EFFECT OF HIGH TEMPERATURE ON PHYSIOLOGICAL, BIOCHEMICAL AND YIELD PARAMETERS IN TOMATO (*Solanum lycopersicum* L.).

by

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THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"Effect of high temperature on physiological, biochemical and yield parameters in tomato (*Solanum lycopersicum* L.)."** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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Certified that this thesis entitled **"Effect of high temperature on physiological, biochemical and yield parameters in tomato (*Solanum lycopersicum* L.)."** is a record of research work done independently by Ms. Amrutha Vijayakumar (2018-11-095) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associate ship to him.

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LIST OF ABBREVIATIONS AND SYMBOLS USED

%	Per cent
@	At the rate of
µg	Microgram
^{o}C	Degree Celsius
m^{-2}	Per metre square
CD	Critical difference
cm	Centimeter
ml	Millilitre
M	Molar
EC	Elecrtical conductivity
ppm	Parts per million
o	Degree Celsius
LMWOA	Low Molecular Weight Organic Acids
AVRDC	Asian Vegetable Research and Development Center
CRD	Completely Randomized Design
rpm	Rotations per minute
et al.	and other Co workers
OD	Optical density
Fig.	Figure
g	Gram
i.e.	That is
KAU	Kerala Agricultural University
mm	Millimeter
viz.	Namely
IPCC	Inter-Governmental Panel on Climate change

NHB	National Horticultural Board
ROS	Reactive oxygen species
mm	Millimeter
HSPs	Heat shock proteins
HSFs	Heat shock factors
µmol	Micromoles
mmol	Millimoles
SOD	Superoxide dismutase
mg	Milligram
nm	Nanometer
s	Seconds
DIF	Day and night temperature difference
A_{663}	Absorbance at 663nm
A_{645}	Absorbance at 645nm
A_{480}	Absorbance at 480nm
A_{510}	Absorbance at 510nm
A_{520}	Absorbance at 520nm
A_{460}	Absorbance at 460nm
GA	Gibberellic acid
ZT	Zeatin
ABA	Abscisic acid
SA	Salicylic acid
JA	Jasmonic acid

INTRODUCTION

1. INTRODUCTION

An increasing population is associated with an increase in demand for food but the food production is not enough to feed the growing population. Global warming and associated heat stress due to climate change is a major threat which affects crop production adversely (Ainsworth and Ort, 2010). The global climate change models predict an increase of 2°C daily mean temperature between the year 2046 and 2065 and 3.7°C by 2100 (IPCC, 2013). This climate change is expected to affect the world of today in many ways, including the extinction of species that cannot escape their environment and a decrease in food productivity.

Tomato (*Solanum lycopersicum* L.) is considered as an important and economic vegetable crop worldwide native to South America. It belongs to the Solanaceae family that encompasses several other crops, such as potato, eggplant and pepper. The genus Solanum includes annual or short-lived perennial herbaceous plants. It is a typical day neutral plant and is mostly self-pollinated crop. It is a warm season crop reasonably resistant to heat and drought and grows well under a wide range of soil and climatic conditions. It is an excellent source of carotenoids, precursor of essential vitamins and antioxidants, lycopene, α- and β- carotene, lutein, zeaxanthin and cryptoxanthin. Lycopene constitutes about 80–90 per cent of the total carotenoid content of red ripe tomatoes (Shi and Le Maguer, 2000). It is the most efficient antioxidant among carotenoids through its scavenging activity of singlet oxygen and peroxyl radicals (Mortensen and Skibsted, 1997; Sies and Stahl, 1998). The limited caloric supply, relatively high fibre content and presence of minerals, vitamins and phenols such as flavonoids make the tomato fruit an excellent ‘‘functional food’’ providing many physiological benefits as well as for meeting basic nutritional requirements.

Tomato is the second most consumed vegetable in the world after potato. The biggest tomato producers are found in Asia, which represents 60.3% of tomato

production. India stands third in area and production of tomato (National Horticultural Board, 2018). Currently, most of the tomato producing agro-climatic regions of India and the world are facing the challenge of fluctuations in temperature conditions during tomato growing seasons (Ayyogari *et al.,* 2014). Global warming and associated heat stress due to climate change is a major threat which affects the crop production adversely. The vegetables are more prone to abiotic stresses and approximately 50% loss in yield are recorded due to various abiotic stresses (Bray *et al.,* 2011).

Even though tomato is the second highest in consumption, the rate of production and productivity are not up to the mark, mainly due to the destructive effect of heat stress associated with global climate change. Heat stress due to high ambient temperature is a deadly threat to crop production worldwide (Kaushal *et al.,* 2016). The different stages of tomato such as germination and early growth with initial leaves (between 25-35 days), vegetative period (20-25 days), flowering (20-30 days), early fruiting (20-30 days) and mature fruiting (15-20 days) depends on environmental factors like air temperature, light condition, soil conditions and nutrients (Shamshiri *et al.,* 2018).

The optimum temperature is between 25ºC and 30ºC during day time and 20^0 C during night in tomato (Camejo *et al.,* 2005), and the daily mean temperature above 34ºC is considered as thermal stress. Heat stress is the major abiotic stress in tomato with high potential impact on crop yield. Tomatoes are grown widely in tropical and subtropical regions where they often experience high temperature during fruit set. Temperature above threshold leads to deleterious effects such as flower abscission, decrease of pollen quality, abnormal growth, reduced fruit set. Tomato plants exposed to a high average temperature of 34^0C / 19^0C exhibit a flower drop of 34% and a decrease of fruit set up to 71% (Hazra *et al.,* 2009).

Average global temperatures are increasing by approximately 0.5°C per decade. A 2-4°C increase over the optimal (25°C) temperature adversely affects plant growth, flowering, gamete development, embryo development and seed germination. It inhibits the ability of pollinated flowers to develop into seeded fruit, inhibits fruit ripening and

reduces yield. Heat stress becomes a major limiting factor for field production of tomatoes (Hamisu *et al*., 2016).

A threshold temperature refers to a value of daily mean temperature at which a detectable reduction in growth begins. In tomato, for example, when the ambient temperature exceeds 35 C °, its seed germination, seedling and vegetative growth, flowering, fruit set and fruit ripening are adversely affected (Miller *et al.,* 2001).

Flowering phases is most sensitive to high temperature (38°C for 3 to 4 h) during meiosis and fertilization (Iwahori *et al.,* 1965). Failure of fertilization after exposure to heat mainly affects pollen germination, pollen tube elongation, pollen and ovule production and their viability, pollen dehiscence, pollination effectiveness and stigma exertion (Firon *et al.,* 2006; Saeed *et al.,* 2007).

In Kerala, during the last ten years the annual mean minimum temperature has increased by 0.5^{o}C. The study aims to evaluate the performance of cultivars under study to heat stress and find the genotype adapted to cultivate under high temperature conditions with desirable characteristics. The aim of the study also includes identifying traits that could be used to improve the high temperature tolerance in tomato.

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

Solanum lycopersicum (2n=24) is an important vegetable crop under Solanaceae family which is cultivated under tropical and subtropical regions all over the world. It is a warm season crop requiring temperature from 15 to 30ºC. This crop has a good potential to be cultivated everywhere and under different conditions but it faces lots of problems due to chances of incidence of different abiotic stresses nowadays (Faruq *et al*., 2012) as it influences fruit set of majority of crops including tomato (Marine *et al.,* 2017). It is a warm season crop which requires temperature from 15 to 30ºC. Tomato is the second most important vegetable used throughout the world after potato. Tomatoes are important part of human diets and they contain about 94% water, 2.5% total sugars, 2% total fibre, 1% proteins, and other nutritional compounds (acids, lipids, amino acids, and carotenoids) (Koh *et al.,* 2012). Fresh fruits of tomato are in great demand round the year throughout the country. They are good source of potassium, folate, vitamin E, soluble and insoluble dietary fibers and rich source of lycopene and ascorbic acid (Kaur and Kapoor, 2008).

According to the reports of Intergovernmental Panel on Climatic Change (IPCC, 2012), the global mean surface air temperature has increased by 0.5°C in the 20th century. It is further expected to increase by 1.5–4.5°C by the late 21st century. AVDRC reported that under tropical environments tomato plants are exposed to enhanced high temperature situations during the different growing season. Climatic analysis of areas where tomato is grown predicts hike in temperature both its intensity and quantity above normal temperature in the next decades (Bell *et al.,* 2000). Any rise in temperature beyond a threshold level for a period of time can cause irreversible damage to plant growth and development and this is called as heat stress. An increase in temperature 10˚–15˚C above normal temperature can result heat stress (Wahid *et al.,* 2007). Heat resistance refers to the capacity of the plant to develop and create economic production even in high temperatures.

The optimum temperature for tomato growth is 25^0C to 30ºC during day time and 20^0C during night (Camejo *et al.*, 2005). Temperature above 34ºC causes heat stress (Ahmed *et al.*, 2013). The temperatures above 26^0C during day and and 20ºC during night causes adverse affects on fruit setting and temperature above 38ºC during day and 27ºC during night completely stops fruit setting ability (Stevens and Rudich, 1978). The impacts of heat stress depend not only on the degree of temperature rise, but also on the duration of the temperature stress or degree days (Mesihovic *et al.,* 2016). An exposure to temperature of 32°C for a few hours is not the same when exposured of the same temperature for several days. The effects of heat stress differ depending upon the developmental stage of a plant at the time of stress condition. Zinn *et al.* (2010) reported that reproductive stage in plant is more sensitive to high temperature than compared to the vegetative growth stage of tomato.

The vegetables are more prone to abiotic stresses and approximately 50% loss in yield is recorded due to various abiotic stresses (Bray *et al.* 2011). Under heat stress, the basic physiological processes, such as photosynthesis, assimilate partitioning, growth and development are affected significantly (Bokszczanin *et al.* 2013). High temperatures during reproductive stage causes significant flower drop in tomato (Hanna and Hernandez, 1982) and further reduces fruit set (Bhandari *et al.,* 2017). The flower, plant reproductive part is adversely affected. The poor fruit set under high temperature in tomato are mainly caused by stigma tube elongation, poor pollen germination, poor pollen tube growth and carbohydrate starvation of pollen.

Mittler (2012), studied how plants behaved to high temperature by altering the cell membrane fluidity (1). The changes in cell membrane fluidity causes activation of calcium channels (2). The intake of calcium into the cell produces a transduction signal causing the reactive oxygen species (ROS) production and the transcription factor activation (3). Among these transcription factors, the heat shock factors (HSFs) are found prominently (Scharf *et al.,* 2012). They induce the production of heat shock proteins (HSPs), which have the key role in the heat shock regulation (HSR) mechanism. HSPs are able to re-organise denaturated proteins that are produced under high temperatures

and also to prevent protein aggregation (Vierling, 1991). Along with the accumulation of HSPs and ROS, specific metabolites are also accumulated under heat stress, such as antioxidants and osmolytes (Wahid *et al.*, 2007) (4). ROS are pivotal messengers of the stress signalling cascade, but they are harmful for the cell, since they are very reactive and can induce lipid peroxidation and membrane oxidation (Driedonks *et al.,* 2015). Hence, the antioxidant production that have ROS scavenging properties are essential to maintain ROS homeostasis.

Heat tolerance is administered by additive and non-additive genes (Solieman *et al.,* 2013; Gabry *et al*., 2014). Heat tolerance is a complex character to understand in genetics (Bhattarai *et al*., 2016). The abiotic stress tolerance can be improved by the detoxification of ROS, in tomato melatonin play an important role in protecting photosynthetic apparatus through detoxifying ROS species (Martinez *et al.*, 2018). In general, tomato production that is resistant to heat is extremely required.

Heat stress tolerance is not an easy character to enhance because of its low heritability and sensitivity to the surrounding environment (Vilareal *et al*., 1978; Hazra *et al.,* 2009). Heat tolerant plants can be developed by the combined accumulation of heat tolerance from the yield attributing traits which are developed by the indirect selection in generations (Bhattarai *et al*., 2016). An ellaborated study of the effects and impact of heat stress is crucial in understanding the impact of climate change and climate variability on crop production.

5.1. EFFECT OF HEAT STRESS ON PHENOLOGICAL AND MORPHOLOGICAL PARAMETERS

Temperature is an important environmental factor that influence crop growth, development and yield. Heat stress effects series of processes including morphology, physiology, growth, development, yield and quality of crop. Heat stress due to high temperatures is a serious problem to crop yield throughout the world (Hall, 2001).

Heat stress has been considered as one of the most harmful factor that causes changes in biochemical, morphology, and physiology aspects of crops that reduces normal plant growth especially in tomato (Thomas and Prasad, 2003; Wahid *et al.,* 2007). When temperature is high, cellule injury and death may happen that cause disturbance in cellular structure (Schoffl *et al.,* 1999).

High temperature influences anatomy of plants at tissue, cellular and sub-cellular levels which cause low crop growth and yield (Wahid *et al.,* 2007). Some causes closure of stomata and loss of water, diminished cell size, enhanced stomatal number and higher number of root and shoot xylem vessels (Anon *et al.,* 2004).

The life cycle of crop are susceptible to high temperatures, fruit set and flowering are highly sensitive stages; fruit set is influenced by temperatures above 20˚/26˚ C day/night in a small rate and is highly influenced above 26˚/35˚C (Baker and Reddy, 2001). Studying changes in phenology of crop resulted by heat stress can give information of the crop and stress atmosphere interaction (Wollenweber *et al.,* 2003; Howarth, 2005). When crop is under stress the intensity of problems faced by plant is different and are depending to their growth stages (Wollenweber *et al.,* 2003).

Flower production is reduced in all the genotypes under high temperature stress condition. Floral characters were strongly associated with fruit characters and yield. Results of experiment clearly indicated that fruit setting ability in the genotypes was reduced in high temperature condition and genotypes responded varyingly showing their respective tolerance or susceptibility to high temperature stress. Failure of pollen release will prevent fruit set inspite of the pollen viability (Singh *et al.,* 2015).

Phenological development control the plant growth and productivity (Awal and Ikeda, 2003a). Days to flowering, fruiting and maturity of crop are the important phenological factors which determine the productivity of a crop. Temperature plays a major role in phenological development and productivity of crop plants. High temperature influences crops to mature early but under high CO2 concentration duration of crop are extended.

Polyhouse climate influenced the crops to open flower and mature of fruits faster than open field (Nagalakshmi *et al.*, 2001; Cheema *et al.*, 2004; Kang and Sidhu, 2005) due to the increment in required heat unit of the crops (Awal and Ikeda, 2003b) grown inside the polyhouse. It is reported that the development rate in peanut toward emergence, flowering and podding was positively linked with soil temperature (Awal and Ikeda, 2002). Total fruit bearing period was extended under polyhouse. Hence total number of fruit harvests was more in polyhouse than open field (Pandey *et al.*, 2004).

Heat stress before anthesis period shows developmental alterations and diorders in the anthers, epidermis and endothecium, stromium opening and poor pollen formation (Sato *et al.*, 2002). Hazra *et al.* (2007) proved that in tomato, the fruit set failure at high temperatures are due to bud drop, abnormal flower growth, poor pollen formation, poor viability, abortion of ovule and reduced carbohydrate presence. Moreover, it causes photosynthesis inhibition at temperatures above optimum, causing remarkable yield reduction. Intense heat stress (45˚C, 20 min) in tomato leads to programmed cell death (PCD) in terms of DNA fragmentation, cytochrome c release, and activity of special enzymes like caspase (Qu *et al.*, 2009). The reproductive structures in a crop have higher susceptibility to heat stress than compared to vegetative structures (Ruan *et al.*, 2010; Zinn *et al.*, 2010).

Tomato production under high temperature more than the optimum temperature has got adverse effects on plant growth (Zhang *et al.*, 2014) and will decrease productivity. Basic physiological process adversely affected under high temperature are photosynthesis, assimilate partitioning, growth and development (Bokszczanin *et al*., 2013). Under heat stress condition, source and sink activities reduction occur leading to severe reductions in growth, economic yield and harvest index. Assimilate partitioning, occur via apoplastic and symplastic pathways, under high temperature has significant effects on transport and transfer processes in plants (Taiz *et al.*, 2015). Giri *et al.* (2017), studied that in tomato plants temperature above 35^0 C result in reduced shoot dry mass, root dry mass, total dry mass and root:shoot ratio. Tomato production under temperature

greater than the optimum temperature has adverse effect on plant growth (Zhang *et al*., 2014) and will decrease yield (Sato *et al*., 2006).

Nafees *et al.* (2019) conducted an experiment to study influence of temperature on germination of tomato seeds. Germination rate at 40^{o}C was negligible than those at 10^{o}C. To improve the germination under 40^{o}C, seed priming treatment was done and superoxide dismutase (SOD) and protein were estimated. Increased SOD activity is an indicator of the stress tolerance capacity of a plant (Vaktabhai and Kumar, 2017). It is suggested that priming of seed could improve the stress tolerance capacity in tomato. The increase in the protein content in tomato leaf, obtained from primed sets are due to the overall growth of the crop (Vassilevska-Ivanova and Tcekova, 2002). Miller *et al.* (2001) clarified that heat stress higher than 35˚C became a threat for germination of seed, vegetative growth and seedling, flowering stage, fruit set and ripening in tomato.

Positive day and night temperature differences (DIFs) enhances leaf photosynthesis and root dry matter accumulation, root activity and nutrient uptake which promote tomato growth. Negative DIFs negatively affect tomato growth. Root activity and Pmax are correlated with Low Molecular Weight Organic Acids secretion (LMWOA) by tomato roots. Oxalic acid is the main organic acid secreted by tomato roots. Positive DIFs facilitate secretion of oxalic acid, formic acid, malonic acid, lactic acid, acetic acid and propionic acid by tomato roots, whereas negative DIFs facilitate secretion of malic acid, citric acid and propionic acid. Total LMWOA concentrations under positive DIFs are significantly higher than under 0°C DIF in the flowering and fruit setting stages, while negative DIFs significantly decrease total LMWOA concentrations in the mature stage compared with 0°C DIF(Yang *et al.,* 2016).

Tomato crop has HSPs for promoting resistance to heat stress. The resistance resulting from HSPs causes improved physiological parameters including photosynthesis, better use of water and nutrient, and integrity of membrane (Camejo *et al.,* 2005; Ahn and Zimmerman, 2006; Momcilovic and Ristic, 2007). These developments cause tomato growth to be possible under heat stress situation.

Heat-tolerant tomato genotypes are reported to have the ability to fruit set at higher temperatures than sensitive types (AVRDC, 2001). Heat tolerance in tomato was studied by Saeed *et al.* (2007), data indicated that among the genotypes, Cchaus was the best, followed by 2413L with greater tolerance to heat stress showing high membrane thermostability and lowest number of flowers shed producing highest fruit yield during high temperature conditions. Positive association of fruit yield with membrane thermostability but negative with number of flowers shed, stigma tube elongation and antheridial cone splitting.

5.2. EFFECT OF HEAT STRESS ON REPRODUCTIVE CHARACTERS

The reproductive development is more sensitive to high temperatures than the vegetative growth in tomato (Geranova *et al.,* 2016). Prasad *et al.* (2008), reported that heat stress negatively affects fruit set. The male gametophyte is sensitive to high temperatures, and the pistil and the female gametophyte are considered to be more tolerant (Zinn *et al.,* 2010). The vulnerability of anthers is more than the female organs to temperature changes (Peet *et al.,* 1998: Sato *et al.,* 2006). With high day and night temperatures over optimum temperatures, the plant shows symptoms of irregular flower development, reduction in pollen production, pollen viability, fruit drop and ovule abortion all ultimately leading to decreased yield (Somraj *et al*., 2017). Chandola (2016) reported that the effect of temperature induction at seedling stage remains till maturity of plant and reflected in terms of morpho-physiological and biochemical parameters of the plant.

Studies suggest that high temperature affects stigma tube elongation and cone splitting, resulting in poor pollen germination and poor pollen tube growth (Abdul-Baki and Stommel, 1995). Peet *et al.,* (1998) reported that heat stress affects meiosis and pollen germination, ovule development and viability of embryo style and stigmatic conditions, pollen grains number and endosperm development, pre-embryo and fertilized embryo influenced improperly by high temperature in tomato (Foolad, 2005). The changes in tomato anthers, including failure of anther dehiscence and tapetum

development occur under heat stress 7-15 days before anthesis during the stages of pollen development (Sato *et al.,* 2006) and during late pollen development shows irregularities in normal pollen and anther development. High temperature during reproductive development changes the morphology and structure of tomato flowers (Sato *et al.,* 2002; Firon *et al.,* 2006) and show significant flower drop later decreases yield. In tomato, reproductive processes like micro and megasporogenesis, pollen and stigma viability, pollen germination, stigma exertion, anthesis, pollination, pollen tube growth, fertilization, and early embryo development are highly susceptible to heat stress (Srivastava *et al.*, 2012). Failure in these processes decreases self fertilization rate and increases early embryo abortion, leading to lower number of seeds or grains, thus limiting crop yield. The assessment of *in-vitro* pollen germination and tube growth when exposed the pollen to high temperature before germination is a screening tool for plant tolerance to temperature (Abdulbaki *et al*., 1995; Marine *et al*., 2017)

5.3. EFFECTS OF HIGH TEMPERATURE ON PHYSIOLOGICAL PARAMETERS

5.3.1. POLLEN VIABILITY (%)

The pollens are highly sensitive to small changes in the environment, are used to study the plant behaviour under different temperature conditions (Hebbar *et al*., 2018). Pollen viability and pollen germination are physiological parameters sensitive to stress (Patel *et al*., 2014 and Singh *et al*., 2014). Pollen production and viability are susceptible to slight changes in temperature higher than the optimum levels (Thomas and Prasad, 2003). A decrease in pollen production, release, viability, fruit set, and yield in tomato above optimum temperatures (Peet *et al.,* 1998; Sato *et al.,* 2000). Pollen viability, germination percentage decreased in moderate and high temperature environments, pollen germination reduced 13 times when the temperature increased moderately from optimum (Pressman *et al.,* 2002). Singh *et al.* (2005) conducted an experiment to evaluate twenty tomato genotypes for high temperature stress during kharif season in glasshouse condition with 44/23 ^{0}C day/night temperature. Data revealed that there was

significant differences in pollen viability of different genotypes based on heat tolerance capacity. Significant reduction in fruit setting (%), stylar exertion rate (%), pollen viability (%), number of branches plant^{-1}, fruit length and width, number of fruit plant^{-1}and weight indicated the reduced carbohydrate supply and carbohydrate transport pathway at specific development stages, reduced allocation of assimilates under high temperature stress compared with control temperature condition.

