, the average MSI ranged from 54.7–71.8 respectively. Comparing the performance of varieties at the highest sodicity levels of 50 mM, it could be observed that variety CO 6 showed less reduction (21.5 %) in MSI (29.5 %) over the control.

#### Total dry matter production (TDMP)

Total dry matter production is an important index for sodicity tolerance and significant varietal variations in TDMP were observed due to stress treatments (Table 11). The TDMP of aggregatum onion varieties was 58.0 and 60.0 mg with an average of 59.0 mg under control conditions. While observing the effect of different sodicity stresses imposed using  $\text{NaHCO}_3$  at 10, 20, 30, 40 and 50 mM levels on TDMP, the highest reduction of 59.32 % was recorded at the sodicity of 50 mM compared to the control. At 10, 20, 30, 40 and 50 mM concentrations, the average TDMP was 54.5, 49, 44, 32.5 and 24.5 % respectively. Comparing the performance of varieties at the highest sodicity levels of 50 mM, it could be observed that variety CO 6 showed less reduction in TDMP (50.00 %) and CO 5 showed the highest reduction in TDMP (67.24 %) over the control.

#### Effect of sodicity stress on seedling physiology of aggregatum onion (bulb propagation) varieties for sodicity stress

##### Vigour index

The vigour index of aggregatum onion varieties was 3360 and 3380, with an average vigour index of 3370 under control (Table 12). While observing the effect of different sodicity stresses imposed using sodium bicarbonate at 25, 50, 75 and 100 mM levels on vigour index, the highest reduction of 97.97 % was recorded at the sodicity of 100 mM compared to the control. At 25, 50, 75 and 100 mM concentrations, the average vigour index was 2482,

**Table 9.** Effect of sodium bicarbonate on the stress-tolerant index (STI) of aggregatum onion (seed propagation)

| Varieties | STI     |       |       |       |       |       | Mean |
|-----------|---------|-------|-------|-------|-------|-------|------|
|           | Control | 10 mM | 20 mM | 30 mM | 40 mM | 50 mM |      |
| CO 5      | 100     | 88.1  | 75.9  | 62.5  | 47.0  | 35.9  | 68.2 |
| CO 6      | 100     | 92.8  | 88.3  | 80.0  | 68.3  | 54.1  | 80.5 |
| Mean      | 100     | 90.4  | 82.0  | 71.2  | 57.6  | 44.9  | 74.4 |
|           | V       |       | S     |       | V × S |       |      |
| SEd       | 0.49    |       | 0.85  |       | 1.20  |       |      |
| CD (0.05) | 1.01    |       | 1.75  |       | 2.48  |       |      |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

**Table 10.** Effect of sodium bicarbonate on the membrane stability index (MSI) of aggregatum onion (seed propagation)

| Varieties | MSI (%) |       |       |       |       |       | Mean |
|-----------|---------|-------|-------|-------|-------|-------|------|
|           | Control | 10 mM | 20 mM | 30 mM | 40 mM | 50 mM |      |
| CO 5      | 73.0    | 72.1  | 68.1  | 64.8  | 57.8  | 51.4  | 64.5 |
| CO 6      | 74.2    | 71.5  | 69.2  | 66.6  | 62.3  | 58.2  | 67.0 |
| Mean      | 73.6    | 71.8  | 68.6  | 65.6  | 60.0  | 54.7  | 65.7 |
|           | V       |       | S     |       | V × S |       |      |
| SEd       | 0.67    |       | 1.16  |       | 1.64  |       |      |
| CD (0.05) | 1.38    |       | 2.40  |       | 3.40  |       |      |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

**Table 11.** Effect of sodium bicarbonate on Total dry matter production (TDMP) (mg) of aggregatum onion (seed propagation)

| Varieties | TDMP    |       |       |       |       |       | Mean |
|-----------|---------|-------|-------|-------|-------|-------|------|
|           | Control | 10 mM | 20 mM | 30 mM | 40 mM | 50 mM |      |
| CO 5      | 58      | 54    | 47    | 42    | 28    | 19    | 41   |
| CO 6      | 60      | 55    | 51    | 46    | 37    | 30    | 46   |
| Mean      | 59      | 54    | 49    | 44    | 32    | 24    | 43   |
|           | V       | V     | S     | V × S | V × S |       |      |
| SEd       | 0.41    | 0.41  | 0.27  | 0.98  | 0.98  |       |      |
| CD (0.05) | 0.78    | 0.78  | 0.51  | 1.90  | 1.90  |       |      |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

**Table 12.** Effect of sodium bicarbonate on the vigour index of aggregatum onion (bulb propagation)

| Varieties  | Vigour index |        |        |       |        |        |
|------------|--------------|--------|--------|-------|--------|--------|
|            | Control      | 25 mM  | 50 mM  | 75 mM | 100 mM | Mean   |
| Perambalur | 3360.0       | 1844.5 | 650.0  | 94.6  | 10.2   | 1191.9 |
| Thuraiyur  | 3380.0       | 3120.0 | 2163.0 | 826.4 | 127.6  | 1923.4 |
| Mean       | 3370         | 2482   | 1406.5 | 460.5 | 68.09  | 1557   |
|            | V            | S      | V × S  |       |        |        |
| SEd        | 22.7         | 35.9   | 50.8   |       |        |        |
| CD (0.05)  | 47.4         | 74.9   | 106.0  |       |        |        |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

1406.5, 460.5 and 68.09 respectively. Comparing the performance of varieties at the highest sodicity levels of 100 mM, it could be observed that among the varieties, Thuraiyur showed less reduction in vigour index (96.22 %) and Perambalur showed the highest reduction in vigour index (99.70 %) over the control.