The competition occur in the locular fluid of anther for nutrients during high temperature stress, this small difference cause the irregularities in metabolic activities of microspores, which results in dead and fully nonviable pollen within the same anther locule (Carrico *et al.*, 2017). Reduced carbohydrate production in anthers during heat stress causes poor pollen development and viability (Pressman *et al.*, 2002). The genotypes with high pollen viability have high temperature tolerance than the sensitive genotypes under high temperature (Dane *et al*., 1991). The high temperature tolerance in the tomato can be correlated with the pollen viability under high temperature (Firon *et al*., 2006). Xu *et al*. (2017) found that heat tolerant varieties produced flowers with high pollen viability under heat stress condition. Heat stress increases the accumulation of proline in tomato leaf tissues (Kuo *et al*., 1986), leading to the reduction of proline in reproductive tissues and thereby reducing the pollen viability (Abdelmageed *et al*., 2003).

In kharif season, pollen viability and germination rates were less under high temperature in green house condition than in open field conditions (Vollenweider and Günthardt-Goerg, 2006). Due to the decreased starch content and decreased sugar content in pollen grains before anthesis time, pollen viability was severely affected (Pressman *et al*., 2002). The temperature induced changes in the transcriptomic and proteomic profiles gives idea of pollen thermo-tolerance mechanism (Frank *et al.*, 2009). The total number of pollen and the percent viable pollen are two independent pollen quality traits, and the product of both total number of pollen per flower and pollen viability percent provide the degree of thermo tolerance, and there is no correlation between two traits (Marine *et al.*, 2017). The pollen germination and pollen release properties are important for the fruit set ability under high temperature. The pollen germination or pollen release failure can stop

fruit set even if the pollen is viable (Sato *et al.*, 2000). Male gametophytic pollen tolerance of tomato genotypes to high temperature stress are possible using the pollen viability as a screening tool (Muller *et al*., 2016; Marine *et al.*, 2017).

ROS plays a role in the formation of viable pollen, during tapetum degeneration and pollen maturity ROS level in the anther will be at its maximum (Rieu *et al.*, 2017). Heat hastens up-regulation of GST and APX gene in tomato anther and pollen, resulted in increased production of corresponding proteins, those show the thermo-tolerance mechanism (Fragkostefanakis *et al*., 2016). Ethylene play a vital role in pollen thermo-tolerance, pollen from ethylene insensitive tomato mutants show higher sensitivity towards mild heat stress, while external application of ethylene before heat stress reduced the sensitivity and improved the pollen thermo-tolerance (Firon *et al.*, 2012). The identification of tomato genotypes with high pollen viability under high temperature conditions forms a valuable key to study pollen thermo-tolerance mechanisms, but also helps to understand the underlying genetics and to breed for thermo-tolerance. Recently, a QTL study of pollen viability under high temperature has been carried out using a mapping population derived from CLN 1621L (tolerant) and CA4 (sensitive) tomato genotypes (Kardivel, 2010). In this study, QTL LOD scores for pollen viability were low, suggesting a high complexity of this trait, besides genetic factors many other factors may play a role.

Stress before and after the anthesis causes a significant increase in floral abortion and lower seed setting rates in many grain crops. Exposure to high temperature stress during flowering resulted in pollen sterility and loss of seed set in legumes (Ahmed *et al.*, 1992; Salem *et al.*, 2007) and in cereals (Saini *et al.*, 1984; Jagadish *et al.*, 2014). Lower seed set under high temperature stress are caused by poor anther dehiscence, hence low pollen grains germination occur on the stigma, or decreases pollen viability. Short term exposure of high temperature stress can also influence pollen viability, seed set and grain growth (Prasad *et al.*, 2006). Exposure to temperature of >37ºC for a period of 1 h during the flowering stage decreases seed set in rice (Matsui *et al.*, 2000; Jagadish *et al.*, 2010). Exposure to temperature of >33ºC

for 6 h after anthesis decreases pollen viability and thus seed set rate in groundnut (Prasad *et al.,* 2003). High temperature stress during flowering in soybean causes decreased pollen germination by degrading tapetal cells and programmed cell death. In addition to this in sorghum, high temperature stress increases pollen reactive oxygen species production and membrane damage, causing lower pollen germination potential (Prasad and Djanaguiraman, 2011). Prasad *et al.* (2002) reported pollen viability was more sensitive and more than 50 percent reduction in pollen viability was observed in plants grown at 37^0C/27^0C day/night temperature. Giorno *et al*. (2013) reported that in tomato, failure to set fruit are mainly attributed to the sensitivity of developing anthers and pollen grains. In both monocots and dicots, pollen heat sensitivity occurs under various levels of high temperature (Mesihovic *et al.,* 2016). The pollen heat sensitivity occur from pollen meiosis to pollen mitosis I at a great extent (Rieu *et al.,* 2017). Exposure to heat at microspore stage results microspore abortion, reduced number of pollen grains at anthesis and reduced proportion of mature viable pollen grains which are capable to germinate (Mesihovic *et al*., 2016). Paupiere *et al*. (2017) conducted a study in which genotypic differences in total pollen production under heat stress was studied in tomato accessions to high temperature. Each of the 17 genotypes of tomato was analyzed for their pollen quality under a 32°C (day) and 26° (night) conditions. The total number of pollen per flower and the rate of viable pollen were less for those grown under stress.

Plant growth regulators in pollen release

The plant growth regulator, stress hormone abscisic acid (ABA) accumulate in plants during several abiotic stress like heat, cold or drought (Vishwakarma *et al.,* 2017). ABA regulate the osmotic stress signal transduction response and contribute plant stress tolerance through the up-regulation of stress-responsive genes (Fujita *et al.,* 2011) and interaction with the sugar signalling pathway (Dekkers, 2008). Increase in ABA levels in the stamens are correlated with anther abnormalities and sterility (Singh and Sawhney, 1998). Endogenous ABA is a stress-responsive signal induces pollen abortion by interrupting apoplastic sugar transport in the anther, both cold or drought sensitive wheat

and rice anthers accumulate high levels of ABA and high levels of pollen abortion occur due to reduced sucrose transport and sucrose metabolism (De Storme and Geelen, 2014).

5.3.2. CELL MEMBRANE THERMOSTABILITY (%)

Electrolyte leakage measure under heat stress is useful for classifying genotypes based on heat stress tolerance by Blum (1988). An increase in percentage of electrolyte leakage are observed in stress sensitive genotypes indicating increased cell leakage through cell membranes (Chengkun *et al.,* 1996; Karim *et al.,* 1999). The cell membranes under stress maintain the role in respiration and photosynthesis. Heat stress increases the kinetic energy and motion of molecules in membranes, which lose chemical bonds in biological membranes molecules. This causes lipid bilayer proteins denaturation or a increase in fatty acids that are unsaturated (Savchenko *et al.,* 2002). The stability and roles of biological membranes are susceptible to high temperature, as heat stress changes membrane proteins tertiary and quaternary structures. These changes increase the permeability of membranes and enhances loss of electrolytes. The enhanced solute leakage, as a result of diminished cell membrane thermo stability (CMT), has been applied as an indirect estimation of heat-stress resistance in different crop species, involving potato and tomato (Chen and Murata, 2002), soybean (Martineau *et al.,* 1979), cotton (Ashraf *et al.,* 1994), cowpea (Ismail and Hall, 1999), wheat (Blum *et al.,* 2001), sorghum (Marcum, 1998), and barley (Wahid and Shabbir, 2005). Functions of cell membrane was affected by heat stress and electrolyte outflow significantly increased in the sensitive genotypes. Alsadon *et al*. (2015) classified the heat stress tolerance of tomato cultivars into three groups: heat tolerant, moderately heat tolerant and heat sensitive. Saeed *et al.* (2014) carried out an experiment to assess heat tolerance and correlation studies in tomato. Varieties with greater tolerance to heat stress showed high membrane thermostability and lowest number of flowers shed and produced highest fruit yield during hot period. Association of fruit yield was positive with membrane thermostability but negative with number of flowers shed, stigma tube elongation, anthredial cone splitting. High temperature also affects photosynthesis (Larkindale, 2005), changes membrane fluidity and changes the overall balance of metabolic

processes, leading to over-production of reactive oxygen species (ROS) and oxidative stress-induced damage (Song *et al.,* 2005).

5.3.3. TOTAL CHLOROPHYLL CONTENT (mg g^{-1} fresh weight)

The photosynthetic parameters such as chlorophyll a: b proportion, chlorophyll and carotenoids levels reduced under heat stress (Morales *et al.,* 2003; Wahid, 2007). Leaf chlorophyll content decreases significantly in stress (Manabendra and Baruah, 2000). The efficient activity of photosynthetic apparatus is affected by short time exposure to high temperature (Camejo *et al*., 2005), the inactivation is related to the membrane integrity and carotenoid content of the plant (Gerganova *et al*., 2016). Total chlorophyll content decreases at high temperature compared to control temperature conditions, at 35^{o}C the chlorophyll activity decreases and reduces efficiency of excitation energy capture by photosystem II (Lu *et al*., 2008). Loss of chlorophyll content is related with the grain filling ability due to its correlation with the leaf N status, photosynthetic capacity and RUBP carboxylase activity (Seeman *et al*., 1987).

In tomato, delayed senescence is one feature of heat tolerance (Sharma *et al*., 2014). Under heat stress conditions tomato genotypes cannot stay green due to decrease in chlorophyll a, chlorophyll b and carotenoid content and show premature chlorosis and withered leaves (Zhou *et al*., 2015). Reduced antenna pigment under stress condition results in decrease in chlorophyll content (Camejo *et al.,* 2006). Heat injury symptoms according to Tikkanen *et al*. (2010) are related to the maximum quantum efficiency of PSII (Fv/Fm).

5.3.4. PRESENCE OF STYLAR EXERTION

In tomato, flowers with elongated stigma tube had low pollination and thus the yield per plant reduced significantly (Hanna and Hernandez, 1982). Therefore, the genotypes producing flowers with normal stigma tube under high temperature can produce high fruit yield. The stigma and style exertion under high temperature affect fruit setting ability (EL Ahmadi and Stevens, 1979). Under high temperature stigma tube

elongation and antheridial cone splitting occurs in tomato (Peet *et al.,* 1998). More style and stigma elongation in flowers reduced the pollen proximity to stigma in heat sensitive genotypes and reduce self fertilization (Alsamir *et al.,* 2017). The exertion of stigma tube in tomato more than 1mm results in the reduction of fruit yield (Rudich *et al*., 1977). The genotypes producing flowers having no stigma exertion at high temperature are stable and produces high fruit yield (Saeed *et al*., 2007). The male and female gametes viability and degree of style protrusion are the important measure of reproductive success under high temperature (Bhattarai *et al*., 2016). The heritability of style exertion is relatively high (Levy *et al*., 1978). Singh *et al.* (2015) reported that under average day and night temperature of 38.4˚C and 19.7˚C respectively in tomato flower drop is highly associated with stylar exertion rate.

5.3.5. PHOTOSYNTHETIC RATE

Photosynthesis is an important growth factor which is highly sensitive to heat stress (Allakhverdiev *et al.,* 2008) and its assimilation rate decreases with every single degree rise of temperature after 30^0C where its rate is at its peak (Salvuccci and Crafts-Brandner, 2004). The photosynthetic rate and respiratory rate declines with hike in temperature and the photosynthetic rate declines faster than respiratory rate (Taiz and Zeiger, 2015). Plants differ with respect to their heat tolerance and in the threshold temperatures which they can survive and in all plants net photosynthetic rate decreased significantly when exposed to temperature greater than 38^OC. The biochemical reactions of photosynthesis are affected which included irreversibly damaging RuBisCO, oxygen complexes, chloroplast ultrastructure, thylakoid membrane and PSII reaction centres. Any limitation in photosynthesis can reduce plant growth at high temperatures. Evaluation of tomato cultivars under two temperature set up (37/27 °C or 37/22 °C day/night) showed that the tolerant cultivars showed higher photosynthetic rate under heat stress conditions in comparison to the heat sensitive ones (Abdelmageed and Gruda, 2009).

5.3.1. Chloroplast structure:

Exposure of tomato varieties at 30^{o}C for 30 days showed changes in the leaf microstructure and chloroplast ultrastructure. The changes occuring in chloroplast under heat stress are disordering of chloroplast lamella, increased number of plastoglobulus, loss of grana stacking, swelling of grana and altered organization of thylakoids (Yoshioka *et al.,* 2010). Photochemical reactions in thylakoid lamellae and carbon metabolism in the stroma of chloroplast are the important site of injury at high temperatures. Zhou *et al.* (2015) observed swollen chloroplast, decomposed starch grain, destroyed chloroplast ultrastructure, increased plastoglobulus number and grana stalking in heat susceptible genotypes are more destructive under heat stress condition than tolerant genotypes.

5.3.2. Photosynthetic apparatus:

The decline of net photosynthesis rate at high temperature is due to the changes in the structural organisation of photosynthetic apparatus. The changes of the thylakoid membrane under heat stress is directly associated to a decrease of photosystem II activity which is linked to the rate of photosynthesis (Yamamoto *et al.,* 2008). Photosynthetic apparatus is very heat susceptible or sensitive and photosystem II is the most sensitive element of photosynthetic apparatus, and the damage to it is often the dangerous response under heat stress. PSII is highly thermolabile, and its activity is reduced or partially stopped under high temperatures, which may be due to the properties of thylakoid membranes where PSII is located (Bukhov *et al.*, 1999; Guo *et al.*, 2006).

Heat stress results in the dissociation of oxygen evolving complex (OEC), causing an imbalance between the electron flow from OEC toward the acceptor side of PSII in the direction of PSI reaction centre. Heat stress causes dissociation of a manganese (Mn) stabilizing 33-kDa protein at PSII reaction centre complex followed by the release of Mn atoms which impair other parts of the reaction centre like the D1 and/or the D2 proteins. Damaged PSII units and loss of the oxygen evolution capacity resulted to a restricted electron transport (Sonoike, 2011). Hence the electron transport play a prevailing role in limiting photosynthesis at high temperatures.

5.2.3. Chlorophyll content:

Reasons for the reduced chlorophyll content under heat stress is associated to the decrease in chlorophyll content, lipid peroxidation of chloroplast and thylakoid membrane (Camejo *et al*., 2006; Hortensteiner, 2009). Under stress condition the enzyme which form carbon-carbon and carbon-nitrogen bonds in the pyrrole ring of porphobilinogen i.e, 5-aminolevulinic acid dehydratase (porphobilinogen synthase) is inactivated leading to decrease in the chlorophyll content (Taiz and Zeiger, 2015). It is reported that in plants when high temperature is induced a reduction of chlorophyll content was observed (Balouchi, 2010; Reda and Mandoura, 2011) that is related either to impaired chlorophyll synthesis, due to an impaired activity of various enzymes responsible for biosynthesis of chlorophyll (Dutta *et al.,* 2009), and/or to accelerated chlorophyll degradation.

Total chlorophyll content decreases at low as well as high temperature compared to ambient temperature conditions. Exposure to 35^{o}C, the chlorophyll activity decreases significantly due to the influence of temperature on the efficiency of excitation energy capture by photosystem II (Bacci *et al*., 1996). Pushpalatha (2008) observed that the chlorophyll content of plants grown at high temperature condition showed less chlorophyll content than the control ones. Rahbarian *et al.* (2011) observed that under stress condition chlorophyll a, chlorophyll b, total chlorophyll content and carotenoid content of chickpea reduced significantly, though heat tolerant genotypes showed higher values. Loss of chlorophyll content coincides with the grain filling in the crop due to its correlation with the leaf N status, photosynthetic capacity and RUBP carboxylase activity (Guendouz and Maamari, 2012).

In tomato, delayed senescence is one of the traits of heat tolerance (Sharma *et al*., 2014). Under heat stress conditions tomato genotype cannot stay green due to decrease in chlorophyll a, chlorophyll b and carotenoid content and it showed premature chlorosis and withered leaves (Mathur *et al.,* 2011; Zhou *et al*., 2015). Porphyrins, particularly chlorophyll a content reduced with temperature at early stages (Camejo and Torres, 2001). Reduced antenna pigment under stress condition results in decrease in chlorophyll content (Camejo *et al.,* 2006). Heat shock decreases the number of photosynthetic

pigments (Todorov *et al.,* 2003), rubisco binding proteins (RBP), soluble proteins, and large and small subunits (SS) of rubisco in darkness, exhibiting their functions as HSPs and chaperones (Kepova *et al.,* 2005).

5.2.4. Stomatal closure:

Under stress, maintenance of high transpiration rate maintained the leaf temperature status and protects photosystems from heat stress (Ilan *et al.,* 1995). To avoid excess water loss from plant body stomata gets closed. This reduces the CO_2 intake into plant body which thereby reduces photosynthetic rate (Killi *et al.,* 2017). Leaf water status, leaf stomatal conductance and intercellular CO_2 concentration is highly affected at heat stress, the reduction in the intercellular CO_2 concentration due to stomatal closure under heat stress impaired photosynthesis (Rivero *et al.,* 2014; Haworth *et al.,* 2016).

5.3.6. TRANSPIRATION RATE

Plants when exposed to abiotic stresses during any stages of the life cycle have mechanisms to overcome such stresses including the production and accumulation of compatible solutes (Chen and Murata, 2008; Hayat *et al.,* 2012) elevated transpiration rates that promote leaf cooling and more efficient photosynthesis. Stomatal conductance (Acatrinei *et al.,* 2010) can be used to assess transpiration rates and estimate evaporative cooling.

5.3.7. STOMATAL CONDUCTANCE

Stomatal regulation is a protective mechanism for heat tolerance in the heat sensitive group under heat stress in which both stomata and pores are regulated. The ability of plants to cool the leaf surface by increasing transpiration at high temperatures plays an important role in heat tolerance (Camejo *et al.,* 2006; Sharma *et al*., 2014). The leaf temperature decreased more in the heat tolerant genotypes under heat stress, which indicated that the heat tolerant genotypes had better leaf cooling. The ability to maintain high rates of photosynthesis in the tolerant genotypes under heat stress showed a demand for higher stomatal conductance, which resulted in better evaporative cooling as

compared to the heat sensitive group that was affirmed by the lower *in-situ* leaf temperature in the heat tolerant cultivars. Stomatal conductance and net photosynthesis are reduced by high temperature stress due to decreased Rubisco activase enzyme (Crafts-Brander and Salvucci, 2002; Morales *et al.,* 2003). The small temperature hike did not influence the transpiration rate (E) both at peak fruiting and final harvest stages. But, the reductions in stomatal conductance (gs) were observed at both the growth stages. At peak fruiting stage, 1.5°C temperature increase caused 24% reduction and 1.7°C temperature increase at final harvest stage caused 32% reduction in the stomatal conductance (Mamatha *et al.,* 2015).

5.4.8. CHLOROPHYLL FLUORESCENCE

Chloroplasts play a pivotal role in photosynthesis and is the most heat sensitive organelle (Junga *et al.,* 2013). Heat stress decreased photosynthesis through alterations in the photosynthetic apparatus (Ogweno *et al.,* 2008; Abdelmageed and Gruda, 2009). Among the photosynthetic apparatus, photosystem II (PSII) is regarded as the most heat sensitive element (Song *et al.,* 2013). When plants are subjected to heat stress, the damage to PSII is the immediate response and this can reveal the primary effects of heat stress on plants (Mathur *et al.,* 2011). The photochemical efficiency of PSII is measured with chlorophyll a fluorescence as an effective technique to detect damage in PSII (Baker and Rosenqvist, 2004; Baker, 2008).

Chlorophyll fluorescence used as a tool to study the alterations of photosystem I and photosystem II activity (Gerganova *et al*., 2016). The ratio between variable fluorescence (F_v=F_m x F_o) and maximum fluorescence (F_m) or the maximum potential quantum efficiency of PSII (F_v/F_m) provides an estimate of the maximum quantum efficiency of PSII is the best tool to phenotype different tomato genotypes for heat tolerance (Zhou *et al.,* 2015). When plants are subjected to abiotic stresses including heat stress a decrease in F_v/ F_m is observed (Willits and Peet, 2001; MolinaBravo *et al.,* 2011; Sharma *et al.,* 2012). The reason for the stress induced reduction in F_v/F_m is an increase in non-photochemical processes leading to a decrease in F_m and subsequent photo

inactivation of PSII reaction centers, leading to an increase in F_o (Baker, 2008; Murchie and Lawson, 2013). Chlorophyll fluorescence is a physiological parameter that can be used to correlate heat tolerance.

Under abiotic stress condition (heat stress), a decline in chlorophyll fluorescence were observed. Non-photochemical quenching under stress condition leading to decrease in Fm and the following increase in Fo, due to the photo-inactivation of PS II, is the main reason for the decline of Fv/Fm. It was observed that in tomato, Fv/Fm under control condition is higher than Fv/Fm under stress condition (Zhou *et al*., 2015).

5.5. EFFECT OF HEAT STRESS ON QUALITY PARAMETERS

Increasing temperature can alter tomato quality by changing the physical properties (size, colour, etc.) of the fruit also the flavour and nutritional quality. Elicitors are molecules which, at low concentrations, induce plant defence systems by promoting the synthesis of biologically active metabolites. The plant response induced by the application of an elicitor, can affect tolerance to other non-related abiotic or biotic stresses (cross-tolerance). The application of methyl jasmonate (MJ) (100 μM), salicylic acid (SA) (200 μM) treatments enhanced the value of the red/green colour component showing an enhancement of the tomato red colour. The application of certain compounds can be considered an effective tool for increasing tomato fruit yield and quality under high temperature conditions. (Hernández *et al.*, 2015).

Organic metabolite analysis under heat stress showed a significant reduction in citric acid, proline, aminobutyric acid, fructose, malic acid, myo-inositol and sucrose (%). The change in all metabolites was greater in heat tolerant genotypes with the exception of fructose and sucrose where sensitive genotypes produced a higher variation (Alsamir *et al.*, 2017). L-proline was greater in tolerant genotypes under stress. Change in sucrose was lower in the tolerant genotypes than sensitive genotypes (Guo *et al.*, 2018). Organic metabolites like glycine, betaine, proline and mannitol play a role in maintaining membrane integrity and scavenging reactive oxygen species (Wahid *et al.*, 2007; Szabados and Savouré, 2010; Sharma *et al.*, 2019).

Physiological imbalances in stress-protective metabolites, such as carbohydrates, polyamines and proline occur under stress. These solutes are low molecular weight metabolites that are soluble in water and non-toxic at high concentrations. The compatible solutes include polyols, sugars, amino acids, betaines and some other compounds (Rhodes *et al.,* 1993). Proline, glycine betaine and aminobutyric acid are compounds produced in response under high temperature (Chen and Murata, 2011; Slama *et al.*, 2015).

According to Tigist *et al.* (2013), an increase in soluble solid content was found in tomatoes grown at higher temperature compared to tomatoes grown at optimum temperature. The increase in temperature reduced the pH content of the fruits. The rate of lycopene synthesis was completely or partially inhibited at 32^{o}C in fruits and temperatures of 30–35^{0}C drastically reduced the lycopene content, but not that of β-carotene (Dumas *et al.,* 2003).

High temperature increases the soluble solid content in tomatoes (Hernandez *et al.,* 2018). A temperature increase from 26 to 30˚C increases the amount of soluble solids, this is due to carbohydrate biosynthetic enzyme activity (Beckles, 2012). With the increase in temperature, soluble solids was found to be increased but with sink activities and soluble solids decrease with increase in respiration (Gautier *et al.,* 2005). Citric acid and malic acid are main acids found in tomato fruit. Citric acid increased from maturation to end of post harvest life and malic acid decreased from maturation to end of post harvest life (Oms-Oliu *et al.,* 2011). The amount of acid content was found to increase with the increase in temperature during growth in tomato fruit (Weerakkody, 2003). pH is inversely related with acid content. The other organic acids (ascorbic acid, dehydroascorbic acid, citramalic, shikimic, fumaric, isocitric, succinic, lactic, malic, saccharic, gluconic, gulonic andtartaric acids) other than titrable acids also contribute to pH content of the fruit (Oms-Oliu *et al.,* 2011). With the increase in temperature, pH of the fruit content decreases (Weerakkody, 2003).

Varietal difference was found in firmness (Moraru *et al.,* 2004), dry matter (Anza *et al.,* 2006; Moraru *et al.,* 2004), soluble solids (Baldwin *et al.,* 1991; Gómez *et al.,* 2001; Moraru *et al.,* 2004), titrable acidity (Baldwin *et al.,* 1991; Gómez *et al.,* 2001; Moraru *et al.,* 2004) and pH content(Gómez *et al.,* 2001; Moraru *et al.,* 2004).

Shi and Maguer (2000) reported the inhibition of lycopene production at higher temperatures (38°C). Shivashankara *et al*. (2015) observed variations in different tomato genotypes for fruit quality parameters at high temperature. Increase in temperature increased TSS and titrable acidity but decreased total sugars, lycopene, and total carotenoids concentration in five genotypes of tomato (Lokesha *et al.,* 2019). The sugars contribute to the total soluble solids content of tomato fruits (Selahle *et al*., 2014). TSS ranged from 4 to 6 °Brix in tomato fruits. The change in the glucose to fructose ratio and the organic acids content is the main cause for changes in the TSS changes in tomato. For the taste of tomatoes, TSS was reported as a beneficial indicator (Klunklin and Savage, 2017). TSS increased in majority of the genotypes under temperature stress compared to control, which is supported by Shivashankara *et al*. (2015).

Total phenols and total flavonoids content increased with increase in temperature in all the genotypes. However, the genotypes IIHR-2841 and IIHR-2202 showed a significant increase in total phenols content under high temperature stress compared to control (Lokesha *et al.,* 2019). The phenolic substances have a protective role on ascorbic acid content (Toor and Savage, 2006) the presence of phenolics and flavonoids in tomato fruits helped to maintain the vitamin C level. A significant increase in total phenolic acids and flavonoids under high temperature were reported in strawberry (Wang and Zheng, 2001) and also in other crops (Toor *et al.,* 2006; Wang, 2006).

Lycopene constitutes 80-90 per cent of the total carotenoids in tomato fruits (Sharma *et al*., 1996). Lycopene can exist as different conformational isomers, but the predominant form is found in tomato fruits in all-trans-lycopene forms (around 95%). The lycopene content in tomato fruits differ with stages of maturity, different cultivar and temperature under development. When tomatoes ripened, carotenoids and lycopene

content increased within the plastids (Valverde *et al.*, 2002). All the tomato genotypes recorded higher carotenoids and lycopene content in control conditions, however susceptible genotypes produced lesser amounts compared to tolerant genotypes both under control and stress conditions (Lokesha *et al.*, 2019). Firmness get enhanced under certain temperature range (27/14˚C) and further increase in difference between day and night (30/11˚C) resulted in reduction in firmness value (Khanal, 2012). The polysaccharides and cell wall enzymes have significant role in firmness, under certain temperature the activity of polysaccharides and cell wall enzymes are activated positively. After attaining optimal temperature further increase in temperature results in deactivation of enzymes (galactosyl and arabinosyl), and accumulation of polyuronides (Mitcham & McDonald, 1992). Decrease in tomato firmness is due to changes in cell wall number, cell turgor properties and cell wall composition (Woolf *et al.* 1999).

5.6. HORMONAL INTERACTIONS UNDER STRESS CONDITION

Hormones play an important role in the physiological and developmental processes during a plant's life cycle (Takei *et al.*, 2004). Plant endogenous hormones adapt to the environment by means of dynamic change (Shelia *et al.*, 2003). Cross-talk in hormone signalling decides organism's ability to integrate different signal and respond appropriately. Hormonal homeostasis, stability, content, biosynthesis and compartmentalization are changing under heat stress (Takatsuka and Umeda, 2014).

Hormones play a role in the regulation of flowering time, leaf senescence, fruit ripening and pollen development. Auxin, gibberellins and abscisic acid has an important role in the development of the tapetum, which is essential for the nourishment metabolites to the pollen. In addition, hormones such as ethylene, jasmonic acid and brassinosterioids also involved in pollen development. Auxin is involved in plant growth, senescence, fruit formation, leaf abscission and apical dominance. Blocking of auxin biosynthesis pathway will leads to severe alterations in floral organ development and a lack of pollen production. Auxin is also involved in the coordination of pollen maturation and anther dehiscence (Marine, 2017). Auxin production reduces under high level of

ABA in the plant at high temperatures (Hazra *et al.,* 2007). Gibberellins (GA) act in hypocotyl elongation, floral transition, fruit patterning and plant defence mechanisms. GA mutation results in defective pollen germination, elongation and pollen development. GA content in plants reduced under temperature conditions (Hazra *et al.,* 2007).

The results showed that GA3 first increased and then decreased with an increase of day and night temperature difference. The same results were found in plant height and leaf area; the reason was that GA3 improve branch elongation and leaf expansion which was confirmed by Khan *et al.* (2006). The IAA and ZT are involved in stem diameter, and the stem diameter had a significant positive correlation with IAA and ZT (GA3 was significantly positive correlated with plant height increment supported by Hu *et al.* (2017) who indicated plant height of *Zea mays* seedlings were positively correlated to GA3. GA3 have a positive effect to promote stem growth by stimulating both cell division and cell elongation (Gupta and Chakrabarty, 2013). Plant height increase was positively correlated to IAA, in accordance with Wu *et al.* (2009), who also suggested that IAA promoted normal stem elongation. Evidence from physiological studies indicates that IAA affects cell expansion during shoot elongation (Yuan and Yang, 2018). ZT was positively correlated with stem diameter increment, in agreement with Xu (2008), who also pointed out higher level of cytokinins was a key factor in controlling stem swelling processes. Similar to plant height increment, leaf area increment, and fruit diameter increment were also significantly positive correlated with all of GA3, IAA and ZT (Yuan and Yang, 2018).

The soluble sugars content of tomato fruit was significantly positively correlated with GA3, IAA and ZT similar to reports of Swarup (2002) and Li *et al.* (2016). Brenner (1995) indicated that exogenous GA3, IAA and ZT increased sugar content of fruit in different fruit development stages. Li *et al.* (2016) indicated that a high content of endogenous ZT favoured sugar accumulation in tubers. The soluble sugars were not significantly correlated with ABA, while Casey *et al.,* 2016 indicated that exogenous ABA increased soluble sugars content of fruit. Similar to soluble sugars, vitamin C and soluble protein were also significantly positive correlated with all of GA3, IAA and ZT

(Yuan and Yang, 2018). The results were provident with O'Neill and Ross (2002) who indicated that IAA increased protein synthesis.

Jasmonic acid plays a role in fruit ripening, seed germination, root growth, resistance to biotic stresses and protein storage and in pollen fertility. A mutation in the biosynthesis of jasmonic acid, defective in anther dehiscence, led to an inhibition of pollen release.

Ethylene regulates growth and developmental processes in plants, including from seed germination to flowering, fruiting and tolerance to environmental stresses. High temperature suppresses ethylene production results in impaired ripening and plays a role in locule opening. Abscisic acid is important in seed development, plant growth and in withstanding environmental stresses (Taiz and Zeiger, 2015). ABA induction is an important component of thermotolerance, as it involved in the induction of several HSPs.

Among other hormones, salicylic acid (SA) is involved in heat-stress responses elicited by plants. SA is a component of signalling pathways in response to systemic acquired resistance (SAR) and the hypersensitive response (HR). SA stabilizes the trimers of heat shock transcription factors and helps them bind heat shock elements to the promoter of heat shock related genes. Long term thermotolerance can be induced by SA.

5.7. EFFECT OF HEAT STRESS ON YIELD PARAMETERS

5.7.1. Yield per plant:

Hot climates throughout crop period can negatively affect the vegetative and reproductive growth phases of crops and can result in up to 70 per cent losses in tomato yield (Sato *et al*., 2002). High temperatures cause significant loss in tomato productivity due to reduced fruit set and poor quality of fruit (Pervez *et al*., 2009; Nahar and Ullah, 2012). The dry weight ratio was found to be less in the fruits grown at higher temperature (32±1 ^{0}C) than in the fruits grown in control temperature (27±1 ^{o}C) (Kang *et al.,* 2002).

Alsamir *et al.* (2017) reported that high temperature in tomato reduced number of fruits, flower to fruit set ratio and fresh fruit weight. The characters less influenced

by temperature were number of flowers per inflorescence and dry weight of plant. Fruit setting percentage under high temperature condition is not depending on how many flowers were produced in the plant (Singh *et al.,* 2015). Pollen release and pollen viability are major limiting factors for fruit set under high-temperature stress (Sato *et al.,* 2000). The major factor of fruit production process in plant is pollen development phase (Dane *et al.,* 1991).

Heat stress effects adversely on roots and nutrient with less recovery percentage in severely stressed plants even after seven days of stress removal. The relative effects of heat stress on plant nutrient content and concentration were correlated with relative effects on root to shoot mass, nutrient uptake rate per g of root, and levels of nutrient-uptake and N-assimilatory proteins (Giri *et al.,* 2017).

5.7.2. Fruit setting %:

Fruit setting percentage is affected by changing temperatures especially during hot summers (Bita and Gerats, 2013). Fruit set can be influenced by the exposure of plants to high day and night temperatures for several days or weeks during reproductive phase (Sato *et al*., 2000). During fruit set temperature above 30^0 C is threat for yielding (Xu *et al*., 2015). The most sensitive phases are flowering and fruit set during heat stress (Bhattarai *et al*., 2016). Reduced flower production, ovule and pollen viability, pollen dehiscence, stigma and stylar exertion (El Ahmadi and Stevens, 1979), diminished photosynthetic and assimilate translocation rate (Dinar and Rudich, 1985) these are some of the factors which reduced fruit set in tomato under high temperature. Fruit setting is limited by pollination where style protrude out of the anther cone (Dane *et al*., 1991). Fruit setting and pollen viability are positively correlated with the number of flower per inflorescence (Xu *et al*., 2017). Heat tolerance level of a genotype can be determined by fruit setting percentage, fruit set ranged from 41% to 84% under optimum conditions (Abdulbaki and Stommel, 1995). Heat tolerant genotypes had high fruit set under controlled condition than high temperature condition, ranged from 45%

to 85%, heat sensitive genotypes show 45% fruit set in optimum condition, while shown no fruit set under high temperature condition (Mohammed and Tarpley, 2010).

Yield is a function of various components that can be broadly divided into the number of plants (germination and emergence), dry matter production (growth, tillers, potential reproductive sites), seed numbers (reproductive processes and seed set), and seed size (product of seed filling rate and seed filling duration). High temperature stress influences yield through seed numbers by influencing pollen or ovule function, which results in lower seed set. High temperature stress directly influences seed fill duration by decreasing the grain fill duration, leading to smaller seed size and lower yields (Prasad *et al.,* 2002, 2003, 2006, 2008). High temperature stress can also decrease biomass production, particularly if the stress is high enough to cause decrease in photosynthesis. High temperatures and low soil moisture can result in poor seedling emergence and early season vigour. Lower fruit yield at higher temperature is due to limited carbohydrate supply (Islam, 2011). Positive correlation was found among the degree of tolerance and fruit set percentage, fruit number and yield (Ibrahim, 2016). A positive correlation between the pollen viability and temperature tolerance were observed by Paupiere *et al.,* 2017 while exposing the flowering plants to high temperature in greenhouse. Tomato has the ability to produce fruits and flowers in this season but the fruit setting percentage is very low (Wani *et al*., 2015). So development of tomato cultivars which are tolerant to heat stress and improved fruit set is highly worthy in the tomato crop production regions where mean daily temperature range is ≥ 35^{o}C during the growing season (Solenkey *et al.,* 2015).

5.7.3. Average fruit weight:

Treatments with salicylic acid and brassinosteroids increased significantly total fruit yield when compared with control plants. No significant effect of the treatments was observed on fruit weight. Pollen quality and quantity depends on the amount of carbohydrate and soluble solid content in pollen. With the increase in temperature (32/26˚C) the amount of starch content in pollen grains was significantly lower than the

control (28/22˚C) pollen grains (anther walls and inner fluid) (Pressman *et al.,* 2002). Surender (2013) reported that average fruit weight and yield per plant significantly decreased at high temperature compared to optimum temperatures.

Heat stress also reduces carbohydrate accumulation in pollen grains and the ATP level of stigmatic tissue (Firon *et al.,* 2006). Reduction in the sink and source strength can lead to reduced fruit set and other yield related parameters in tomato. Reproductive development fails when sugar metabolism and proline transport are disrupted under heat stress (Jain *et al.,* 2007). The exogenous application of organic metabolites can mitigate the effects of heat stress (Wahid *et al.,* 2007).

5.7.4. Intensity of fruit drop and flower drop:

Fruit number and fruit weight were the important yield components, which were severely affected under high temperature stress and ultimately yield was markedly reduced. Regessa *et al.* (2012) recorded observations for days to flowering, number of flowers, number of fruiting clusters, fruit setting rate, number of fruits and yield per plant under a high temperature regime of $40/28^0$C (day/night) during the flowering and fruiting seasons in May and June. The lines Sonali, Hotset, Kewalo, Saladette and NDTVR-60 were considered heat tolerant as they recorded higher fruit setting rate, fruit number and yield per plant under relatively high temperatures. Gaikwad (2009) observed that fruit set in tomato is reduced markedly when average maximum day time and minimum night time temperatures go above 32 and 21^0C, respectively.

Higher temperatures can lead to pre- and post-harvest harms, involving twigs and leaves burning, sunburns on stems and branches, senility of leaf and abscission, the defects in development of shoot and root, fruit discoloration, and decreased fruit weight and yield (Vollenweider and Gunthardt-Goerg, 2006; Kumar and Dudi, 2011). Abdelmageed and Gruda (2009), reported that morphological traits like fruit and flower number per crop, percentage of fruit fresh weight and fruit set were different in heat resistant and heat susceptible tomato genotypes and the results were different in field and glasshouse conditions in tomato.

5.7.5. Plant height:

In a study, the plant height was significantly higher at conditions of 550 ppm CO2 compared with 700ppm and the control plants (Mamatha *et al.,* 2015). It was also concluded that gladiolus plants grown at 700 ppm recorded maximum plant height as compared to plants grown at 900 ppm and the control (400 ppm) conditions (Kadam et al. 2012). This implies that increased CO_2 increases the plant height up to some extent; beyond that the plant height tends to decrease. The CO_2 concentration up to which the plant height increases may differ with crop. The study showed positive influence of CO_2 concentration on the number of branches and leaves. The increased number of branches and increase in the plant height are in agreement with Conroy *et al.* (1990).

5.7.6. Total dry weight per plant:

Tomato seedlings grown at 900 ± 100 ppm of CO_2 recorded higher shoot dry mass, root dry mass as well as total dry mass as compared to seedlings grown at 350 ppm of CO2 (Fierro *et al.*, 1994). Tomato cv. Tiny Tim plants grown at 675 ppm of CO2 showed increased biomass of 37, 53, 39, and 41% in leaf, stem, root, and total vegetative plant biomass, respectively (Reinert *et al.*, 1997). Dry mass increase resulted in increased P_N. The higher P_N at CO_2 contributed to higher biomass production in mung bean (Chowdhury *et al.,* 2005). Increased production of biomass in genotypes was also associated with increased net assimilation rate (Fierro-Cabo *et al.,* 1994) and relative growth rate. (Yelle *et al.,* 1990; Li *et al.,* 2016).

MATERIALS AND METHODS

3. MATERIALS AND METHODS

The objective of the thesis entitled "Effect of high temperature on physiological, biochemical and yield parameters in tomato (*Solanum lycopersicum* L.)" was to study the effect of high temperature on physiology, biochemical, yield and quality parameters in tomato. The research work was conducted at the Department of Plant Physiology, College of Agriculture, Vellayani during the year from 2018-2020. The observations were taken at the respective stages. The high temperature stress was induced from flower initiation to maturity stage by keeping the pots in a temperature controlled green house facility (45 days). Phenological, physiological, biochemical parameters were taken at flowering stage. Physiological and biochemical parameters were taken before induction of temperature stress and at 15^{th} and 25^{th} days after induction of temperature stress. Quality parameters and yield parameters were taken at the harvesting stage.

3.1 EXPERIMENTAL DETAILS

3.1.1. Location

The field experiment was conducted in temperature controlled polyhouse located at farm office, College of Agriculture Vellayani, situated at 8°5' N latitude and 76°9' E longitude and an altitude of 29 m above mean sea level.

3.1.2. Experimental Material

Seeds of 20 different genotypes were collected (released tomato varieties from KAU, IIHR, IARI).

3.1.3. Experimental Details

Seeds of 20 different genotypes were collected (released tomato varieties from KAU, IIHR, IARI). They were sowed in portrays. Irrigation was done regularly and were transplanted to pots after one month of sowing. The observations were taken at respective stages. The high temperature stress was induced from flower initiation to maturity stage by keeping the pots in a temperature controlled green house facility (45 days). Phenological, physiological, biochemical parameters were taken at flowering

stage. Physiological and biochemical parameters were taken before induction of temperature stress and at 15th and 25th days after induction of temperature stress. Quality parameters and yield parameters were taken at harvesting stage.

Location : Instructional farm, College of Agriculture, Vellayani.