#### Stress tolerance index (STI)

Stress tolerance index was calculated based on the vigour index of the seedlings as percentage ratio between the values under different sodicity stress treatment and control. The results revealed that with an increase in sodicity level, there was a decreasing trend in STI in both aggregatum onion varieties (Table 13). The mean STI of varieties reduced from 100 (control) to 73.55, 41.67, 13.61 and 2.04 due to 25 mM, 50 mM, 75 mM and 100 mM sodicity levels. At the highest sodicity level of 100 mM, Thuraiyur showed less reduction in STI (96.23 %); the poor-performing variety, Perambalur, showed the highest reduction in STI (99.7 %) over the control.

#### Membrane stability index (MSI)

Membrane stability index is an important index for sodicity tolerance and significant varietal variations in MSI were observed due to stress treatments (Table 14). The MSI of aggregatum

onion varieties was 81 and 85, with an average MSI of 83 under control. The higher reduction in MSI of 59.03 % was recorded at the sodicity of 100 mM compared to the control. At 25, 50, 75 and 100 mM concentration, the average MSI was 74, 60, 41 and 34 % respectively. Comparing the performance of varieties at the highest sodicity levels of 100 mM, it could be observed that among the varieties, Thuraiyur showed less reduction in MSI (50.76 %) and Perambalur showed the highest reduction in MSI (67.90 %) over the control.

#### Total dry matter production (TDMP)

The TDMP of aggregatum onion varieties was 70 and 71 mg with an average of 70 mg under control (Table 15). The higher reduction in TDMP of 22.85 % was recorded at the sodicity of 100 mM compared to the performance of varieties at the highest sodicity levels of 50 mM. It could be observed that among the varieties, Thuraiyur showed less reduction (19.71 %) and Perambalur showed the highest reduction in TDMP (27.14 %) over the control.

#### Alteration in gene expression under sodicity stress

Gene expression studies in aggregatum onion varieties revealed downregulation of Glyceraldehyde-3-phosphate dehydrogenase

**Table 13.** Effect of sodium bicarbonate on stress-tolerant index (STI) of aggregatum onion (bulb propagation)

| Varieties  | STI     |       |       |       |        |       |
|------------|---------|-------|-------|-------|--------|-------|
|            | Control | 25 mM | 50 mM | 75 mM | 100 mM | Mean  |
| Perambalur | 100     | 54.82 | 19.34 | 2.81  | 0.30   | 35.5  |
| Thuraiyur  | 100     | 92.33 | 63.99 | 24.44 | 3.77   | 56.9  |
| Mean       | 100     | 73.55 | 41.67 | 13.63 | 2.04   | 46.18 |
|            | V       | S     | V × S |       |        |       |
| SEd        | 0.49    | 0.78  | 0.10  |       |        |       |
| CD (0.05)  | 1.02    | 1.62  | 0.23  |       |        |       |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

**Table 14.** Effect of sodium bicarbonate on the membrane stability index (MSI) of aggregatum onion (bulb propagation)

| Varieties  | MSI (%) |       |       |       |        |      |
|------------|---------|-------|-------|-------|--------|------|
|            | Control | 25 mM | 50 mM | 75 mM | 100 mM | Mean |
| Perambalur | 81      | 72    | 56    | 31    | 26     | 53   |
| Thuraiyur  | 85      | 76    | 64    | 51    | 41     | 63   |
| Mean       | 83      | 74    | 60    | 41    | 34     | 58   |
|            | V       | S     | V × S |       |        |      |
| SEd        | 0.55    | 0.87  | 1.23  |       |        |      |
| CD (0.05)  | 1.15    | 1.81  | 2.57  |       |        |      |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

**Table 15.** Effect of sodium bicarbonate on total dry matter production (TDMP) of aggregatum onion (bulb propagation)

| Varieties  | TDMP (mg) |       |       |       |        |      |
|------------|-----------|-------|-------|-------|--------|------|
|            | Control   | 25 mM | 50 mM | 75 mM | 100 mM | Mean |
| Perambalur | 70        | 62    | 61    | 58    | 51     | 60   |
| Thuraiyur  | 71        | 66    | 63    | 61    | 57     | 63   |
| Mean       | 70        | 64    | 62    | 60    | 54     | 62   |
|            | V         | S     | V × S |       |        |      |
| SEd        | 0.48      | 0.32  | 1.08  |       |        |      |
| CD (0.05)  | 0.82      | 0.60  | 2.01  |       |        |      |

V: Variety, S: Sodicity, CD: Critical difference, SEd: Standard error (deviation), mM: millimolar.