Design : CRD

Treatment levels: 2 (control and high temperature)

T1 : Ambient temperature

T2 : 36 +/- 2°C

Genotypes : 20

3.1.4. Planting material:

Sl. No.	Varieties	Released from	Sl. No.	Varieties	Released from
1	Nandi	UAS & AVRDC	12	IIHR-26372	IIHR collections
2	IC-45	IIHR collections	13	Palam Pride	HPAU
3	Pusa Rohini	IARI	14	Arka Abha	IIHR
4	Pusa Ruby	IARI	15	Arka Alok	IIHR
5	IIHR-2200	IIHR collections	16	Manulakshmi	KAU
6	Anagha	KAU	17	Sakthi	KAU
7	Akshaya	KAU	18	Manuprabha	KAU
8	Vellayani Vijay	KAU	19	Arka Samrat	IIHR
9	Arka Vikas	IIHR	20	Arka Sourabh	IIHR
10	Kashi Vishesh	ICAR-IIVR	21	PKM-1	TNAU
11	Vaibhav	UAS & AVRDC	22	Arka Rakshak	IIHR

3.2. Preparation and planting:

Tomato seeds were grown in potting compost (coir pith compost and vermicompost @ 2:1 ratio) and labelling was done properly. Irrigation was provided regularly and were kept in polyhouse with microclimatic temperature controller. The one month old seedlings were transplanted to pots with potting mixture made from soil, sand and cow dung. Six replications were maintained for a single variety as the control in the first stage of experiment. They were grown under control (ambient) environment until the flower initiation stage. The average maximum and minimum temperature for control conditions during this period were 32.1^0C and 24^0C and average maximum and minimum RH were 90.6% and 59.2% respectively. The high temperature stress was induced from flower initiation to maturity stage by keeping the pots in a temperature controlled green house (average maximum temperature during this period was 35.5^oC and average minimum temperature was 26.05^oC and maximum and minimum RH of 93.2% and 65.7% respectively). Nutrient application and pest control measures were given as per the package of practices recommended by Kerala Agricultural University. Phenological, physiological, biochemical parameters were taken at flowering stage before induction of temperature stress. The daily temperatures including maximum and minimum temperatures were recorded under control as well as heat stress conditions using digital thermo-hygrometer throughout the experiment.

20 days after transplanting, a set of 22 genotypes with three replicates were transferred to temperature controlled green house for heat stress induction. Data were recorded on days to first flowering and days to first fruiting for control and stress induced plants. Physiological and biochemical parameters were taken again on 25 days after induction of temperature stress.

3.3. Observations recorded

Phenological, physiological, biochemical parameters were taken at the flowering stage before induction of temperature stress. Data were recorded on days to first flowering and days to first fruiting for control and stress induced plants. Physiological and biochemical parameters were taken again on 15^{th} and 25^{th} days after induction of temperature stress.

Plate 1. Seedlings at germination stage

Plate 2. Seedlings at 20 days after sowing

Plate 3. Overview of tomato plants in control condition

Plate 4. Overview of tomato plants in polyhouse (high temperature condition)

3.4. Parameters Observed

3.4.1. PHENOLOGICAL PARAMETERS

3.4.1.1. Days to first flowering

It was recorded as the number of days taken from the date of sowing to the date when flowering occurred even in a single plant in both treatments.

3.4.1.2. Days to first fruiting

It was recorded as the number of days taken from the date of sowing to the date on which the plants produced at least one fruit.

3.4.2. PHYSIOLOGICAL PARAMETERS

3.4.2.1. Pollen viability (%)

Viability of pollen grains was tested according to the method of staining using IKI (Iodine potassium iodide) proposed by Baker and Baker (1979). In this method, 1 g of potassium iodide and 0.5 g iodine were dissolved in 100 ml distilled water for the IKI solution. Pollen viability counts were made five minutes after pollen was placed on an IKI solution. Pollen grains stained dark (dark red or brown colour) were counted as alive.

3.4.2.2. Leaf membrane thermostability (%)

For the estimation of leaf membrane stability index (MSI), the procedure of Sullivan (1972) was followed. Under stress, the extent of membrane integrity permits a measure of membrane stability to electrolyte leakage. Using punch machine, round leaf discs of 0.75 cm in diameter were made after removing completely expanded uppermost leaves. In two sets of 50 ml glass tubes, 10 leaf discs were taken and washed slowly with de-ionized distilled water by changing it three times to remove surface adhered electrolytes. Then glass tubes were filled up to 10 ml of distilled water in order to submerge the washed leaf discs. Of the two sets, one set of test tube was placed in a water bath at 45°C for 1 hour. Then both the sets were exposed to 22°C temperature in an air conditioned room for an overnight. Very next day, electrical conductivity of each test

tube sample was recorded with the help of LF 538 EC meter after shaking it well. Then kill the leaf tissues, both sets of test tube samples were auto-claved at 121°C temperature for 15 minutes at 15 Ibs pressure, which were allowed overnight to cool down to 22°C temperature. Subsequently, electrical conductivity was recorded for the 2nd time. Under stress, the extent of membrane integrity permits a measure of membrane stability to electrolyte leakage. Relative cell injury percentage (RCI%) as an appraisal of cell membrane thermostability was worked out by using 1st and 2nd electrical conductivity readings and the following formula; CMT% = {1- (T1 / T2)} / {1- (C1 / C2)}] × 100 where T & C indicate electrical conductivity (EC) of heat treated and controlled sets of test tube, and the subscripts 1 & 2 refer to 1st and 2nd EC readings respectively. The cell membrane thermostability and relative high temperature injury were estimated using equations 2 and 3 as follows:

Cell membrane thermostability (%) = [(1- (T1/ T2) / (1- (C1/ C2)] x 100

Relative heat injury (%) = 100 - CMS

Where C, T and CMS refer to the electrical conductivity of control, heat treated samples and cell membrane stability, respectively. The subscript 1 and 2 refer to electrical conductivity readings before and after boiling, respectively. The genotypes were classified according to Kuo, *et al.* (1993) as follows: Heat tolerant (HT): HI < 25%, moderately heat tolerant (MHT): 25% < HI < 50%, slightly heat tolerant (SHT): 50% < HI < 75%, heat sensitive (HS): HI > 75%.

3.4.2.3. Presence of Stigma exertion

Stigma exertion indicates flowers which showed the stigma becoming more elongated than the anthers were observed and the tomato varieties showing stigma exertion were recorded.

3.4.2.4. Total chlorophyll content (mg g^{-1} fresh weight)

Estimation of chlorophyll (DMSO method)

Chlorophyll content of leaf samples was estimated as per the procedure described by Arnon (1949). A weighed quantity of leaf sample (0.5g) was taken from the third fully expanded leaf and it was cut into small bits. These bits were put into test tubes and incubated overnight at room temperature with 10 ml DMSO: 80% acetone mixture (1:1 v/v). The coloured solution was transferred into a measuring cylinder and made up to 25 ml with the DMSO-acetone mixture. The absorbance was measured at 663, 645, 480 and 510nm. The chlorophyll content was measured by substituting the absorbance values in the given formulae.

$$Chla = \left(12.7 \times A_{663} - 2.69 \times A_{645}\right) \times \frac{V}{1000} \times \frac{1}{freshweight}$$

$$Chlb = \left(22.9 \times A_{645} - 4.68 \times A_{663}\right) \times \frac{V}{1000} \times \frac{1}{freshweight}$$

$$TotalChl(a+b) = \left(8.02 \times A_{663} - 20.2 \times A_{645}\right) \times \frac{V}{1000} \times \frac{1}{freshweight}$$

$$Carotenoid = \left(\frac{7.6 \times A_{480} - 1.49 \times A_{510} \times V}{w \times 1000} \right)$$

Where,

A = Absorbance at specific wavelength (645 and 663 nm)

V = Final volume of the chlorophyll extract (ml)

W = Fresh weight of the sample (g)

a = Path length of light (1 cm)

3.4.2.5. Photosynthetic rate (µmol CO_2 m^{-2} sec^{-1})

Photosynthetic rate was measured using portable photosynthetic system (CIRAS-3 SW, PP System International, MA, USA) during day time between 9.00- 10.30 am from the third leaves and were expressed in µmole CO_2 m^{-2} s^{-1}.

3.4.2.6. Transpiration rate (mmol H_2O m^{-2} sec^{-1})

Transpiration rate was measured using portable photosynthetic system (CIRAS-3 SW, PP System International, MA, USA) during day time between 9.00- 10.30 am from the third leaves and were expressed in mmol H_2O m^{-2} $s^{-1.}$

3.4.2.7. Stomatal conductance (mmol H_2O $m^{-2}sec^{-1}$)

Stomatal conductance was measured using portable photosynthetic system (CIRAS-3 SW, PP System International, MA, USA) during day time between 9.00- 10.30 am from the third leaves and were expressed in mmol H_2O m^{-2} $s^{-1.}$

3.4.2.8. Chlorophyll fluorescence (Fv / Fm)

Chlorophyll fluorescence was measured using portable photosynthetic system (CIRAS -3 SW, PP System International, MA, USA). The leaves were covered with black cloth or aluminium foil about 3 hours before the observation taken to provide the dark adaption. The chlorophyll fluorescence was taken 3 hours after covering by clamping the leaf in the space provided in photosynthetic system.

3.4.3. BIOCHEMICAL PARAMETERS

3.4.3.1. Starch content (mg g^{-1} fresh weight)

The estimation of starch in plants was done following the Anthrone method (Hodge and Hofreiter, 1962). A known quantity of plant sample (0.1g) was homogenized in hot 80% ethanol to remove sugars. The homogenate was centrifuged and the residue was retained. The residue was washed repeatedly with hot 80% ethanol till the washing does not give any colour with anthrone reagent. Then the residue was dried well over a water bath. The dried residue was mixed with 5ml water and 6.5 ml 52% perchloric acid and was extracted at 0oC for 20 min. This solution was centrifuged and the supernatant was saved. The extraction was repeated using fresh perchloric acid. The supernatants after centrifugation were pooled and made up to 100 ml.

An aliquot of 0.1 ml of the supernatant was taken and again made up to 1 ml using distilled water. The standard was prepared by taking 0.2, 0.4, 0.6, 0.8 and 1 ml of

the working standard solution and made up the volume to 1 ml in each tube using distilled water. Anthrone reagent (4 ml) was added to both the sample and standard test tubes. These test tubes were heated for eight minutes in a boiling water bath and cooled rapidly. The intensity of colour change from green to dark green was measured at 630 nm. The glucose content in the sample was calculated using the standard curve. This value was multiplied by a factor of 0.9 to arrive at the starch content.

3.4.3.2. Soluble sugar content (mg g^{-1} fresh weight)

The carbohydrate content in plants was estimated by Phenol-sulphuric acid method by (Dubois *et al.*, 1956). Plant sample of weight 0.1 g was homogenized in 80% ethanol to remove the sugars. The homogenate was centrifuged and 0.1 ml of supernatant was taken in a test tubes and made up the volume to 1 ml with water. 1 ml of phenol solution and 5 ml of 96% sulphuric acid was also added to the test tube and shaken well. After 10 minutes the test tubes were kept in a water bath at 25-300 C for 20 min and read the colour at 490 nm in a spectrophotometer.

10 ml of stock (100 mg standard glucose in 100 ml water) diluted to 100 ml with distilled water was taken as the working standard. 0.2, 0.4, 0.6, 0.8 and 1 ml of working standard diluted to 1 ml with water was used as standard.

3.4.4. QUALITY PARAMETERS

3.4.4.1. Lycopene content

The lycopene content in the fruit was quantified by the method explained by Ranganna (1976). Five grams of fruit sample was crushed and extracted repeatedly with acetone until the residue becomes colourless. This acetone extract was transferred to separating funnel containing 15 mL of petroleum ether and mixed gently. To this, 5 mL of 5 per cent sodium sulphate solution in water was added and mixed thoroughly by shaking. This aided in separating out any water present in the separating funnel and helped to form a clear extract. The lower phase (petroleum ether extract containing carotenoid) was transferred to another separating funnel to remove any residual acetone and finally the extract was transferred to the amber coloured bottle. The extraction

procedure with petroleum ether was repeated until the acetone phase becomes colourless. Acetone phase was discarded and a small quantity of anhydrous sodium sulphate was added to the petroleum ether extract. Then petroleum ether extract was transferred to 25 mL volumetric flask and diluted to 25 mL with petroleum ether and from this, 5 mL was again diluted to 25 mL with petroleum ether for colour measurement. Optical density (OD) of the extract was measured at 503 nm in UV-VIS-spectrophotometer (Elico SL-160) using petroleum ether as a blank (Sadasivam and Manikam 1992). Lycopene content of the sample was calculated by using the following formula:

Absorbance (1 unit) = 3.1206µg lycopene/ml

$$\text{Lycopene (mg } 100g^{-1}) = (3.1206 \times \text{O.D. of sample} \times \text{volume made up} \times \text{dilution} \times 100) / (\text{weight of sample} \times 1000)$$

3.4.4.2. Titratable acidity (%)

Titration method was used to estimate titrable acidity (AOAC, 2000). Two milliliter of juice was titrated against 0.1 N sodium hydroxide (NaOH) using six drops of phenolphthalein as an indicator. The appearance of pink colour was taken as an end point of titration. Titratable acidity was expressed in terms of mg anhydrous citric acid in 100 mL of juice and calculated as follows:

$$\text{Titratable acidity} = \text{Volume of NaOH used (mL)} / \text{Volume of juice taken (mL)} \times 0.0064 \times 100$$

3.4.4.3. Total soluble solids (TSS)

The total soluble solids of the selected samples were determined with a digital refractometer (Model: (Model DG-NXT, ARKO India Ltd) at room temperature, 2-3 drops of juice extracted from cut fruit was used and the value was expressed in°Brix units. The refractometer was washed with distilled water each time after use and dried with the help of blotting paper.

3.4.4.4. Estimation of ascorbic acid (vitamin C)

The ascorbic acid content in plants was estimated volumetrically by the method explained by Sadasivam and Manickam (2008). Working standard solution of

5ml containing 100µg/ml of ascorbic acid was pipetted out into a 100 ml conical flask. 4% oxalic acid was added to it and titrated against 2, 6- dichlorophenol indophenol dye (V1 ml). End point was noted on appearance of pink colour which persisted for a few minutes. The sample (0.5g) was weighed and ground in a mortar with pestle using 15ml 4% oxalic acid.

The homogenate was filtered through a double layered cheese cloth. The filtrate was made up to a known volume and centrifuged at 10,000 rpm for 10 min. The supernatant was collected and made up to 25ml using oxalic acid. 5.0 ml aliquot was pipetted into a conical flask to which 10ml of 4% oxalic acid was added. This was titrated against dichlorophenol indophenol (DCPIP) solution until the appearance of pink colour (V2 ml). The amount of ascorbic acid is calculated as follows:

$$Ascorbicacid = \frac{0.5mg}{V_1 ml} \times \frac{V_2}{5ml} \times \frac{100}{weightof\ sample}$$

3.4.5. YIELD PARAMETERS

3.4.5.1. Plant height (cm)

The height of plants was measured from the base of the stem to the tip of the shoot at harvesting stage of control and the high temperature stress plant and the average height was calculated on per plant basis and expressed in cm.

3.4.5.2. Number of fruits per plant

The number of fruits harvested from three replication plants at each picking (harvest) were counted and total number of fruits per plant was calculated.

3.4.5.3. Fruit setting %

Fruit set was also expressed in percentage by counting the total number of flowers as well as total number of fruits per plant.

Fruit setting % = (Total number of fruits / Total number of flowers) x 100

3.4.5.4. Average fruit weight (g)

Average fruit weight was calculated by adding the weight of fruits from each of three replication plants at harvest and divided it by total number of fruits and expressed in grams per fruit.

3.4.5.5. Intensity of fruit drop

Data on the fruit drop were recorded under each treatment from the date of fruit setting till the time of fruit harvesting, at fifteen days intervals. The percentage of fruit drop under each treatment was calculated by taking the average of the data obtained from each replication within a treatment.

3.4.5.3. Intensity of flower drop

Data on the flower drop were recorded under each treatment from the date of first flowering till the time of harvesting, at regular intervals. The percentage of flower drop under each treatment was calculated by taking the average of the data obtained from each replication within a treatment.

3.4.5.6. Total yield per plant

The weight of all the fruits collected per plant was taken and the total yield was calculated at the harvesting stage.

3.4.5.7. Total dry matter per plant (g)

Three replication plants of each genotype were uprooted and then transferred to hot air oven (NSW-142, Caltar) at 80 ^{0}C for 72 hours (until constant weight obtained) and their total dry weight was recorded after harvesting in both control and the treated plants and the mean was expressed as g plant^{-1}.

RESULTS

4. RESULTS

The present study "Effect of high temperature on physiological, biochemical and yield parameters in tomato (*Solanum lycopersicum* L.)." was done in temperature controlled polyhouse facility of farm office, College of Agriculture, Vellayani. The objective of the study was to identify the the effect of high temperature on physiology, biochemical, yield and quality parameters in tomato. The aim of this study also include to evaluate the performance of cultivars under study to heat stress and find the genotype adapted to cultivate under high temperature conditions with desirable characteristics, thereby to identify traits that could be used to improve the high temperature tolerance in tomato. The data obtained during the progression of study were statistically analysed and the results are presented in this chapter.

4.1. EVALUATION OF THE PERFORMANCE OF GENOTYPES UNDER HEAT STRESS TO PHENOLOGICAL PARAMETERS

4.1.1. Days to first flowering

Almost all the tomato genotypes under heat stress showed delayed flowering and fruiting (Table 2 and Fig 1). Plants grown under control conditions showed flowering after 45-55 days after sowing. Vellayani Vijay took minimum number of days for flowering (52-56 DAS) and maximum number of days was taken by Arka Sourabh (70-72 DAS) under control conditions. Early flowering was observed in Kashi Vishesh (72-75 DAS) and delayed flowering in Pusa Rohini (86-91 DAS) under high temperature conditions. Delay in flowering was different among varieties, tolerant genotypes showed minimum delay Kashi Vishesh (10-12 days) than that of control whereas, susceptible genotypes showed maximum delay in flowering, Pusa Rohini (25-30 days) than that of the control plants.

4.1.2. Days to first fruiting

All the tomato genotypes under heat stress showed delayed fruiting (Table 3 and Fig 2). Plants grown under control conditions showed fruiting after 62-75 days after

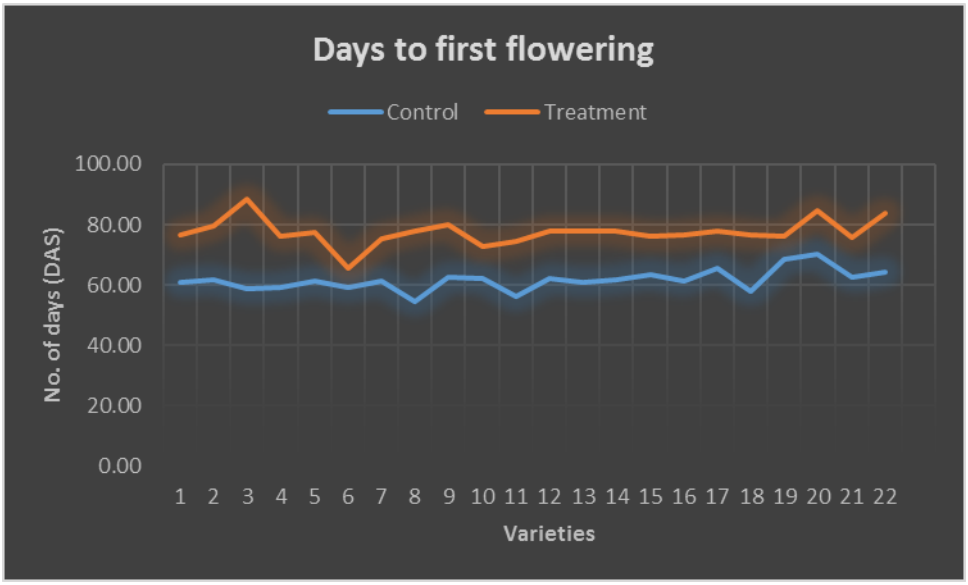


Figure 1. Line graph showing the days taken to first flowering for varieties grown under both control and high temperature conditions expressed in days after sowing (DAS)

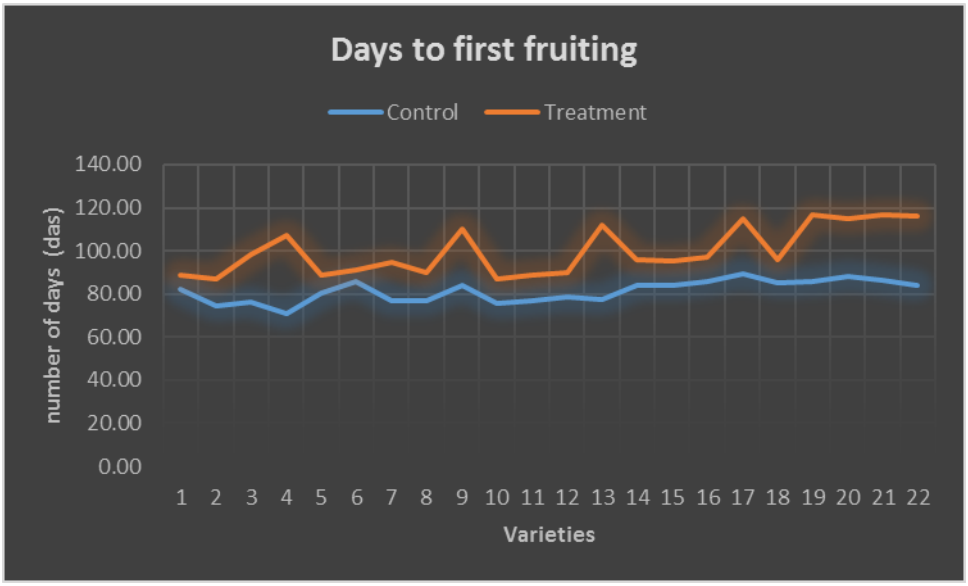


Figure 2. Line graph showing the days taken for first fruiting for varieties grown under control and high temperature stress conditions expressed in days after sowing (DAS)

sowing. Vellayani Vijay took minimum number of days for fruiting (72-80 DAS) and maximum number of days was taken by Pusa Rohini (72-95 DAS) under control conditions. Early fruiting was observed in Kashi Vishesh (87 DAS) and delayed fruiting in Manulakshmi (97 DAS) under high temperature conditions. Delay in fruiting was different among varieties, tolerant genotypes showed minimum delay Kashi Vishesh (8-12 days) than that of control whereas, susceptible genotypes showed non-significant fruiting under stress conditions.