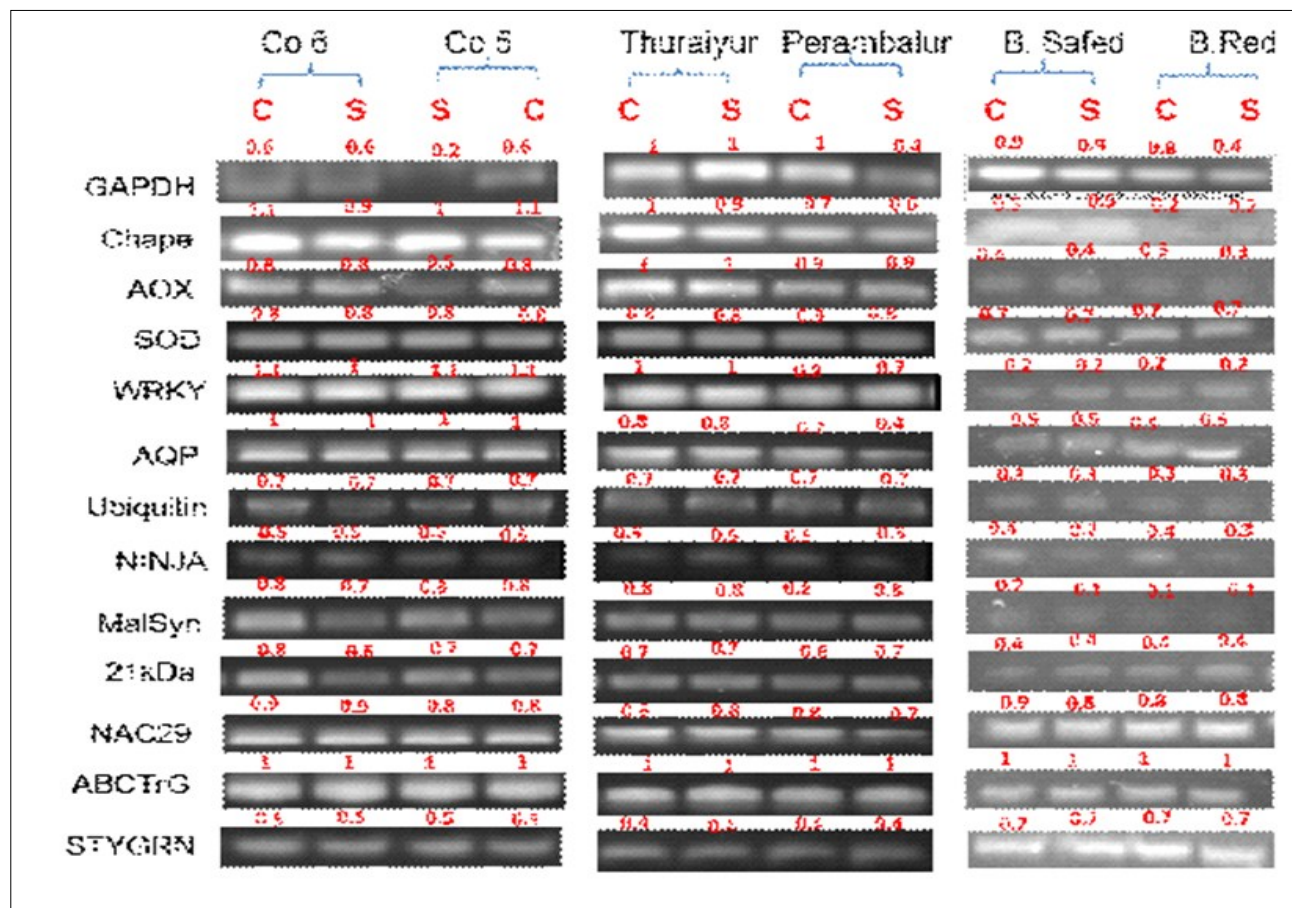


**Fig. 1.** Alteration of gene expression under sodicity stress.

(GAPDH) and alternative oxidase (AOX) under sodicity in the susceptible variety CO 5; the tolerant variety CO 6 did not show any change (Fig. 1). However, the CO 6 variety showed a slight decrease in the gene expressions of Chaperon, WRKY, MalSyn and 21 kDa. Remarkable downregulation of GAPDH and aquaporin (AQP) genes was observed in the susceptible aggregatum variety Perambalur when subjected to sodicity (Fig. 1). This variety also showed slight downregulation of Chaperon, WRKY and NAC genes and upregulation of 21 kDa under sodicity. The tolerant variety, Thuraiyur, showed minor downregulation of Chaperon.

In bulb onion varieties, significant downregulation of GAPDH was seen in the susceptible variety, Bhima Red; no alteration was observed in the tolerant variety, Bhima Safed, when subjected to sodicity (Fig. 1). Both tolerant (Bhima Safed) and sensitive (Bhima Red) varieties showed downregulation of NINJA under sodicity stress. In the tolerant variety Bhima Safed, MalSyn and NAC29 were also somewhat down-regulated under sodicity.

## Discussion

### Effect of sodicity stress on physiological parameters

In the present investigation, the mean vigour index decreased to 55, 39 and 70 % under the extreme sodicity concentrations in bulb, aggregatum (seed propagation) and aggregatum (bulb propagation) onion varieties respectively, over the control. Significant varietal differences were observed in vigour index as a result of sodicity stress. The varieties Bhima Safed (82 %), CO 6 (45 %) and Thuraiyur (96 %) showed less reduction in vigour index compared with Bhima Red (96 %), CO 5 (47 %) and Perambalur

(99 %), which showed maximum reduction in vigour index under sodicity and this might be due to reduced germination, shoot and root length (Fig 2–5).

Research indicates that a drastic reduction in germination rate, length of radicle and plumule, seedling length and seed vigour in *Zea mays* was noticed when exposed to saline stress (14). Vigour index was also reduced in wheat and groundnut by salinity (15, 16). Similarly, the STI of onion varieties under severe sodicity stress reduced to 89, 55 and 97 % in bulb, aggregatum (seed propagation) and aggregatum (bulb propagation) onion varieties respectively, over the control (Fig. 6 and 7). The varieties Bhima Safed (82 %), CO 6 (45 %) and Thuraiyur (96 %, Fig. 4) showed less reduction in STI compared with Bhima Red (96 %), CO 5 (64 %) and Perambalur (99 %), which showed maximum reduction in STI under sodicity. Based on these observations, the varieties viz., Bhima Red, CO 5 and Perambalur were categorised as highly sensitive and susceptible to sodicity stress and, therefore, these varieties are considered unsuitable for cultivation in sodic soils (17). Also, a similar experiment was conducted and reported that the groundnut varieties viz., TMV 2, CO 5, JL 24 and BSR 1 were more sensitive to  $\text{NaHCO}_3$ . Among the 18 onion varieties screened in this study, Bhima Safed, CO 6 and Thuraiyur were able to maintain higher STI even under high sodicity conditions and, therefore, grouped as tolerant to sodicity stress.

Membrane disruption is the first symptom of sodicity stress and membrane integrity is needed for sodicity tolerance. Sodic stress causes damage to the organelle membranes, such as the nuclear membrane, endoplasmic reticulum, mitochondrial membranes and chloroplast membranes (18). In the present study, high sodicity concentration caused more than 20 % damage

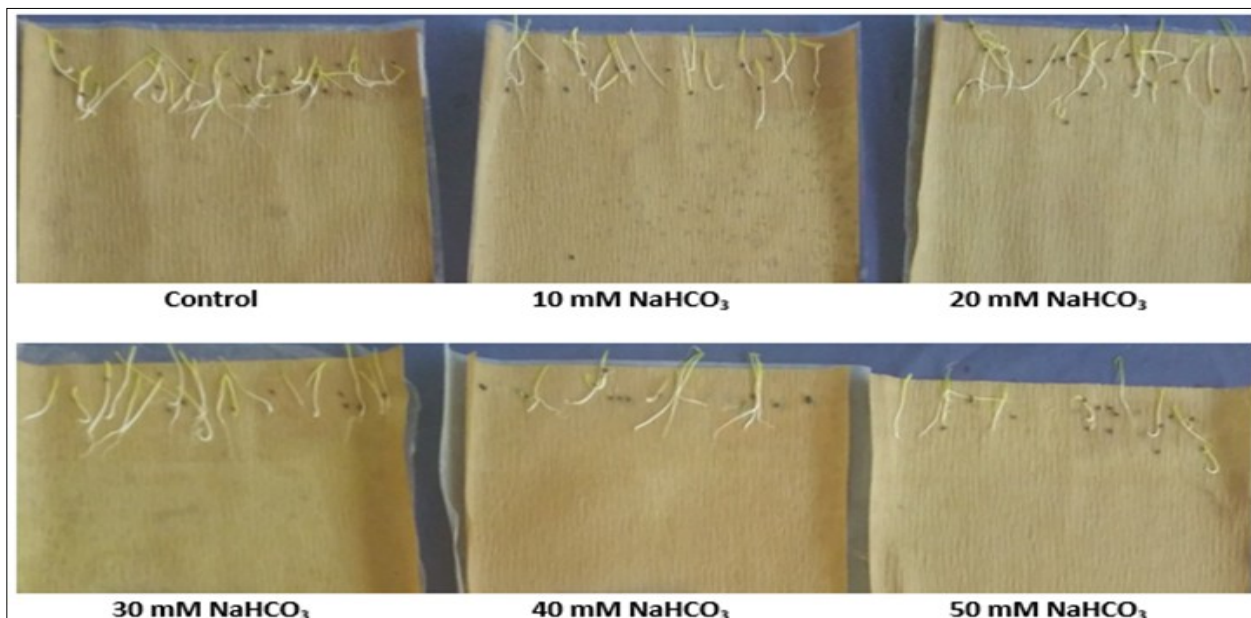


**Fig. 2.** Screening of bulb onion variety. Bhima Safed at different sodicity ( $\text{NaHCO}_3$ ) concentrations for the vigour index.