4.2 EVALUATION OF GENOTYPES UNDER HEAT STRESS FOR PHYSIOLOGICAL PARAMETERS

4.2.1. Presence of stigma exertion

The exerted style, stigma is elongated than the anther cone during reproductive stage reduces self-pollination. All genotypes under heat stress conditions showed stigma exertion which resulted in flower burning and finally flower drop resulting in reduced fruit yield. Arka Sourabh showed the highest stigma exertion length (Plate 6). Excessive elongation of the styles in heat sensitive genotypes minimized pollen reach to the stigma and reduced self fertilization and reduces fruit setting rate.

4.2.2. Membrane stability index (MSI)

Membrane stability index is a measure of heat tolerance in plants. Under heat stress condition all tomato varieties showed a reduction in MSI showing the possibility of increased cell leakage. A decrease in the MSI value was observed even for 15 days and 25 days after stress induction when compared to control plants (Fig 3). Nandi (87.63%) showed the highest MSI followed by Vellayani Vijay (76.67%) and minimum MSI recorded for Arka Sourabh (7.62%) followed by PKM-1 (13.53%) when grown under control conditions. Under heat stress conditions, Nandi (51.8%) and Arka Rakshak (25.13%) showed maximum and minimum MSI respectively (Table 4). The mean MSI of tomato varieties was 51.27% and 37.56% under control and heat stress conditions respectively. The percentage reduction in MSI was highest in Pusa Ruby (52%) and lowest in IIHR-2200 (11%).

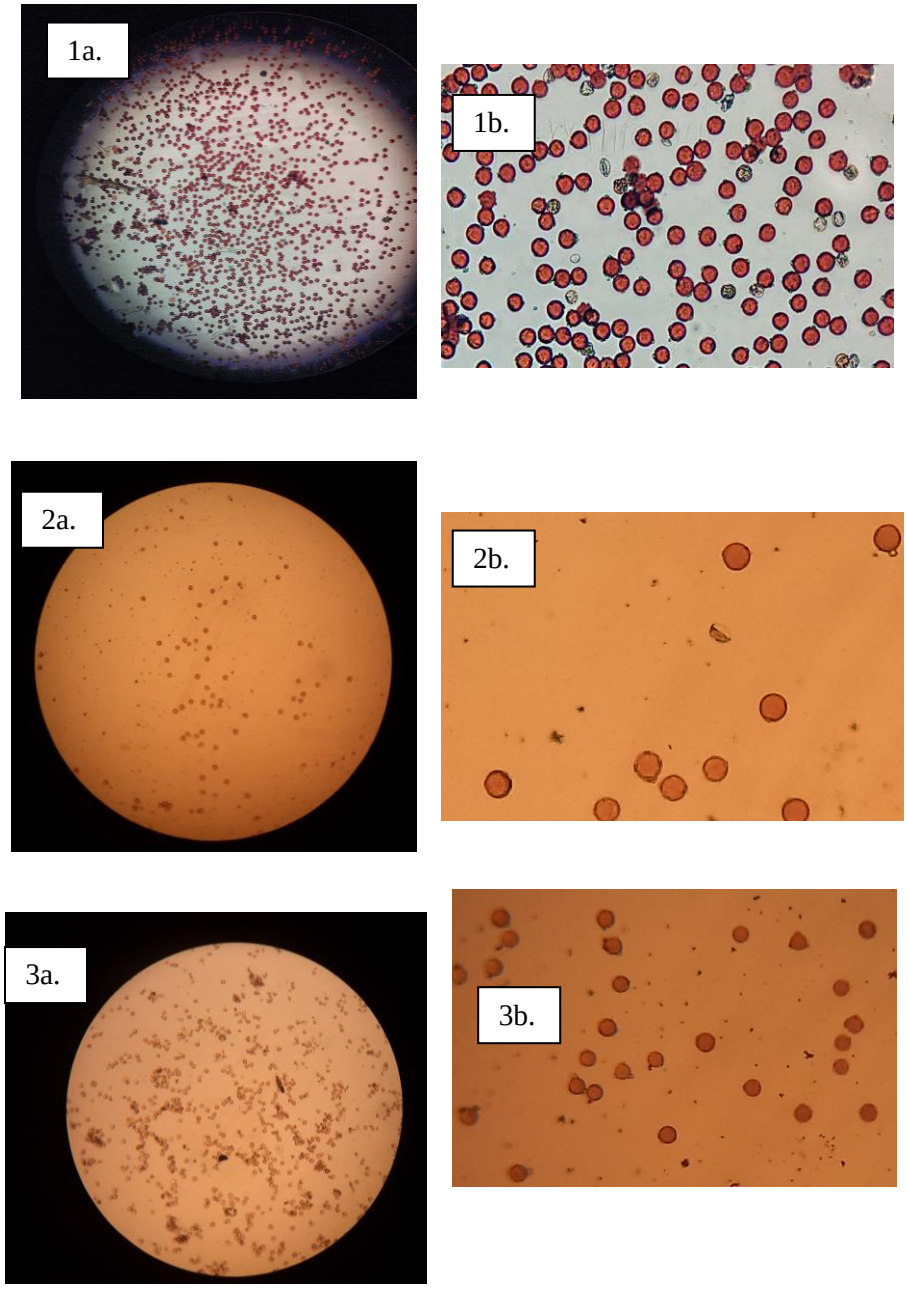


Plate 5. Pollen viability of different tomato genotypes observed under a) microscopic view b) magnified view 40x. Varieties observed 1. Anagha (control) 2. Nandi (high temperature condition) 3. Arka Vikas (high temperature condition)

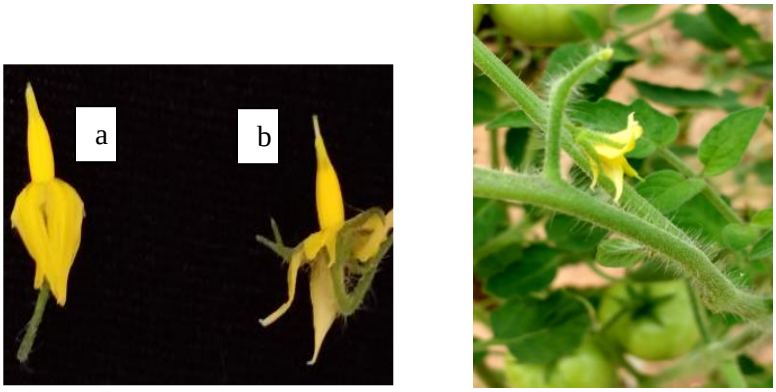
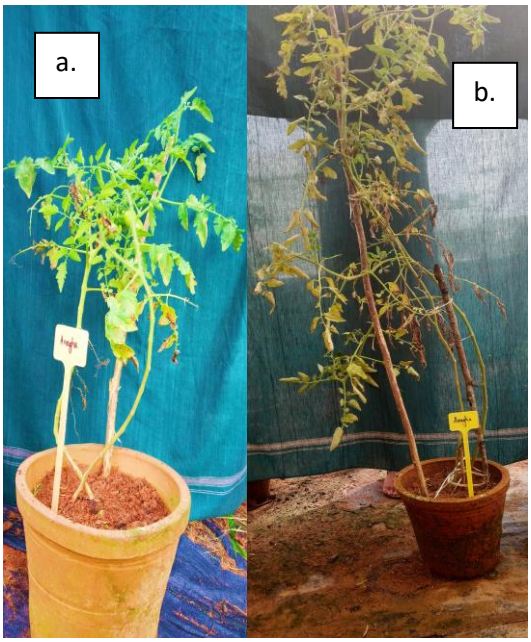
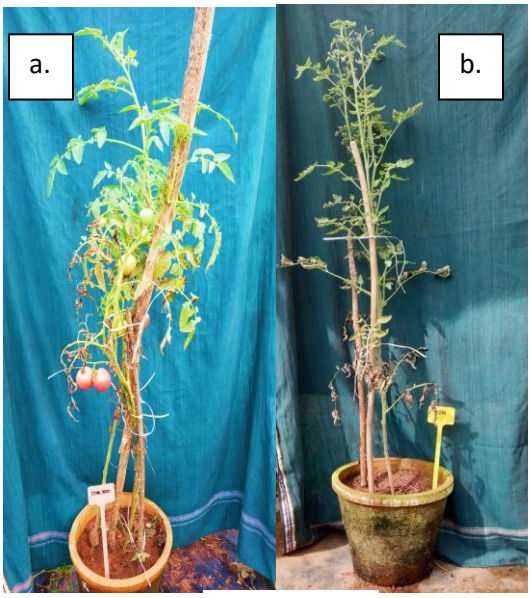


Plate 6. Stigma exertion observed in Arka Sourabh under heat stress a) control b) stress condition.

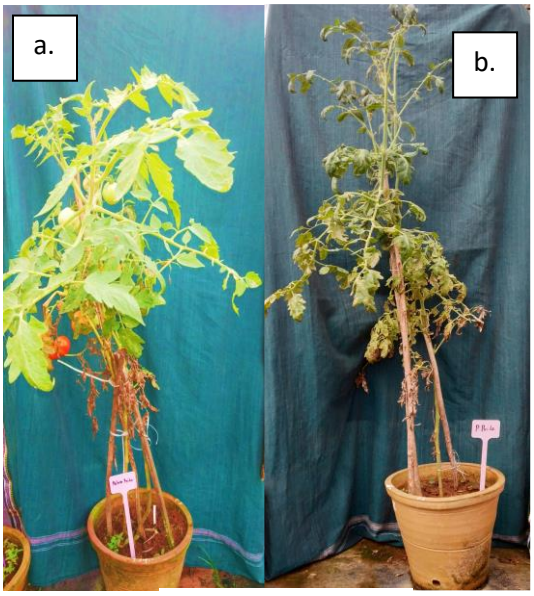
Vaibhav



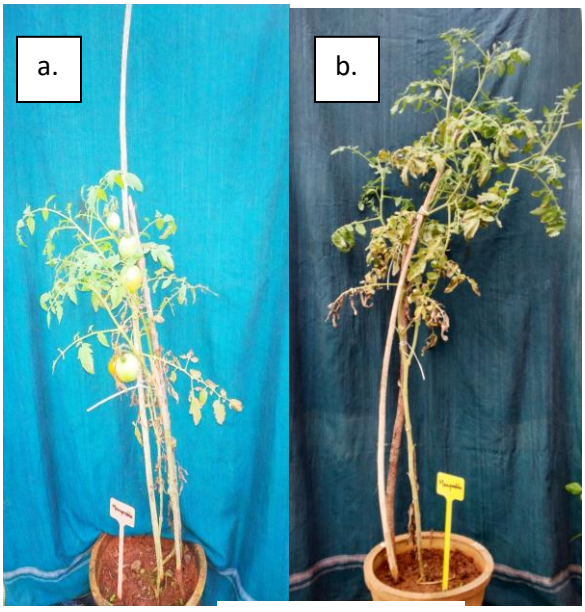
Anagha



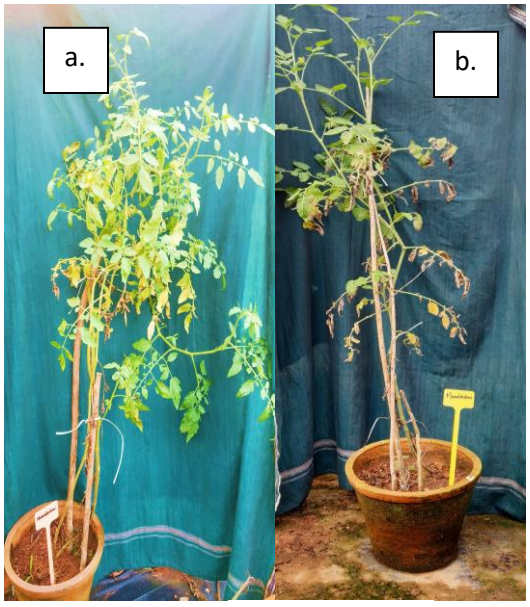
IIHR-2200



Palam Pride



Manuprabha



Manulakshmi

Plate 7. Genotypes at maturity stage a) under control condition b) under high temperature stress

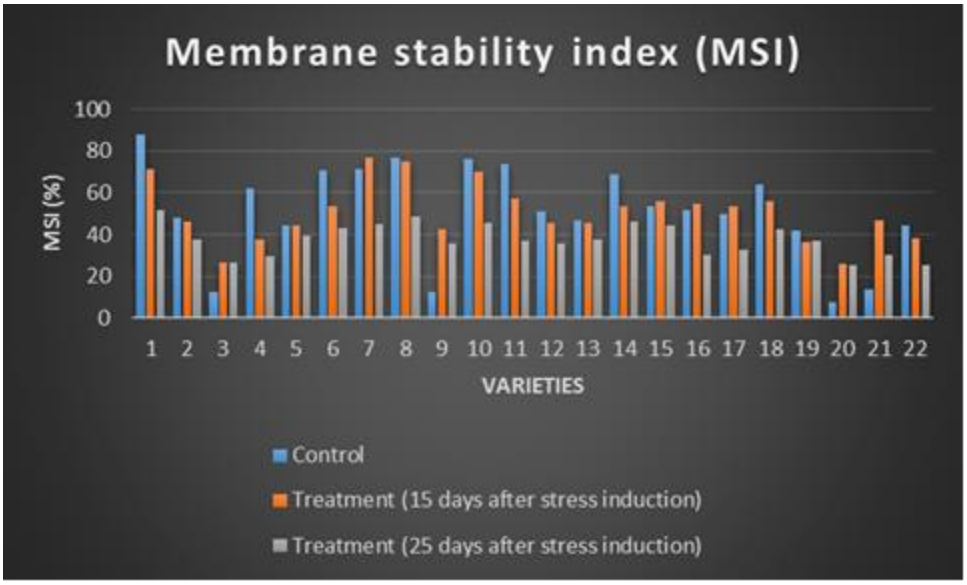


Figure 3. Graph showing MSI of varieties grown under control and high temperature stress conditions (15^{th} and 25^{th} days after heat stress induction) expressed in %.

4.2.3. Pollen viability

Under medium temperature increase, concentration of soluble sugar enhances slightly. Continuous high temperature lowers starch concentration and causes reduction in soluble sugar content in mature pollen grain. This probably is the reason for a reduced pollen viability under heat stress condition. Relatively tolerant genotypes showed significantly lesser decrease in percent pollen viability as compared to relatively susceptible genotypes.

Reduced carbohydrate production and assimilation in the tomato anthers during heat stress results in defective pollen development and viability. Pollen viability is maximum for Anagha (97.45%) which is on par with all varieties except Pusa Rohini (90.08%), Sakthi (92.29%), Arka Sourabh (91.69%), PKM-1 (92.09%) and Arka Rakshak (89.92%) and minimum for Arka Vikas (88.91%) followed by Arka Rakshak (89.92%) under control conditions. But under high temperature conditions pollen viability is reduced significantly for all varieties with maximum viability for Nandi (87.38%) and minimum for Arka Vikas (36.31%) (Table 5). The percentage reduction in pollen viability was maximum for Arka Sourabh (56.68%) and minimum for Nandi (8.03%).

4.2.4. Total chlorophyll content

Reduction in photosynthesis under heat stress is linked to the decrease in chlorophyll content, lipid peroxidation of chloroplast and lipid peroxidation of thylakoid membrane are the main reason for the reduced chlorophyll content. A decrease in the total chlorophyll content value was observed even for 15 days and 25 days after stress induction when compared to control plants. Similar results are obtained in this experiment also. Total chlorophyll content was highest for Arka Alok (2.3 mg g^{-1} fresh weight) followed by Arka Sourabh and minimum for Arka Vikas (1.28 mg g^{-1} fresh weight) under control condition. Under heat stress conditions, Arka Alok (0.71 mg g^{-1}

fresh weight) had highest chlorophyll content and Arka Samrat (0.36 mg g^{-1} fresh weight) had the minimum chlorophyll content (Table 6). The percentage reduction in chlorophyll content was maximum for Anagha (77%) and minimum for Arka Vikas (67%).

4.2.5. Photosynthetic rate

Photosynthetic rate was reduced significantly in all the genotypes under heat stress condition compared to control condition. A decrease in photosynthetic rate was observed for plants after 15 days and further reduction for 25 days after stress induction when compared to control plants. The results related to the photosynthetic rate at flowering stage of tomato varieties are presented in the table 7.

Under heat stress condition, the highest photosynthetic rate was observed in Arka Alok (19.22 µ CO_2 moles m^{-2} s^{-1}), while the lowest was observed in Arka Abha (14.20 µ CO_2 moles m^{-2} s^{-1}). Vellayani Vijay (23.03 µ CO_2 moles m^{-2} s^{-1}) showed a highest photosynthetic rate in control condition whereas the lowest was in Manuprabha (16.93 µ CO_2 moles m^{-2} s^{-1}). The mean photosynthetic rate of tomato varieties was 19.76 µ CO_2 moles m^{-2} s^{-1} and 16.13 µ CO_2 moles m^{-2} s^{-1} under control and heat stress conditions respectively. The percentage reduction in photosynthetic rate was highest in Palam Pride (30%) and minimum for Manulakshmi (9%).

4.2.6. Transpiration rate

A decrease in photosynthetic rate was observed for plants after 15 days and 25 days after stress induction when compared to control plants. Under control conditions, Vaibhav (1.36 mmol H_2O m^{-2} $s^{-1)}$ and Manuprabha (1.36 mmol H_2O m^{-2} $s^{-1)}$ showed highest transpiration rate which is on par with Akshaya (1.33 mmol H_2O m^{-2} $s^{-1)}$ and lowest for Palm Pride (0.49 mmol H_2O m^{-2} sec^{-1}). Vellayani Vijay and Arka Rakshak showed highest and lowest transpiration rates under high temperature stress that is 0.83 mmol H_2O m^{-2} s^{-1} and 0.35 mmol H_2O m^{-2} s^{-1} respectively (Table 8 and Fig 5). The percent reduction in transpiration rate was maximum for Arka Sourabh (67%) and minimum for Kashi Vishesh (12%). The average transpiration rate of tomato genotypes were 0.55 and 0.85 mmol H_2O m^{-2} $s^{-1}$for heat stress and control condition respectively.

4.2.7. Stomatal conductance

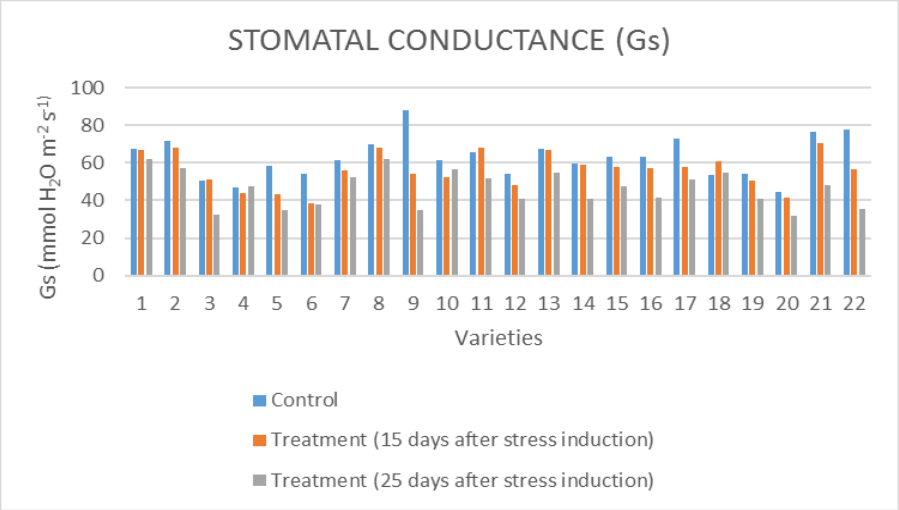


Figure 4. Graph showing stomatal conductance (Gs) of varieties grown under control and high temperature stress conditions (15^{th} and 25^{th} days after heat stress induction) expressed in mmol H_2O m^{-2} s^{-1}.