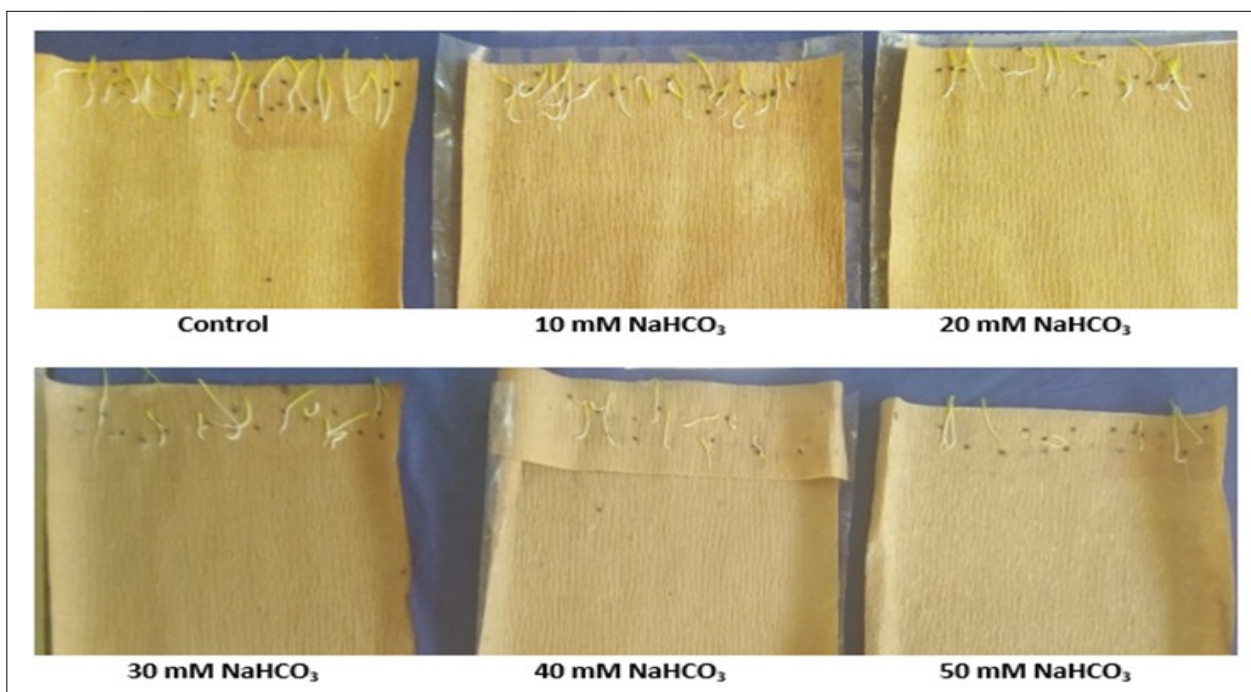


**Fig. 3.** Screening of bulb onion variety. Bhima Red at different sodicity ( $\text{NaHCO}_3$ ) concentrations for the vigour index.



**Fig. 4.** Screening of aggregatum onion (bulb propagation) var. Thuraiyur at different sodicity ( $\text{NaHCO}_3$ ) concentrations for the vigour index.



**Fig. 5.** Screening of aggregatum onion (bulb propagation) var. Perambalur at different sodicity (NaHCO<sub>3</sub>) concentrations for the vigour index.

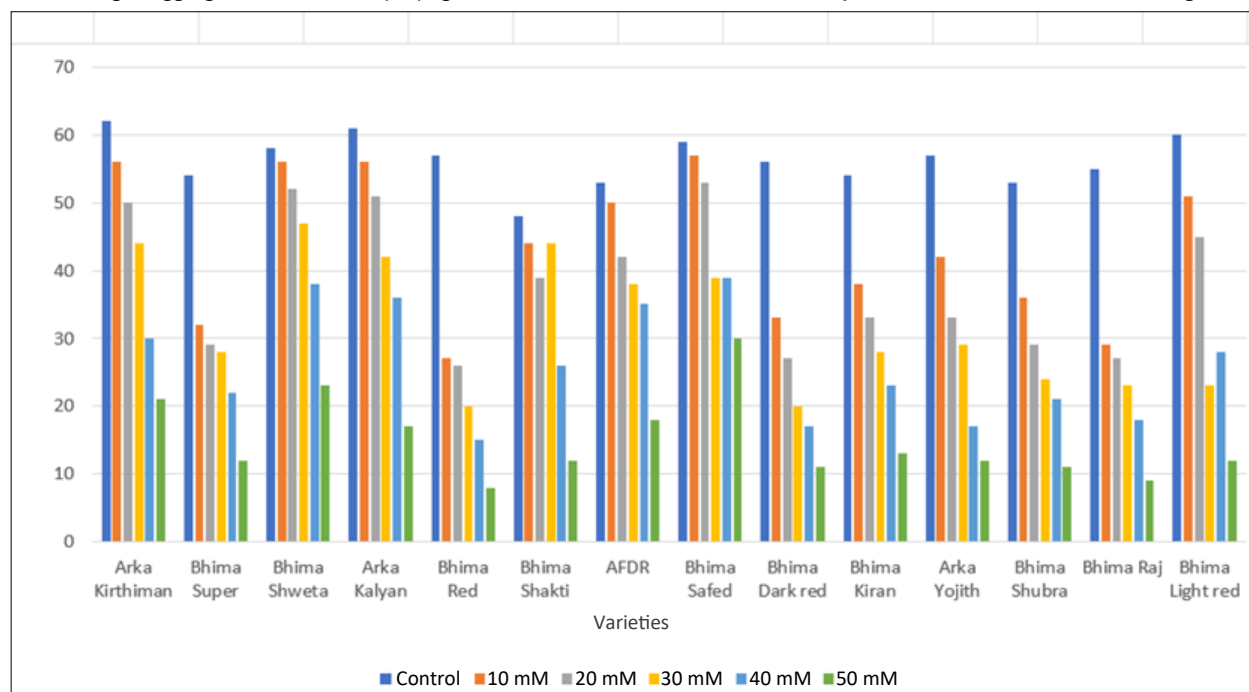


**Fig. 6.** Effect of sodium bicarbonate (NaHCO<sub>3</sub>) on stress-tolerant index of bulb onion and aggregatum onion (seed propagation) varieties.

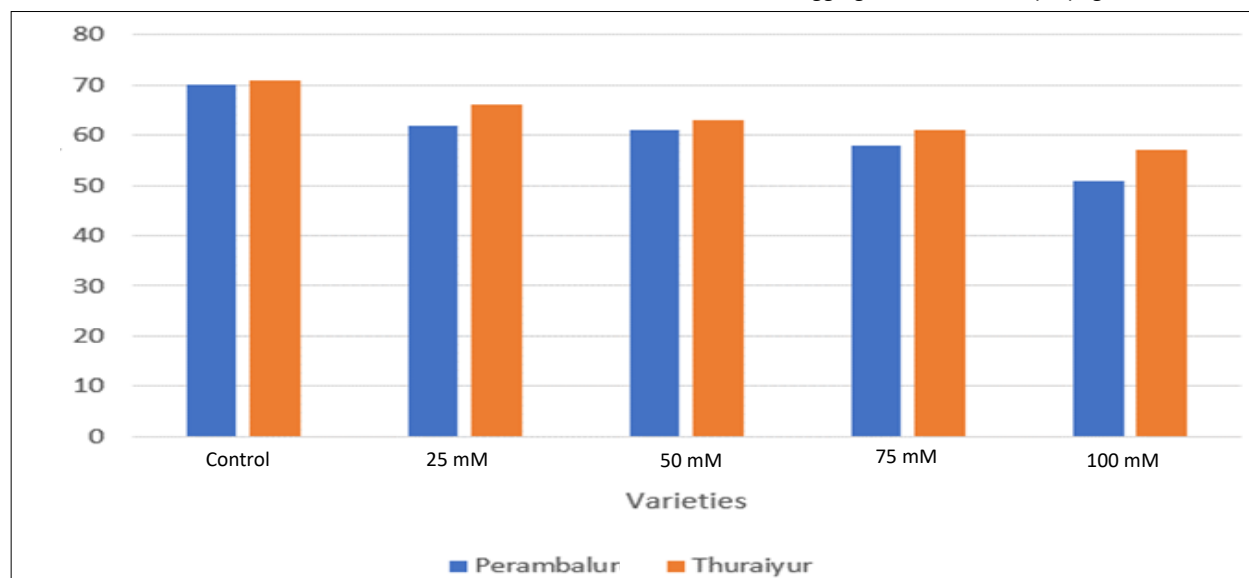


**Fig. 7.** Effect of sodium bicarbonate (NaHCO<sub>3</sub>) on stress tolerance index of bulb onion and aggregatum onion (bulb propagation) varieties.

in Bhima Red, CO 5 and Perambalur to the cellular membrane. Increase in electrolyte leakage and loss of chlorophyll are attributed to membrane damage. While observing the response of the varieties to sodicity stress, among the 18 genotypes, the tolerant genotypes Bhima Safed, CO 6 and Thuraiyur were able to maintain higher membrane integrity even under high sodicity stress. The susceptible varieties, Bhima Red, CO 5 and Perambalur showed lesser response in terms of membrane stability.

In the present study, a reduction in TDMP was recorded in sodicity stress conditions in all the varieties (Fig. 6). The most susceptible genotypes (Bhima Red, CO 5 and Perambalur) exhibited more than 65 % reduction over absolute control, whereas the tolerant genotypes (Bhima Safed, CO 6 and Thuraiyur) recorded only 50 % reduction in seedling dry matter over control (Fig. 7a and 7b). Research indicates that TDMP of seedlings depends on the germination percentage and plant height (19). Low water uptake and restricted metabolic activities decreased the plant's dry weight. Most of the tolerant genotypes accumulated more dry matter under control that slightly decreased under stress; however, moderately tolerant and susceptible genotypes recorded a decrease in total dry weight of seedlings. Research has studied 30 rice genotypes comprising salinity stress-tolerant and sensitive types grown hydroponically in NaCl medium at the seedling stage and found that the seedling biomass was reduced due to increased concentration of NaCl (20).