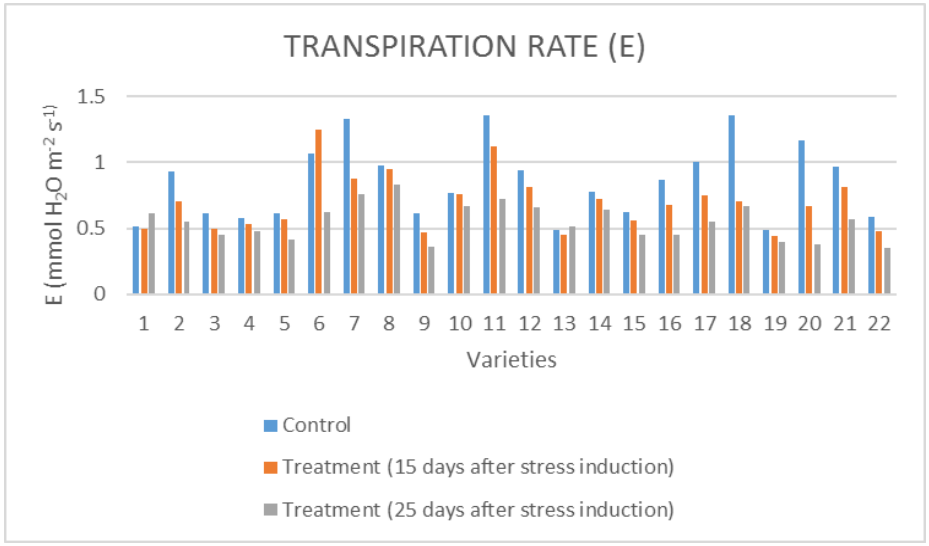


Figure 5. Graph showing transpiration rate (E) of varieties grown under control and high temperature stress conditions (15^{th} and 25^{th} days after heat stress induction) expressed in mmol H_2O m^{-2} s^{-1}.

The results revealed that stomatal conductance decreased significantly in almost all the genotypes under stress condition compared to control condition. Arka Vikas (88.33 mmol H_2O m^{-2} s^{-1}) showed highest and Arka Sourabh (43.33 mmol H_2O m^{-2} s^{-1}) showed lowest stomatal conductance under ambient environment which is on par with Arka Sourabh whereas, Nandi and Vellayani Vijay (62.33 mmol H_2O m^{-2} s^{-1}) had highest which is on par with IC-45. Arka Sourabh (32 mmol H_2O m^{-2} s^{-1}) showed lowest rates of stomatal conductance under heat stress conditions (Table 9 and Fig 4). The mean stomatal conductance of tomato varieties was 62.86 mmol H_2O m^{-2} s^{-1} and 46.30 mmol H_2O m^{-2} s^{-1} under control and heat stress conditions respectively. The percentage reduction in stomatal conductance was highest in Arka Vikas (88%) and minimum for Kashi Vishesh (15%).

4.2.8. Chlorophyll fluorescence

Chlorophyll fluorescence is the ratio of variable fluorescence to maximum fluorescence (Fv/Fm) and the base fluorescence (F_0) are physiological parameters used to correlate heat tolerance. Chlorophyll fluorescence used as a tool to study the alterations of photosystem I and photosystem II activity. Under abiotic stress condition especially heat stress, a decline in chlorophyll fluorescence was observed (Table 10). Non-photochemical quenching occur in stress condition leading to decrease in Fm and the following increase in Fo, due to the photo-inactivation of PS II, is the main reason for the decline of Fv/Fm. It was observed that in tomato, Fv/Fm under control condition was higher than Fv/Fm under stress condition.

Among the genotypes, Nandi (0.75) and Anagha (0.75) recorded the maximum chlorophyll fluorescence which is on par with Akshaya (0.73) under heat stress condition,

while the minimum chlorophyll fluorescence was recorded in Arka Vikas and Arka Sourabh (0.46). In ambient condition, the highest chlorophyll fluorescence was observed in Anagha, Vellayani Vijay, Arka Alok, Manulakshmi and Manuprabha (0.74) which is on par with Nandi and Kashi Vishesh (0.72), while the lowest was observed in Palam Pride (0.62). The percent derease in chlorophyll fluorescence was more in Arka Sourabh (30%) and less in Akshaya (no change). The average chlorophyll fluorescence of the tomato varieties at flowering stage was 0.6 and 0.68 under heat stress and control conditions respectively.

4.3. EVALUATION OF GENOTYPES UNDER HEAT STRESS FOR BIOCHEMICAL PARAMETERS

4.3.1. Starch content

Significant genotypic differences for starch content was observed in tomato under high temperature. Among the genotypes, Vaibhav (312.97 mg g^{-1} fresh weight) recorded the maximum starch accumulation followed by Manulakshmi (304.45 mg g^{-1} fresh weight) under control condition, while the minimum starch content was recorded in Arka Vikas (209.70 mg g^{-1} fresh weight). In heat stress condition, the highest starch content was observed in Anagha (235.67 mg g^{-1} fresh weight), while the lowest was observed in Arka Sourabh (84.37 mg g^{-1} fresh weight). The percent decrease in starch content was more in Arka Sourabh (68%) and less in Anagha (13%). The average starch content of the tomato genotypes at flowering stage was 170.71 mg g^{-1} fresh weight and 262.86 mg g^{-1} fresh weight under heat stress and control conditions respectively (Table 11 and Fig 6).

Relatively tolerant genotypes had lesser per cent decrease in starch content in leaves just before anthesis as compared to heat susceptible types. The high temperature caused a reduction in enzyme activity involved in starch synthesis and impaired assimilate partitioning processes.

4.3.2. Soluble sugars

Significant genotypic differences for soluble sugar content was observed in tomato under high temperature. The probable reason for decreased soluble sugar content in plants could be decreased activity of acid invertase which converts sucrose into glucose and fructose. Maximum soluble sugar concentration was observed in Nandi (77.73 mg g^{-1} fresh weight) and lowest concentration in Arka Rakshak (51.92 mg g^{-1} fresh weight) under control conditions, whereas under stress conditions Vellayani Vijay (59.6 mg g^{-1} fresh weight) showed maximum soluble sugar content and minimum in Arka Rakshak (35.73 mg g^{-1} fresh weight) Table 12

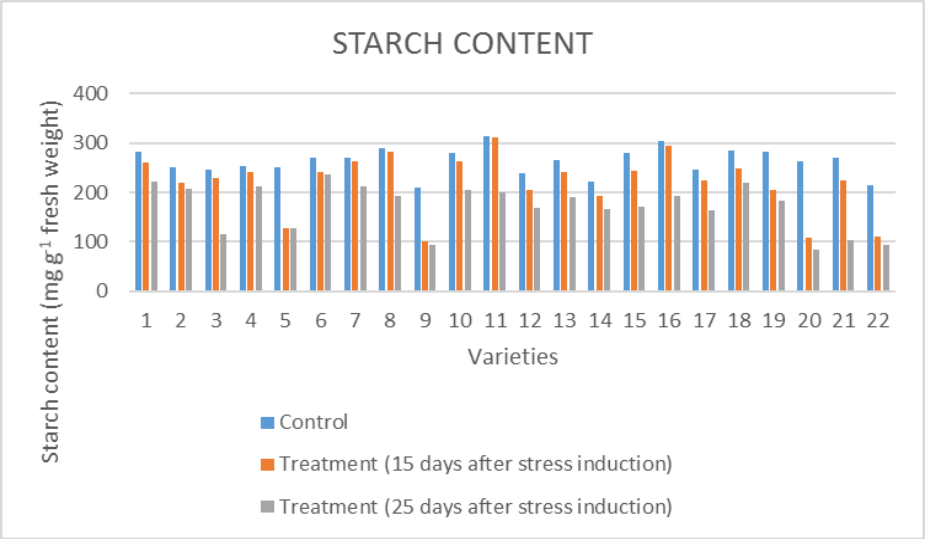


Figure 6. Graph showing starch content in leaves of different varieties grown under control and high temperature stress conditions expressed in mg g^{-1} fresh weight.

The average soluble sugar content of the tomato genotypes at flowering stage was 48.83 mg g^{-1} fresh weight and 61.19 mg g^{-1} fresh weight under heat stress and control conditions respectively. The percent decrease in soluble sugar content was more in Arka Rakshak (31.2%) and less in IIHR-2200 (3%).

4.4. EVALUATION OF GENOTYPES UNDER HEAT STRESS FOR QUALITY PARAMETERS

4.4.1. Lycopene content

The lycopene content decreased with rise in temperature and ambient condition recorded the highest lycopene content in fruits (2.03 mg g^{-1} fresh weight). At polyhouse for susceptible varieties there was no significant fruit set. The highest lycopene content was recorded in IIHR-2200 (5.49 mg g^{-1} fresh weight) followed by Pusa Rohini (3.53 mg g^{-1} fresh weight) and the lowest was observed in Arka Alok (0.36 mg g^{-1} fresh weight) followed by Arka Vikas (0.41 mg g^{-1} fresh weight) under the control conditions whereas, maximum lycopene content was recorded for Nandi (2.94 mg g^{-1} fresh weight) followed by IC-45 (2.75 mg g^{-1} fresh weight) and minimum was recorded for Arka Vikas (0.35 mg g^{-1} fresh weight) followed by Arka Alok (0.37 mg g^{-1} fresh weight) under high temperature conditions (Table 13).

The percent reduction in lycopene content under stress conditions was maximum for IIHR-2200 (52%) followed by Arka Sourabh (21%) and minimum for Kashi Vishesh (3%). The average lycopene content under control condition was 2.03 mg g^{-1} fresh weight and 1.75 mg g^{-1} fresh weight for temperature stress conditions.

4.4.2. Titrable acidity

Titratable acidity of tomato fruits was found to be significantly different with the highest concentration in high temperature conditions when compared to low temperature regimes (control). The susceptible varieties did not fruit significantly under high temperature conditions. The highest titrable acidity was recorded for Kashi Vishesh (0.76%) which is on par with Vaibhav (0.75%) and Nandi (0.71%), minimum was recorded for IC-45 (0.33%) under control conditions and maximum for Kashi Vishesh (0.86%) which is on par with Vaibhav (0.80%) and Nandi (0.81%), and minimum for IC-45 (0.37%) under high temperature conditions (Table 14).

The average titrable acidity under control condition was 0.52% and 0.60% under high temperature conditions. The percent increase in titrable acidity under heat stress was highest for Arka Alok (27%) and minimum for Pusa Rohini (2%).

4.4.3. Total soluble solids

In our study, TSS increased in all the genotypes under temperature stress compared to control (Table 15). Highest TSS was recorded for Arka Samrat (5.72%) followed by Kashi Vishesh (5.42%) and lowest for IC-45 (2.32%) under control ambient condition. But under high temperature conditions highest TSS was recorded for Kashi Vishesh (6.23%) and lowest for IC-45 (2.57%). The percent increase in TSS was highest for IIHR-2200 (53%) and lowest for Arka Vikas (1%) under stress conditions.

4.4.4. Vitamin C content

Vitamin C content showed significant differences among the tolerant genotypes, all tolerant genotypes showed higher vitamin C under temperature stress conditions compared to control (Table 16). Vitamin C content increased when the heat stress was imposed during flowering and fruit set stages, indicating that its plant metabolism adapted to high temperature.

Under high temperature conditions, highest concentration of vitamin C was observed for Nandi (32.71 mg g^{-1} fresh weight) and lowest for Arka Sourabh (9.67 mg g^{-1} fresh weight) whereas, ascorbic acid was found highest in Palam Pride (40 mg g^{-1} fresh weight) and lowest in Arka Samrat (9.39 mg g^{-1} fresh weight) for control conditions. The percent increase in vitamin C content was maximum for IIHR-2200 (30%) and minimum for Pusa Ruby (1%).

4.5. EVALUATION OF GENOTYPES UNDER HEAT STRESS FOR YIELD PARAMETERS

4.5.1. Plant height

Under high temperature stress in polyhouse conditions all the genotypes showed an increment in the plant height because of the shading facility of polyhouse and high temperature conditions (Table 17). Elevated CO_2 (570 µmol mol^{-1}) strongly increased plant height weight per stem (Yang *et al.*, 2009).

Maximum plant height was observed for Nandi (143.97 cm) followed by Arka Vikas (127.57 cm) and minimum height for Vellayani Vijay (51.9 cm) under control

conditions and for high temperature conditions, highest value of plant height was observed for IC-45 (219.33 cm) and lowest for Arka Sourabh (128.33 cm). The average value of plant height under control and temperature stress conditions were 96.79 cm and 162.21 cm respectively. The percent increase in plant height was maximum for Vellayani Vijay (70%) and minimum for Arka Vikas (14%).

4.5.2. Number of fruits / plant

The data pertaining to effect of high temperature on number of fruits per plant in tomato genotypes is depicted in Table 18 for control and heat stress respectively. Number of fruits per plant was significantly decreased at high temperature in all the genotypes as compared to control temperature. Maximum fruits were produced by IC-45 (28) and Vellayani Vijay (26) and minimum by Arka Rakshak (4) and Arka Vikas (5) under control conditions. But under heat stress conditions highest number of fruits are produced by Kashi Vishesh (4) Nandi and IC-45 (3). The maximum percent decrease in number of fruits per plant was recorded in IIHR-2200 (93%) and the least percent decrease was recorded in Arka Abha (80%).

4.5.3. Fruit set %

Fruit set significantly decreased at high temperature in all the tomato genotypes as compared to control temperature (Table 19). Highest fruit set % under control condition was recorded in Vellayani Vijay (53.68%) followed by Kashi Vishesh (48.72%) and lowest in Pusa Rohini (13.56%) whereas, highest fruit set % for high temperature stress conditions was recorded in IC-45 (7.69%) followed by Nandi (5.56%) and lowest for Palam Pride (1.23%). The average fruit set percentage under control and high temperature stress was 33.52% and 2.87% respectively. The percent decrease in fruit set % was maximum for Palam Pride (96.42%) and minimum for Arka Rakshak (86.17%).

4.5.4. Average fruit weight

Average fruit weight was significantly decreased at high temperature in all the tomato genotypes as compared to control temperature (Table 20). The maximum average fruit weight was observed for Arka Vikas (37.23g) and minimum for IC-45 (3.91g) under control conditions whereas, it is maximum for Kashi Vishesh (6.61g) which is on par

with Nandi (6.30g) and minimum for Arka Rakshak, Arka Samrat, Arka Sourabh, PKM-1 (0.12g). The maximum percent decrease under heat stress was recorded for Pusa Rohini, Pusa Ruby, Arka Rakshak, Arka Samrat, Arka Sourabh, PKM-1 (susceptible varieties- > 95%) and minimum for IC-45 (77%) as compared to ambient conditions.

4.5.5. Intensity of fruit drop

Intensity of fruit drop was less under temperature stress conditions as the number of fruits produced were less (Table 21). Intensity of fruit drop was maximum for Arka Vikas (63.8%) and minimum for Manuprabha (no fruit drop) under control conditions whereas, it is highest for Nandi (41%) and minimum for Anagha (7.33%). Only tolerant varieties showed fruiting in a significant levels and susceptible varieties produced small, disfigured minute fruits and fruit drop was minimum for them and flower drop was maximum. The varieties and interaction effect of genotypes and temperature regimes showed non-significant variation but treatments showed significant variation for intensity of fruit drop.

4.5.6. Intensity of flower drop

Flower drop percentage was maximum for PKM-1 (59.79%) followed by Manulashmi (50.64%) and minimum for IIHR-2200 (11.11%) followed by IC-45 (12.68%) under control conditions, whereas it is maximum for Arka Rakshak (99.17%) and minimum for IC-45 (92.31%) (Table 22). The average flower drop % were 38.13% and 97.44% under control and high temperature conditions respectively. The percent increase in flower drop % is highest for IIHR-2200 (88.7%) and lowest for PKM-1 (39.6%). The interaction effect of genotypes and temperature regimes showed non-significant variation for intensity of flower drop.

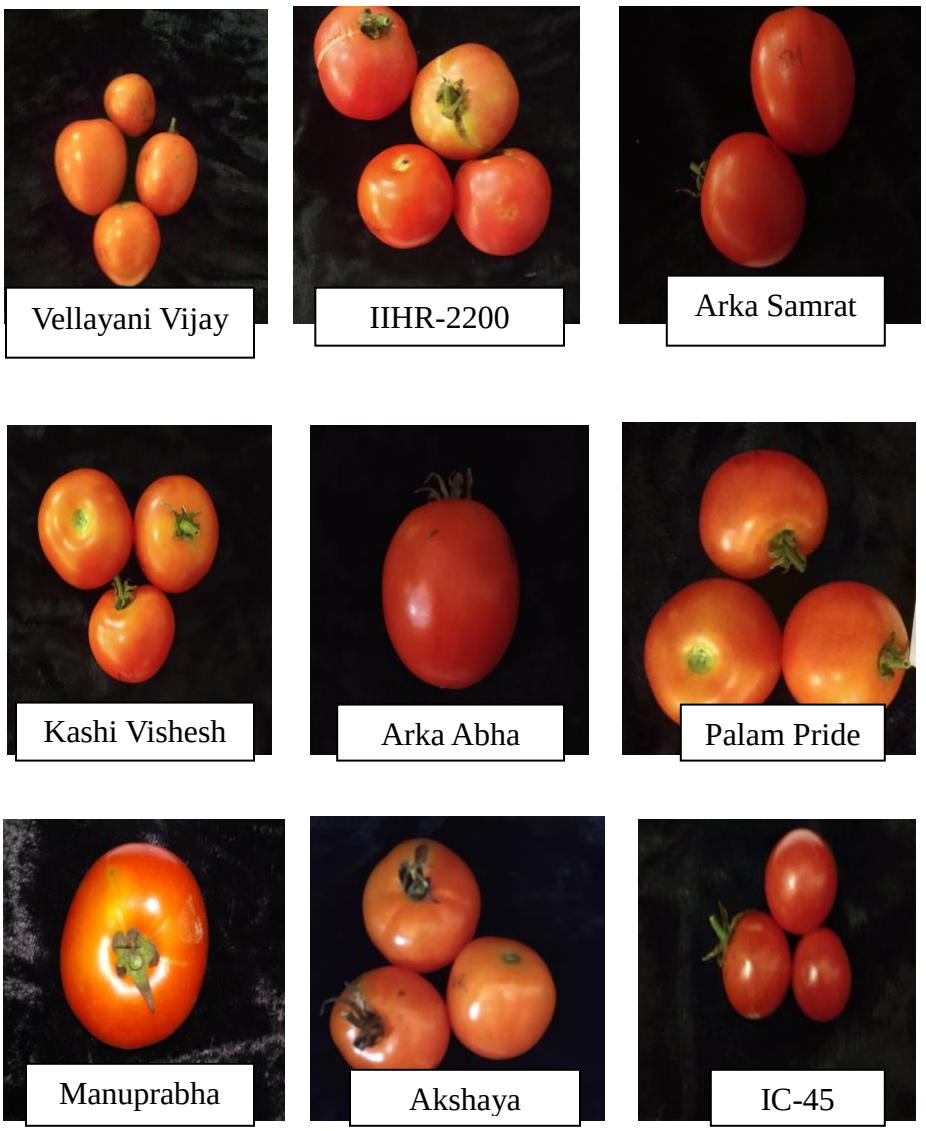


Plate 8. Fruits obtained from different tomato genotypes grown at control condition

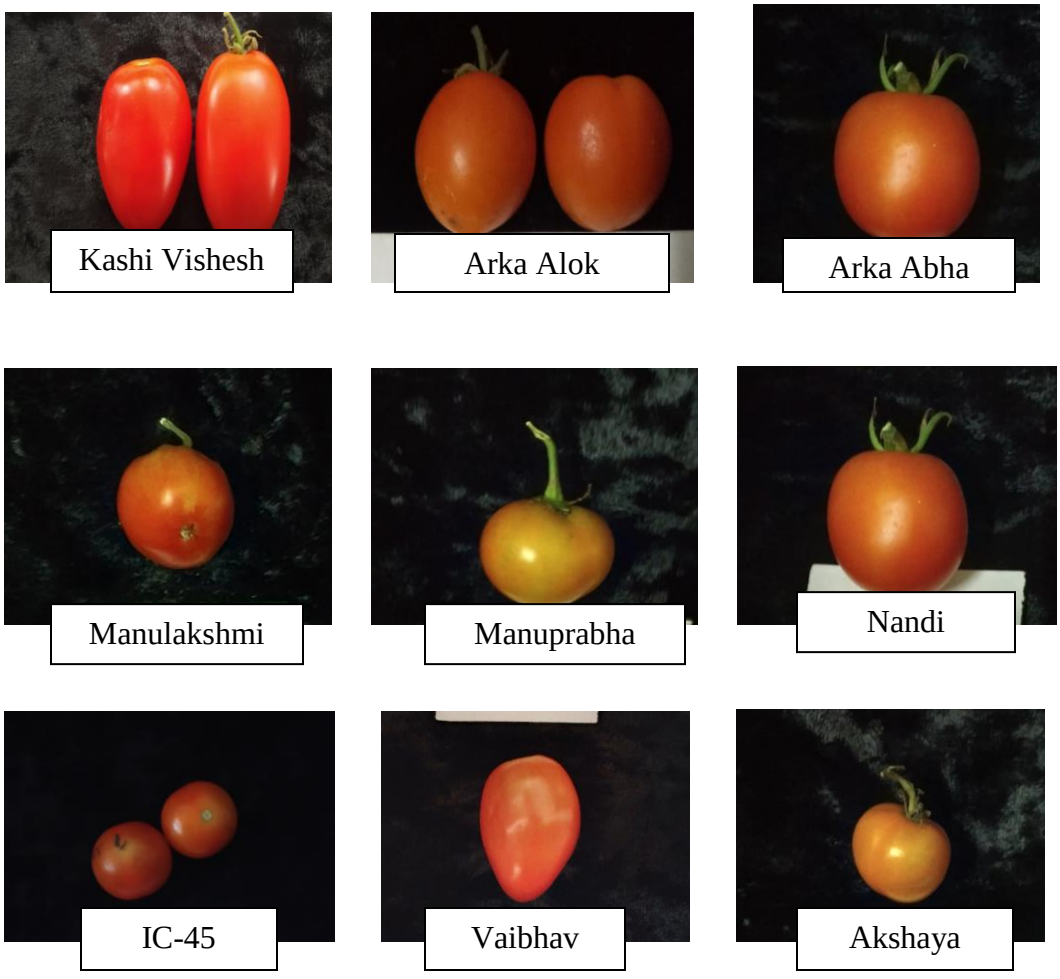


Plate 9. Fruits obtained from different tomato genotypes maintained at high temperature stress condition

4.5.7. Yield per plant

Yield per plant significantly decreased at high temperature in all tomato genotypes as compared to control temperature. Relatively tolerant genotypes had lesser decrease in yield under heat stress conditions as compared to heat susceptible genotypes (Table 23). Nandi (213.12g/plant) gave the maximum yield per plant under control condition whereas, Arka Rakshak (22.41g/plant) provided the minimum yield per plant. Under heat stress conditions only those genotypes that are tolerant as well as moderately tolerant produced higher fruit yield per plant, included Nandi, Anagha, Akshaya, IIHR-2200, Vellayani Vijay, Kashi Vishesh, Arka Abha, Arka Alok, Vaibhav, Manuprabha, Manulakshmi, IC-45 and IIHR-26372. Varieties like Arka Saurabh, Arka Rakshak, PKM-1, Sakthi, Palam Pride, Arka Samrat recorded the maximum percent reduction in yield per plant (99%) and minimum was recorded in Kashi Vishesh (69%).