#### Alteration of gene expression under sodicity stress

The study revealed that tolerant varieties had stable gene expression of GAPDH, AOX and AQP genes under sodicity stress. A marked decrease in GAPDH expression was noticed in all the susceptible onion varieties studied. This shows that GAPDH has a major role in the adaptability of the onion crop to sodicity. The AOX and AQP genes might also support sodicity tolerance as the expression of these genes was stable under sodicity in tolerant varieties. Sodicity injury in the susceptible onion variety may be due to the downregulation of the housekeeping genes such as GAPDH, AOX and AQP. Under salinity stress, GAPDH encodes a key enzyme in the glycolytic pathway and supports cellular adjustment and growth by channeling carbon into the pathway, leading to glycolysis and ATP production. Certain genes, including GAPDH, responded to salinity stress and increased photosynthesis in Rangpur lime (9). In rice plants, AOX response is primarily associated with adaptive reactive oxygen species (ROS) balancing, thereby effective tuning of the antioxidant system and, secondarily, rapid energy production in salinity stress (21). The AQP is involved in the regulation of water transport under salt stress (22, 23).

#### Conclusion

Soil sodicity is an ever-increasing problem in the scenario of climate change. From the laboratory studies, it is concluded that the onion varieties viz., Bhima Safed (bulb onion), CO 6 (aggregatum - seed propagation) and Thuraiyur (aggregatum- bulb propagation) are tolerant to sodicity stress and Bhima Red (bulb onion), CO 5 (aggregatum- seed propagation) and Perambalur (aggregatum- bulb propagation) are more susceptible to sodicity stress. Genomic approaches play a significant role in identifying stress-responsive genes and in screening sodicity-tolerant onion varieties. From the molecular studies, it was evident that the sodicity-tolerant onion varieties, viz., Bhima Safed, CO 6 and Thuraiyur showed stable gene

expression of Glyceraldehyde-3-phosphate dehydrogenase (GAPDH), alternative oxidase (AOX) and Aquaporin (AQP) genes and were not affected by cultivation in sodic soil, whereas the susceptible Bhima Red, CO 5 and Perambalur showed downregulation of these genes. Investigating GAPDH, AOX and AQP signalling pathways will address the exact reason for the suppression of these genes under sodicity. The role of the GAPDH gene in contributing to sodicity tolerance in onion was identified and stable expression of the GAPDH gene may be used as a biomarker for large-scale screening of sodicity-tolerant onion varieties.

#### Acknowledgements

The authors would like to extend my appreciation to the Department of Vegetable Science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Tiruchirappalli, for providing essential resources to conduct this study.

#### Authors' contributions

AR generated the experimental material and initiated the study's concept and data collection. NA designed the research and experimental framework, provided project supervision and manuscript review. MV, CP, SS, MLM, PP and SN provided predominant research guidance and final manuscript approval, collectively ensuring a comprehensive and rigorous scientific investigation. CR, CT edited the manuscript. All authors read and approved the final manuscript.

#### Compliance with ethical standards

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

**Ethical issues:** None

#### References

1. Canton H. Food and agriculture organization of the United Nations-FAO. In: The Europa directory of international organizations 2021. Routledge; 2021. p. 297–305. <https://doi.org/10.4324/9781003179900-41>
2. Kumar P, Sharma PK. Soil salinity and food security in India. *Front Sustain Food Syst.* 2020;4:533781. <https://doi.org/10.3389/fsufs.2020.533781>
3. Gangwar P, Singh R, Trivedi M, Tiwari RK. Sodic soil: Management and reclamation strategies. *Environmental Concerns and Sustainable Development: Volume 2: Biodiversity, Soil and Waste Management.* 2020;175–90. [https://doi.org/10.1007/978-981-13-6358-0\\_8](https://doi.org/10.1007/978-981-13-6358-0_8)
4. Rengasamy P, de Lacerda CF, Gheyi HR. Salinity, sodicity and alkalinity. In: Oliveira T S, Bell R W, editors. *Subsoil constraints for crop production.* Springer; 2022. p. 83–107. [https://doi.org/10.1007/978-3-031-00317-2\\_4](https://doi.org/10.1007/978-3-031-00317-2_4)
5. Stavi I, Thevs N, Priori S. Soil salinity and sodicity in drylands: A review of causes, effects, monitoring and restoration measures. *Front Environ Sci.* 2021;9:712831. <https://doi.org/10.3389/fenvs.2021.712831>
6. Sanwal SK, Kesh H, Kumar A, Dubey BK, Khar A, Rouphael Y, et al. Salt tolerance potential in onion: Confirmation through physiological and biochemical traits. *Plants.* 2022;11(23):3325. <https://doi.org/10.3390/plants11233325>
7. Salunkhe VN, Gedam P, Pradhan A, Gaikwad B, Kale R, Gawande S. Concurrent waterlogging and anthracnose-twister disease in rainy-