4.5.8. Total dry weight per plant (g / plant)

The plants grown under heat stress conditions showed an increment in the total dry weight because those plants produced more branches and produced more number of leaves which are less green in colour. The roots development were well developed for the stress induced plants than those grown under control conditions for same varieties.

Total dry weight per plant was highest for Nandi (0.033 g/plant) and lowest was recorded for Arka Sourabh (0.010 g/plant) under control conditions. For heat stress conditions, Anagha (0.234 g/plant) marked highest total dry weight followed by Nandi (0.117 g/plant) and Arka Sourabh (0.037 g/plant) marked the lowest value. The varieties and interaction effect of genotypes and temperature regimes showed non-significant variation but treatments showed significant variation for total dry weight per plant (Table 24).

Table No. 2. Effect of high temperature on days to first flowering in different tomato varieties expressed in days after sowing (DAS).

Sl. No.	Varieties	Control			Treatment		
1	Nandi	62	60	61	76	76	78
2	IC-45	60	63	62	78	80	81
3	Pusa Rohini	58	58	60	86	89	91
4	Pusa Ruby	56	59	63	74	78	76
5	IIHR-2200	60	61	63	78	78	76
6	Anagha	60	58	59	65	67	65
7	Akshaya	58	62	64	72	76	78
8	Vellayani Vijay	55	56	52	76	80	78
9	Arka Vikas	62	61	64	79	78	83
10	Kashi Vishesh	63	65	58	73	75	70
11	Vaibhav	54	57	58	74	76	73
12	IIHR-26372	61	63	62	75	82	77
13	Palam Pride	60	58	65	75	82	77
14	Arka Abha	62	61	62	79	78	77
15	Arka Alok	62	64	64	76	76	76
16	Manulakshmi	60	62	62	72	78	80
17	Sakthi	62	66	68	78	78	78

18	Manuprabha	58	60	56	76	76	78
19	Arka Samrat	68	69	68	80	76	72
20	Arka Sourabh	72	68	70	86	88	80
21	PKM-1	65	60	62	76	75	76
22	Arka Rakshak	60	61	72	86	80	85

Table No. 3. Effect of high temperature on days to first fruiting in different tomato varieties replication wise data expressed in days after sowing (DAS).

Sl. No.	Varieties	Control			Treatment		
1	Nandi	82	80	84	-	89	-
2	IC-45	72	74	78	87	-	-
3	Pusa Rohini	62	72	95	-	98	-
4	Pusa Ruby	73	69	71	107	-	-
5	IIHR-2200	78	82	81	-	-	89
6	Anagha	84	87	87	-	91	-
7	Akshaya	70	78	83	96	-	93
8	Vellayani Vijay	72	78	81	-	90	-
9	Arka Vikas	82	83	87	-	-	110
10	Kashi Vishesh	78	75	74	-	87	-
11	Vaibhav	72	78	81	89	-	-
12	IIHR-26372	84	78	74	90	-	-
13	Palam Pride	78	75	79	-	112	-
14	Arka Abha	84	86	82	96	-	-
15	Arka Alok	82	84	86	95	-	-
16	Manulakshmi	85	88	84	97	-	-
17	Sakthi	85	89	94	-	-	115

18	Manuprabha	83	83	89	-	96	-
19	Arka Samrat	87	83	87	-	-	117
20	Arka Sourabh	90	88	86	115	-	-
21	PKM-1	88	84	87	-	117	-
22	Arka Rakshak	82	83	87	116	-	-

Table No. 4. Effect of high temperature on leaf membrane thermostability of tomato genotypes expressed in percentage.

Sl. No.	Varieties	Control	Treatment (15 days after stress induction)	Treatment (25 days after stress induction)	Mean
1	Nandi	87.63	71.17	51.89	70.23
2	IC-45	48.26	45.92	37.30	43.83
3	Pusa Rohini	12.34	26.43	26.78	21.85
4	Pusa Ruby	62.14	37.60	29.60	43.11
5	IIHR-2200	44.24	44.32	39.33	42.63
6	Anagha	70.84	53.83	42.95	55.88
7	Akshaya	71.31	76.85	44.82	64.33
8	Vellayani Vijay	76.67	75.12	48.77	66.85
9	Arka Vikas	12.32	42.77	35.88	30.32
10	Kashi Vishesh	76.47	70.12	45.86	64.15
11	Vaibhav	73.63	57.48	37.05	56.05
12	IIHR-26372	50.88	45.62	35.77	44.09
13	Palam Pride	46.74	45.79	37.63	43.38
14	Arka Abha	68.90	53.55	46.27	56.24
15	Arka Alok	53.49	56.20	44.44	51.38

16	Manulakshmi	51.44	55.07	30.03	45.51
17	Sakthi	49.84	53.40	32.48	45.24
18	Manuprabha	64.03	56.10	42.23	54.12
19	Arka Samrat	41.67	36.24	37.02	38.31
20	Arka Sourabh	7.62	25.82	25.18	19.54
21	PKM-1	13.53	46.88	30.03	30.15
22	Arka Rakshak	44.12	38.06	25.13	35.77
	Mean	51.28	50.65	37.57	

Factors	**SE(m)**	**C.D. (0.5%)**
Varieties	0.69	1.92
Treatments	0.25	0.71
Factor (V X T)	1.19	3.33

Table No. 5. Effect of high temperature on pollen viability of tomato genotypes expressed in percentage.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	95.01	87.38	91.19
2	IC-45	95.33	79.82	87.57
3	Pusa Rohini	90.08	44.33	67.20
4	Pusa Ruby	94.82	47.77	71.30
5	IIHR-2200	94.17	50.33	72.25
6	Anagha	97.45	50.81	74.13
7	Akshaya	95.81	54.21	75.01
8	Vellayani Vijay	96.25	63.33	79.79
9	Arka Vikas	88.91	36.31	62.61
10	Kashi Vishesh	96.20	52.34	74.27
11	Vaibhav	95.05	64.56	79.80
12	IIHR-26372	94.94	58.56	76.75
13	Palam Pride	95.88	48.48	72.18
14	Arka Abha	94.00	44.72	69.36
15	Arka Alok	95.03	53.76	74.39
16	Manulakshmi	95.43	46.04	70.74
17	Sakthi	92.29	42.63	67.46
18	Manuprabha	97.19	49.39	73.29

19	Arka Samrat	95.66	42.08	68.87
20	Arka Sourabh	91.69	39.72	65.70
21	PKM-1	92.09	49.07	70.58
22	Arka Rakshak	89.92	45.49	67.71
	Mean	94.24	52.32	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	1.46	4.12	
	Treatments	0.44	1.24	
	Factor (V X T)	2.07	5.83	

Table No. 6. Effect of high temperature on total chlorophyll content of tomato genotypes expressed in percentage.

Sl. No.	Varieties	Control	Treatment (15 days after stress induction)	Treatment (25 days after stress induction)	Mean
1	Nandi	2.12	0.60	0.52	1.08
2	IC-45	1.55	0.55	0.47	0.86
3	Pusa Rohini	1.80	0.57	0.52	0.96
4	Pusa Ruby	1.31	0.76	0.38	0.82
5	IIHR-2200	1.85	0.86	0.41	1.04
6	Anagha	1.74	0.58	0.46	0.92
7	Akshaya	2.20	0.71	0.56	1.15
8	Vellayani Vijay	2.20	0.76	0.58	1.18
9	Arka Vikas	1.28	0.52	0.42	0.74
10	Kashi Vishesh	1.86	0.66	0.56	1.03
11	Vaibhav	1.97	0.70	0.60	1.09
12	IIHR-26372	2.12	0.74	0.64	1.16
13	Palam Pride	1.57	0.56	0.47	0.87
14	Arka Abha	1.86	0.64	0.56	1.02
15	Arka Alok	2.30	0.84	0.71	1.28
16	Manulakshmi	1.96	0.79	0.65	1.13

17	Sakthi	1.46	0.50	0.44	0.80
18	Manuprabha	2.01	0.69	0.60	1.10
19	Arka Samrat	1.29	0.75	0.36	0.80
20	Arka Sourabh	2.22	0.82	0.68	1.24
21	PKM-1	2.01	0.71	0.61	1.11
22	Arka Rakshak	2.07	0.81	0.66	1.18
	Mean	1.85	0.69	0.54	

Factors	**SE(m)**	**C.D. (0.5%)**
Varieties	0.05	0.14
Treatments	0.02	0.05
Factor (V X T)	0.09	0.25

Table No. 7. Effect of high temperature on photosynthetic rate of tomato genotypes expressed in µmol CO_2 m^{-2} sec^{-1}.

Sl. No.	Varieties	Control	Treatment (15 days after stress induction)	Treatment (25 days after stress induction)	Mean
1	Nandi	20.31	18.28	17.03	18.54
2	IC-45	18.69	16.57	15.52	16.93
3	Pusa Rohini	18.10	15.80	14.85	16.25
4	Pusa Ruby	19.20	17.12	16.39	17.57
5	IIHR-2200	20.18	18.37	18.13	18.89
6	Anagha	21.12	17.17	17.75	18.68
7	Akshaya	21.83	21.47	17.70	20.34
8	Vellayani Vijay	23.03	22.22	17.97	21.07
9	Arka Vikas	18.79	14.87	14.10	15.92
10	Kashi Vishesh	21.76	18.82	18.63	19.74
11	Vaibhav	20.95	17.96	15.63	18.18
12	IIHR-26372	18.33	15.79	14.37	16.16
13	Palam Pride	21.05	17.18	14.70	17.64
14	Arka Abha	18.23	16.55	14.20	16.33
15	Arka Alok	21.75	19.07	19.22	20.01
16	Manulakshmi	19.23	18.72	17.33	18.43

17	Sakthi	17.70	17.75	15.63	17.03
18	Manuprabha	16.93	17.31	14.43	16.23
19	Arka Samrat	20.81	16.90	17.00	18.24
20	Arka Sourabh	18.29	15.23	14.30	15.94
21	PKM-1	18.73	16.60	15.47	16.93
22	Arka Rakshak	19.75	16.07	14.59	16.80
	Mean	19.76	17.54	16.13	

Factors	**SE(m)**	**C.D. (0.5%)**
Varieties	0.28	0.78
Treatments	0.10	0.29
Factor (V X T)	0.48	1.36

Table No. 8. Effect of high temperature on transpiration rate of tomato genotypes expressed in mmol H_2O CO_2 m^{-2} sec^{-1}.

Sl. No.	Varieties	Control	Treatment (15 days after stress induction)	Treatment (25 days after stress induction)	Mean
1	Nandi	0.51	0.50	0.61	0.54
2	IC-45	0.93	0.70	0.55	0.72
3	Pusa Rohini	0.61	0.50	0.45	0.52
4	Pusa Ruby	0.58	0.53	0.48	0.53
5	IIHR-2200	0.61	0.57	0.41	0.53
6	Anagha	1.07	1.25	0.62	0.98
7	Akshaya	1.33	0.88	0.76	0.99
8	Vellayani Vijay	0.98	0.95	0.83	0.92
9	Arka Vikas	0.61	0.47	0.36	0.48
10	Kashi Vishesh	0.77	0.76	0.67	0.74
11	Vaibhav	1.36	1.12	0.72	1.07
12	IIHR-26372	0.94	0.81	0.66	0.80
13	Palam Pride	0.49	0.45	0.51	0.48
14	Arka Abha	0.78	0.72	0.64	0.71
15	Arka Alok	0.62	0.56	0.45	0.54

16	Manulakshmi	0.87	0.68	0.45	0.67
17	Sakthi	1.00	0.75	0.55	0.77
18	Manuprabha	1.36	0.70	0.67	0.91
19	Arka Samrat	0.49	0.44	0.40	0.44
20	Arka Sourabh	1.17	0.67	0.38	0.74
21	PKM-1	0.97	0.81	0.57	0.78
22	Arka Rakshak	0.59	0.48	0.35	0.47
	Mean	0.85	0.70	0.55	

Factors	**SE(m)**	**C.D. (0.5%)**
Varieties	0.05	0.13
Treatments	0.02	0.05
Factor (V X T)	0.08	0.22

Table No. 9. Effect of high temperature on stomatal conductance of tomato genotypes expressed in mmol H_2O CO_2 m^{-2} sec^{-1}.

Sl. No.	Varieties	Control	Treatment (15 days after stress induction)	Treatment (25 days after stress induction)	Mean
1	Nandi	67.67	67.00	62.33	65.67
2	IC-45	71.67	68.00	57.33	65.67
3	Pusa Rohini	50.67	51.00	32.67	44.78
4	Pusa Ruby	47.00	43.67	47.33	46.00
5	IIHR-2200	58.33	43.33	35.00	45.56
6	Anagha	54.00	38.67	37.67	43.44
7	Akshaya	61.67	56.00	52.33	56.67
8	Vellayani Vijay	69.67	68.00	62.33	66.67
9	Arka Vikas	88.33	54.33	35.00	59.22
10	Kashi Vishesh	61.33	52.33	56.33	56.67
11	Vaibhav	65.67	68.00	52.00	61.89
12	IIHR-26372	54.00	48.00	40.67	47.56
13	Palam Pride	67.33	66.67	54.67	62.89
14	Arka Abha	59.67	59.33	41.00	53.33
15	Arka Alok	63.33	57.67	47.67	56.22

16	Manulakshmi	63.33	57.33	41.67	54.11
17	Sakthi	73.00	57.67	51.33	60.67
18	Manuprabha	53.67	61.00	55.00	56.56
19	Arka Samrat	54.00	50.67	40.67	48.44
20	Arka Sourabh	44.33	41.33	32.00	39.22
21	PKM-1	76.33	70.67	48.33	65.11
22	Arka Rakshak	78.00	56.67	35.33	56.67
	Mean	62.86	56.24	46.30	

Factors	**SE(m)**	**C.D. (0.5%)**
Varieties	1.90	5.32
Treatments	0.70	1.96
Factor (V X T)	3.29	9.21

Table No. 10. Effect of high temperature on chlorophyll fluorescence of tomato genotypes.

Sl. No.	Varieties	Control	Treatment (15 days after stress induction)	Treatment (25 days after stress induction)	Mean
1	Nandi	0.72	0.79	0.75	0.75
2	IC-45	0.63	0.56	0.55	0.58
3	Pusa Rohini	0.64	0.68	0.55	0.62
4	Pusa Ruby	0.63	0.66	0.64	0.64
5	IIHR-2200	0.64	0.72	0.66	0.67
6	Anagha	0.74	0.77	0.75	0.75
7	Akshaya	0.73	0.81	0.73	0.76
8	Vellayani Vijay	0.74	0.82	0.72	0.76
9	Arka Vikas	0.62	0.57	0.46	0.55
10	Kashi Vishesh	0.72	0.81	0.65	0.72
11	Vaibhav	0.69	0.69	0.60	0.66
12	IIHR-26372	0.67	0.66	0.54	0.62
13	Palam Pride	0.62	0.66	0.52	0.60
14	Arka Abha	0.71	0.78	0.68	0.73
15	Arka Alok	0.74	0.76	0.60	0.70
16	Manulakshmi	0.74	0.73	0.65	0.71

17	Sakthi	0.63	0.64	0.56	0.61
18	Manuprabha	0.74	0.75	0.61	0.70
19	Arka Samrat	0.66	0.66	0.51	0.61
20	Arka Sourabh	0.66	0.65	0.46	0.59
21	PKM-1	0.63	0.55	0.48	0.55
22	Arka Rakshak	0.64	0.53	0.49	0.55
	Mean	0.68	0.69	0.60	

Factors	**SE(m)**	**C.D. (0.5%)**
Varieties	0.008	0.023
Treatments	0.003	0.009
Factor (V X T)	0.014	0.041

Table No. 11. Effect of high temperature on starch content of tomato genotypes expressed in mg g^{-1} fresh weight.

Sl. No.	Varieties	Control	Treatment (15 days after stress induction)	Treatment (25 days after stress induction)	Mean
1	Nandi	281.33	259.73	222.76	254.60
2	IC-45	250.06	219.39	208.07	225.84
3	Pusa Rohini	245.63	228.06	114.08	195.92
4	Pusa Ruby	252.98	241.69	212.82	235.83
5	IIHR-2200	250.73	127.28	127.44	168.49
6	Anagha	271.17	242.21	235.67	249.68
7	Akshaya	271.11	262.61	211.80	248.51
8	Vellayani Vijay	288.52	283.25	191.91	254.56
9	Arka Vikas	209.70	101.90	92.33	134.65
10	Kashi Vishesh	279.95	263.03	204.87	249.28
11	Vaibhav	312.97	311.36	200.21	274.85
12	IIHR-26372	239.47	205.76	168.27	204.50
13	Palam Pride	264.15	240.46	189.25	231.29
14	Arka Abha	221.26	193.61	165.21	193.36

15	Arka Alok	280.82	243.97	171.93	232.24
16	Manulakshmi	304.45	293.69	191.52	263.22
17	Sakthi	245.40	224.59	162.70	210.90
18	Manuprabha	283.79	247.08	219.24	250.04
19	Arka Samrat	283.12	204.92	183.69	223.91
20	Arka Sourabh	262.54	108.49	84.37	151.80
21	PKM-1	269.61	224.55	103.21	199.12
22	Arka Rakshak	214.06	110.09	94.20	139.45
	Mean	262.86	219.90	170.71	

Factors	**SE(m)**	**C.D. (0.5%)**
Varieties	2.61	7.30
Treatments	0.96	2.70
Factor (V X T)	4.52	12.65

Table No. 12. Effect of high temperature on soluble sugar content of tomato genotypes expressed in mg g^{-1} fresh weight.

Sl. No.	Varieties	Control	Treatment (15 days after stress induction)	Treatment (25 days after stress induction)	Mean
1	Nandi	77.73	57.08	53.65	62.82
2	IC-45	57.52	53.52	41.54	50.86
3	Pusa Rohini	56.03	47.44	41.35	48.27
4	Pusa Ruby	60.65	52.33	49.38	54.12
5	IIHR-2200	57.23	60.20	55.53	57.65
6	Anagha	66.43	57.88	49.74	58.02
7	Akshaya	65.88	62.22	56.82	61.64
8	Vellayani Vijay	67.79	62.73	59.60	63.37
9	Arka Vikas	53.41	50.08	46.41	49.97
10	Kashi Vishesh	65.99	63.44	53.30	60.91
11	Vaibhav	63.67	58.31	51.06	57.68
12	IIHR-26372	54.58	48.24	42.33	48.38
13	Palam Pride	61.80	50.25	42.80	51.62
14	Arka Abha	55.91	55.56	50.07	53.85
15	Arka Alok	57.40	52.92	53.46	54.59
16	Manulakshmi	72.03	66.49	56.81	65.11

17	Sakthi	56.96	52.74	45.80	51.83
18	Manuprabha	71.83	71.59	52.91	65.44
19	Arka Samrat	62.56	53.50	43.98	53.35
20	Arka Sourabh	54.94	52.05	46.30	51.10
21	PKM-1	53.83	45.04	45.61	48.16
22	Arka Rakshak	51.92	45.14	35.73	44.26
	Mean	61.19	55.40	48.83	

Factors	**SE(m)**	**C.D. (0.5%)**
Varieties	0.77	2.16
Treatments	0.29	0.80
Factor (V X T)	1.34	3.74

Table No. 13. Effect of high temperature on lycopene content of tomato genotypes expressed in mg g^{-1} fresh weight.