- season onions (*Allium cepa*): Impact and management. *Front Microbiol.* 2022;13:1063472. <https://doi.org/10.3389/fmicb.2022.1063472>
8. Ketehouli T, Idrice Carther KF, Noman M, Wang FW, Li XW, Li HY. Adaptation of plants to salt stress: characterization of Na<sup>+</sup> and K<sup>+</sup> transporters and role of CBL gene family in regulating salt stress response. *Agronomy.* 2019;9(11):687. <https://doi.org/10.3390/agronomy9110687>
  9. Atta K, Mondal S, Gorai S, Singh AP, Kumari A, Ghosh T, et al. Impacts of salinity stress on crop plants: Improving salt tolerance through genetic and molecular dissection. *Front Plant Sci.* 2023;14:1241736. <https://doi.org/10.3389/fpls.2023.1241736>
  10. Ghodke P, Khandagale K, Thangasamy A, Kulkarni A, Narwade N, Shirsat D, et al. Comparative transcriptome analyses in contrasting onion (*Allium cepa* L.) genotypes for drought stress. *PLoS One.* 2020;15(8):e0237457. <https://doi.org/10.1371/journal.pone.0237457>
  11. Abdul-Baki AA, Anderson JD. Vigor determination in soybean seed by multiple criteria 1. *Crop Sci.* 1973;13(6):630–3. <https://doi.org/10.2135/cropsci1973.0011183X001300060013x>
  12. Dhopte AM, Livera-Muñoz M. Useful techniques for plant scientists. Jodhpur: Scientific Publishers; 1989.
  13. Sullivan CY. Techniques for measuring plant drought stress. Drought injury and resistance in crops. 1971;2:1–18. <https://doi.org/10.2135/cssaspecpub2.c1>
  14. Khodarahmpour Z. Screening maize (*Zea mays* L.) hybrids for salt stress tolerance at germination stage. *Afr J Biotechnol.* 2011;10(71):15959–65. <https://doi.org/10.5897/AJB11.2493>
  15. Motamedi M, Khodarahmpour Z, Ahakpaz F. Influence of salicylic acid pretreatment on germination and seedling growth of wheat (*Triticum aestivum* L.) cultivars under salt stress. *Int J Biosci.* 2013;3(3):20–28. <https://doi.org/10.12692/ijb/3.8.226-233>
  16. Mensah JK, Akomeah PA, Ikhajagbe B, Ekpekurede EO. Effects of salinity on germination, growth and yield of five groundnut genotypes. *Afr J Biotechnol.* 2006;5(20):1973–79.
  17. Nithila S, Durga Devi D, Velu G, Amutha R, Rangaraju G. Physiological evaluation of groundnut (*Arachis hypogaea* L.) varieties for salt tolerance and amelioration for salt stress. *Res J Agric Sci ISSN.* 2013;2320:6063.
  18. Qadir M, Schubert S. Degradation processes and nutrient constraints in sodic soils. *Land Degrad Dev.* 2002;13(4):275–94. <https://doi.org/10.1002/ldr.504>
  19. Ibrahim EA. Seed priming to alleviate salinity stress in germinating seeds. *J Plant Physiol.* 2016;192:38–46. <https://doi.org/10.1016/j.jplph.2015.12.011>
  20. Arifuddin M, Musa Y, Farid M, Anshori MF, Nasaruddin N, Nur A, et al. Rice screening with hydroponic deep-flow technique under salinity stress. *IOP Conf Ser Earth Environ Sci.* 2021;648:012123.
  21. Aziz S, Germano TA, Thiers KLL, Batista MC, de Souza Miranda R, Arnholdt-Schmitt B, et al. Transcriptome analyses in a selected gene set indicate alternative oxidase (AOX) and early enhanced fermentation as critical for salinity tolerance in rice. *Plants.* 2022;11(16):2145. <https://doi.org/10.3390/plants11162145>
  22. López-Berenguer C, Martínez-Ballesta MC, García-Viguera C, Carvajal M. Leaf water balance mediated by aquaporins under salt stress and associated glucosinolate synthesis in broccoli. *Plant Science.* 2008;174(3):321–8. <https://doi.org/10.1016/j.plantsci.2007.11.012>
  23. Sutka M, Li G, Boudet J, Boursiac Y, Doumas P, Maurel C. Natural variation of root hydraulics in *Arabidopsis* grown in normal and salt-stressed conditions. *Plant Physiol.* 2011;155(3):1264–76. <https://doi.org/10.1104/pp.110.163113>

#### Additional information

**Peer review:** Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

**Reprints & permissions information** is available at [https://horizonpublishing.com/journals/index.php/PST/open\\_access\\_policy](https://horizonpublishing.com/journals/index.php/PST/open_access_policy)

**Publisher's Note:** Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Indexing:** Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc  
See [https://horizonpublishing.com/journals/index.php/PST/indexing\\_abstracting](https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting)

**Copyright:** © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

**Publisher information:** Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.