Sl. No.	**Varieties**	**Control**	**Treatment**	**Mean**

1	Nandi	3.38	2.94	3.16
2	IC-45	2.67	2.75	2.71
3	Pusa Rohini	3.53	3.28	3.40
4	Pusa Ruby	3.19	2.77	2.98
5	IIHR-2200	5.49	2.60	4.04
6	Anagha	0.90	0.94	0.92
7	Akshaya	1.72	1.58	1.65
8	Vellayani Vijay	2.38	2.20	2.29
9	Arka Vikas	0.41	0.35	0.38
10	Kashi Vishesh	1.58	1.53	1.55
11	Vaibhav	0.99	1.11	1.05
12	IIHR-26372	0.68	0.68	0.68
13	Palam Pride	3.46	3.18	3.32
14	Arka Abha	2.72	2.47	2.60
15	Arka Alok	0.36	0.37	0.37
16	Manulakshmi	1.20	1.20	1.20
17	Sakthi	0.72	0.57	0.65
18	Manuprabha	2.30	1.94	2.12
19	Arka Samrat	3.09	2.80	2.95
20	Arka Sourabh	0.90	0.71	0.81

21	PKM-1	1.45	1.20	1.33
22	Arka Rakshak	1.50	1.30	1.40
	Mean	2.03	1.75	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	0.09	0.24	
	Treatments	0.03	0.07	
	Factor (V X T)	0.12	0.34	

Table No. 14. Effect of high temperature on titrable acidity of tomato genotypes expressed in %.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	0.71	0.81	0.76
2	IC-45	0.33	0.37	0.35
3	Pusa Rohini	0.39	0.40	0.39
4	Pusa Ruby	0.43	0.41	0.42
5	IIHR-2200	0.53	0.61	0.57
6	Anagha	0.54	0.64	0.59
7	Akshaya	0.56	0.69	0.63
8	Vellayani Vijay	0.50	0.68	0.59
9	Arka Vikas	0.48	0.52	0.50
10	Kashi Vishesh	0.76	0.86	0.81
11	Vaibhav	0.75	0.80	0.77
12	IIHR-26372	0.54	0.70	0.62
13	Palam Pride	0.64	0.67	0.66
14	Arka Abha	0.60	0.77	0.69
15	Arka Alok	0.39	0.54	0.47
16	Manulakshmi	0.60	0.71	0.66
17	Sakthi	0.44	0.47	0.45
18	Manuprabha	0.52	0.66	0.59

19	Arka Samrat	0.53	0.56	0.55
20	Arka Sourabh	0.37	0.41	0.39
21	PKM-1	0.43	0.48	0.46
22	Arka Rakshak	0.39	0.42	0.41
	Mean	0.52	0.60	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	0.017	0.047	
	Treatments	0.005	0.014	
	Factor (V X T)	0.023	0.066	

Table No. 15. Effect of high temperature on total soluble solids of tomato genotypes expressed in degree brix.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	5.30	5.76	5.53
2	IC-45	2.32	2.57	2.45
3	Pusa Rohini	3.45	3.54	3.50
4	Pusa Ruby	4.17	4.24	4.20
5	IIHR-2200	2.41	5.13	3.77
6	Anagha	3.85	4.77	4.31
7	Akshaya	5.29	5.55	5.42
8	Vellayani Vijay	4.56	5.60	5.08
9	Arka Vikas	4.63	4.68	4.66
10	Kashi Vishesh	5.42	6.23	5.83
11	Vaibhav	4.75	5.57	5.16
12	IIHR-26372	4.31	4.70	4.51
13	Palam Pride	2.58	2.73	2.65
14	Arka Abha	3.69	4.31	4.00
15	Arka Alok	4.68	4.41	4.55
16	Manulakshmi	4.48	5.32	4.90
17	Sakthi	3.35	3.40	3.37
18	Manuprabha	5.17	5.50	5.33

19	Arka Samrat	5.72	5.77	5.74
20	Arka Sourabh	2.61	2.67	2.64
21	PKM-1	3.69	3.80	3.74
22	Arka Rakshak	3.59	3.68	3.63
	Mean	4.09	4.54	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	0.05	0.14	
	Treatments	0.02	0.04	
	Factor (V X T)	0.07	0.20	

Table No. 16. Effect of high temperature on ascorbic acid content of tomato genotypes expressed in mg g^{-1} fresh weight.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	27.43	32.71	30.07
2	IC-45	14.63	16.00	15.32
3	Pusa Rohini	30.87	30.83	30.85
4	Pusa Ruby	27.37	27.70	27.54
5	IIHR-2200	16.51	23.87	20.19
6	Anagha	20.99	24.87	22.93
7	Akshaya	22.63	23.90	23.27
8	Vellayani Vijay	19.86	21.23	20.55
9	Arka Vikas	15.57	16.23	15.90
10	Kashi Vishesh	23.17	26.83	25.00
11	Vaibhav	17.53	19.86	18.70
12	IIHR-26372	25.15	29.95	27.55
13	Palam Pride	40.00	38.20	39.10
14	Arka Abha	13.20	18.79	16.00
15	Arka Alok	16.27	17.77	17.02
16	Manulakshmi	15.30	15.80	15.55
17	Sakthi	13.24	12.63	12.94
18	Manuprabha	26.63	28.68	27.66

19	Arka Samrat	9.39	9.80	9.60
20	Arka Sourabh	9.46	9.67	9.56
21	PKM-1	11.33	11.80	11.57
22	Arka Rakshak	25.68	26.23	25.96
	Mean	20.10	21.97	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	0.46	1.30	
	Treatments	0.14	0.39	
	Factor (V X T)	0.65	1.84	

Table No. 17. Effect of high temperature on plant height of tomato expressed in cm.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	143.97	161.33	152.65
2	IC-45	85.67	219.33	152.50
3	Pusa Rohini	101.70	154.67	128.18
4	Pusa Ruby	104.17	172.67	138.42
5	IIHR-2200	113.00	166.33	139.67
6	Anagha	96.40	146.67	121.53
7	Akshaya	101.83	165.33	133.58
8	Vellayani Vijay	51.90	176.67	114.28
9	Arka Vikas	127.57	148.67	138.12
10	Kashi Vishesh	84.33	147.00	115.67
11	Vaibhav	91.87	167.67	129.77
12	IIHR-26372	109.97	174.67	142.32
13	Palam Pride	101.23	164.00	132.62
14	Arka Abha	93.33	183.00	138.17
15	Arka Alok	68.83	163.67	116.25
16	Manulakshmi	80.33	172.67	126.50
17	Sakthi	90.17	130.33	110.25
18	Manuprabha	106.37	142.67	124.52
19	Arka Samrat	96.93	159.67	128.30

20	Arka Sourabh	73.50	128.33	100.92
21	PKM-1	109.67	174.33	142.00
22	Arka Rakshak	96.77	149.00	122.88
	Mean	96.80	162.21	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	6.75	19.00	
	Treatments	2.04	5.73	
	Factor (V X T)	9.55	26.87	

Table No. 18. Effect of temperature on number of fruits of tomato genotypes under control and high temperature stress conditions.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	8.00	1.00	4.50
2	IC-45	9.33	1.00	5.17
3	Pusa Rohini	2.33	0.33	1.33
4	Pusa Ruby	3.33	0.33	1.83
5	IIHR-2200	5.33	0.33	2.83
6	Anagha	5.33	0.67	3.00
7	Akshaya	5.67	0.67	3.17
8	Vellayani Vijay	8.67	0.67	4.67
9	Arka Vikas	1.67	0.33	1.00
10	Kashi Vishesh	5.33	1.33	3.33
11	Vaibhav	4.67	0.67	2.67
12	IIHR-26372	3.67	0.67	2.17
13	Palam Pride	4.33	0.33	2.33
14	Arka Abha	5.00	1.00	3.00
15	Arka Alok	3.33	1.00	2.17
16	Manulakshmi	4.00	0.67	2.33
17	Sakthi	3.33	0.33	1.83
18	Manuprabha	4.33	0.33	2.33

19	Arka Samrat	4.33	0.33	2.33
20	Arka Sourabh	2.00	0.33	1.17
21	PKM-1	2.33	0.33	1.33
22	Arka Rakshak	1.33	0.33	0.83
	Mean	4.44	0.59	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	0.47	1.32	
	Treatments	0.14	0.40	
	Factor (V X T)	0.66	1.87	

Table No. 19. Effect of high temperature on fruit set percentage of tomato genotypes expressed in %.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	44.55	5.56	25.05
2	IC-45	30.56	7.69	19.13
3	Pusa Rohini	13.56	1.59	7.57
4	Pusa Ruby	32.63	2.38	17.51
5	IIHR-2200	31.79	2.08	16.94
6	Anagha	40.66	4.17	22.42
7	Akshaya	42.81	2.73	22.77
8	Vellayani Vijay	53.68	2.30	27.99
9	Arka Vikas	15.27	1.96	8.61
10	Kashi Vishesh	48.72	5.13	26.92
11	Vaibhav	38.10	2.38	20.24
12	IIHR-26372	31.64	2.90	17.27
13	Palam Pride	34.43	1.23	17.83
14	Arka Abha	36.33	2.86	19.59
15	Arka Alok	35.80	3.03	19.42
16	Manulakshmi	35.82	1.90	18.86
17	Sakthi	29.43	2.22	15.83
18	Manuprabha	35.68	2.15	18.41

19	Arka Samrat	36.70	2.56	19.63
20	Arka Sourabh	26.16	2.56	14.36
21	PKM-1	24.60	2.22	13.41
22	Arka Rakshak	18.54	2.56	10.55
	Mean	33.52	2.87	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	3.18	8.96	
	Treatments	0.96	2.70	
	Factor (V X T)	4.50	12.67	

Table No. 20. Effect of high temperature on average fruit weight content of tomato genotypes expressed in g.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	26.91	6.30	16.61
2	IC-45	3.91	0.96	2.43
3	Pusa Rohini	34.78	0.27	17.53
4	Pusa Ruby	32.41	0.15	16.28
5	IIHR-2200	15.00	1.14	8.07
6	Anagha	19.84	3.46	11.65
7	Akshaya	23.01	1.45	12.23
8	Vellayani Vijay	17.08	3.25	10.16
9	Arka Vikas	37.23	0.14	18.68
10	Kashi Vishesh	17.24	6.61	11.92
11	Vaibhav	23.99	1.49	12.74
12	IIHR-26372	20.86	1.28	11.07
13	Palam Pride	31.11	0.16	15.64
14	Arka Abha	35.18	1.21	18.19
15	Arka Alok	16.04	0.97	8.51
16	Manulakshmi	19.88	1.03	10.46
17	Sakthi	16.18	0.34	8.26
18	Manuprabha	29.66	1.02	15.34

19	Arka Samrat	31.10	0.12	15.61
20	Arka Sourabh	18.14	0.12	9.13
21	PKM-1	14.76	0.12	7.44
22	Arka Rakshak	11.21	0.12	5.66
	Mean	22.52	1.44	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	1.91	5.37	
	Treatments	0.58	1.62	
	Factor (V X T)	2.69	7.59	

Table No. 21. Effect of high temperature on flower drop percentage of tomato genotypes expressed in %.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	17.88	94.44	56.16
2	IC-45	12.68	92.31	52.49
3	Pusa Rohini	41.90	98.41	70.16
4	Pusa Ruby	40.13	98.10	69.12
5	IIHR-2200	11.11	97.92	54.52
6	Anagha	30.97	98.41	64.69
7	Akshaya	29.87	97.27	63.57
8	Vellayani Vijay	28.49	97.70	63.10
9	Arka Vikas	50.29	98.74	74.52
10	Kashi Vishesh	46.10	94.87	70.49
11	Vaibhav	50.29	97.62	73.96
12	IIHR-26372	30.90	97.10	64.00
13	Palam Pride	41.08	98.77	69.92
14	Arka Abha	45.93	97.14	71.54
15	Arka Alok	28.59	96.97	62.78
16	Manulakshmi	50.64	98.10	74.37
17	Sakthi	49.39	99.03	74.21
18	Manuprabha	43.01	95.40	69.21

19	Arka Samrat	52.46	98.47	75.47
20	Arka Sourabh	37.85	98.78	68.32
21	PKM-1	59.79	99.06	79.42
22	Arka Rakshak	39.57	99.17	69.37
	Mean	38.13	97.44	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	5.87	N/A	
	Treatments	1.77	4.98	
	Factor (V X T)	8.30	N/A	

Table No. 22. Effect of high temperature on intensity of fruit drop in tomato genotypes expressed in %.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	1.58	1.53	1.55
2	IC-45	1.18	1.18	1.18
3	Pusa Rohini	1.73	1.00	1.37
4	Pusa Ruby	1.75	1.00	1.38
5	IIHR-2200	1.34	1.00	1.17
6	Anagha	1.38	1.17	1.28
7	Akshaya	1.41	1.26	1.34
8	Vellayani Vijay	1.31	1.35	1.33
9	Arka Vikas	1.86	1.00	1.43
10	Kashi Vishesh	1.42	1.21	1.32
11	Vaibhav	1.29	1.00	1.15
12	IIHR-26372	1.37	1.00	1.19
13	Palam Pride	1.26	1.00	1.13
14	Arka Abha	1.14	1.00	1.07
15	Arka Alok	1.23	1.18	1.21
16	Manulakshmi	1.34	1.00	1.17
17	Sakthi	1.39	1.00	1.20
18	Manuprabha	1.00	1.00	1.00

19	Arka Samrat	1.36	1.00	1.18
20	Arka Sourabh	1.43	1.00	1.21
21	PKM-1	1.47	1.00	1.24
22	Arka Rakshak	1.61	1.00	1.30
	Mean	1.40	1.09	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	0.12	N/A	
	Treatments	0.04	0.10	
	Factor (V X T)	0.16	N/A	

Table No. 23. Effect of high temperature on yield per plant of tomato genotypes expressed in g/ plant.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	213.12	18.90	116.01
2	IC-45	36.31	1.92	19.11
3	Pusa Rohini	80.37	0.80	40.59
4	Pusa Ruby	106.18	0.15	53.16
5	IIHR-2200	81.06	1.14	41.10
6	Anagha	107.35	3.46	55.41
7	Akshaya	132.50	1.45	66.97
8	Vellayani Vijay	133.59	3.25	68.42
9	Arka Vikas	58.36	0.14	29.25
10	Kashi Vishesh	85.50	26.44	55.97
11	Vaibhav	126.12	6.50	66.31
12	IIHR-26372	57.22	1.28	29.25
13	Palam Pride	142.31	0.16	71.24
14	Arka Abha	179.94	3.62	91.78
15	Arka Alok	59.08	2.92	31.00
16	Manulakshmi	80.32	1.03	40.68
17	Sakthi	56.79	0.34	28.57
18	Manuprabha	135.90	1.02	68.46

19	Arka Samrat	135.02	0.12	67.57
20	Arka Sourabh	36.28	0.12	18.20
21	PKM-1	34.39	0.12	17.25
22	Arka Rakshak	22.41	0.12	11.26
	Mean	95.46	3.41	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	12.17	34.25	
	Treatments	3.67	10.33	
	Factor (V X T)	17.20	48.43	

Table No. 24. Effect of high temperature on total dry weight of tomato genotypes expressed in g.

Sl. No.	Varieties	Control	Treatment	Mean
1	Nandi	0.033	0.117	0.075
2	IC-45	0.026	0.052	0.039
3	Pusa Rohini	0.013	0.038	0.026
4	Pusa Ruby	0.032	0.071	0.051
5	IIHR-2200	0.024	0.066	0.045
6	Anagha	0.014	0.234	0.124
7	Akshaya	0.015	0.081	0.048
8	Vellayani Vijay	0.011	0.074	0.043
9	Arka Vikas	0.014	0.052	0.033
10	Kashi Vishesh	0.018	0.072	0.045
11	Vaibhav	0.015	0.078	0.047
12	IIHR-26372	0.019	0.058	0.039
13	Palam Pride	0.015	0.050	0.032
14	Arka Abha	0.017	0.073	0.045
15	Arka Alok	0.012	0.059	0.036
16	Manulakshmi	0.026	0.075	0.050
17	Sakthi	0.015	0.043	0.029
18	Manuprabha	0.022	0.082	0.052

19	Arka Samrat	0.016	0.047	0.031
20	Arka Sourabh	0.010	0.037	0.024
21	PKM-1	0.014	0.052	0.033
22	Arka Rakshak	0.015	0.075	0.045
	Mean	0.018	0.072	
	Factors	**SE(m)**	**C.D. (0.5%)**	
	Varieties	0.018	N/A	
	Treatments	0.005	0.015	
	Factor (V X T)	0.025	N/A	

4.6. CORRELATION ANALYSIS

Correlation coefficient is a statistical measure, which is used to know the degree and direction of relationship between two or more variables. The degree of association also affects an effectiveness of selection process. The data on various traits which were recorded under the ambient and heat stress conditions in tomato genotypes were subjected to correlation analysis. The results of correlation between some of the characters under both the conditions are presented in table 25 and 26.

Correlation between different traits and yield under control condition

Correlation between different traits and yield under control condition is represented in table no. 25. Under control condition, tomato yield was found to be positively correlated with physiological parameters such as membrane stability index (r = 0.544), photosynthetic rate (r = 0.104), starch content (r = 0.249), soluble sugar content (r = 0.589), transpiration rate (r = 0.024), chlorophyll fluorescence (r = 0.380), pollen viability (r = 0.410), total chlorophyll content (r = 0.300). Similarly, negative correlation was observed for yield with physiological parameters like stomatal conductance (r = -0.213) under control condition. Significant positive correlation were observed with yield and membrane stability index (r = 0.544**), starch content (r = 0.249*), soluble sugar content (r = 0.589**), chlorophyll fluorescence (r = 0.380**), pollen viability (r = 0.410**).

Yield was found to have significant positive correlation with quality parameters such as titrable acidity (r = 0.488**), total soluble solids (r = 0.361**), ascorbic acid (r = 0.351**) and lycopene content (r = 0.337**) under control conditions.

In case of yield parameters, positive correlation was observed for plant height (r = 0.229), number of fruits (r = 0.541), fruit set % (r = 0.507), average fruit weight (r = 0.567), total dry mass (r = 0.220). Negative correlation was observed for yield with intensity of fruit drop (r = -0.303) and intensity of flower drop (r = -0.021). Significant

positive correlation were observed with yield and number of fruits (r = 0.541**), fruit set % (r = 0.507**), average fruit weight (r = 0.567**).

Correlation between different traits and yield under heat stress condition

Correlation between different traits and yield under heat stress condition is shown in the table no. 26. Correlation study revealed that tomato yield per plant under heat stress condition was positively correlated with physiological parameters such as membrane stability index (r = 0.258), photosynthetic rate (r = 0.482), stomatal conductance (r = 0.321), transpiration rate (r = 0.103), starch content (r = 0.414), soluble sugar (r = 0.381), chlorophyll fluorescence (r =0.260) and pollen viability (0.252) and total chlorophyll content (r = 0.347). Significant positive correlation were found out between yield and membrane stability index (r = 0.258*), photosynthetic rate (r = 0.482**), stomatal conductance (r = 0.321*), starch content (r = 0.414**), soluble sugar (r = 0.381*), chlorophyll fluorescence (r =0.260*) and pollen viability (0.252*) and total chlorophyll content (r = 0.347**).

In case of correlation of yield per plant with quality parameters, significant positive correlation was observed with total soluble solids (r = 0.261*), and positive correlation was observed with titrable acidity (r = 0.005), ascorbic acid (r = 0.161) and lycopene content (r = 0.011) under high temperature conditions.

In case of yield parameters, positive correlation was observed for plant height (r = 0.044), number of fruits (r = 0.699), fruit set % (r = 0.936), average fruit weight (r = 0.604), intensity of fruit drop (r = 0.227) total dry mass (r = 0.034). Significant positive correlation was observed with number of fruits (r = 0.699**), fruit set % (r = 0.936**), average fruit weight (r = 0.604**), Negative correlation was observed for yield with intensity of flower drop (r = -0.656).

Table No. 25. Pearson Correlation Matrix (Control)

1. Yield 2. Membrane stability index (MSI) 3. Photosynthetic rate (A) 4. Stomatal conductance (Gs) 5. Starch content 6. Soluble sugar content 7. Transpiration rate (E) 8. Chlorophyll fluorescence (CF) 9. Pollen viability (PV) 10. Total chlorophyll content 11. Titrable acidity (TA) 12. Total soluble solids (TSS) 13. Ascorbic acid content 14. Lycopene content 15. Plant height 16. Number of fruits 17. Fruit set % 18. Average fruit weight 19. Intensity of fruit drop 20. Intensity of flower drop 21. Total dry weight Correlations @ * P <- 0.05, ** P <- 0.01, *** P <- 0.001

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.000	0.544**	0.104NS	-0.213NS	0.249*	0.589**	0.024NS	0.380**	0.410**	0.030NS	0.488**	0.361**	0.351**	0.337**	0.229NS	0.541**	0.507**	0.567**	-0.303*	-0.021NS	0.220NS
2	0.544**	1.000	0.365**	-0.157NS	0.409**	0.665**	0.157NS	0.605**	0.628**	0.184NS	0.593**	0.460**	0.393**	0.093NS	-0.065NS	0.600**	0.653**	-0.035NS	-0.326**	-0.193NS	0.326**
3	0.104NS	0.365**	1.000	-0.149NS	0.380**	0.303*	-0.251*	0.280*	0.276*	0.088NS	0.225NS	0.209NS	0.127NS	0.206NS	-0.218NS	0.301*	0.426**	-0.243*	0.046NS	-0.156NS	0.159NS
4	-0.213NS	-0.157NS	-0.149NS	1.000	-0.227NS	-0.185NS	-0.085NS	-0.394**	-0.368**	-0.198NS	-0.029NS	0.047NS	0.024NS	-0.234NS	0.256*	-0.057NS	-0.179NS	-0.091NS	0.279*	0.120NS	-0.055NS
5	0.249*	0.409**	0.380**	-0.227NS	1.000	0.660**	0.322**	0.531**	0.553**	0.280*	0.417**	0.413**	-0.021NS	-0.037NS	-0.301*	0.319**	0.448**	-0.098NS	-0.407**	-0.004NS	0.009NS
6	0.589**	0.665**	0.303*	-0.185NS	0.660**	1.000	0.166NS	0.604**	0.594**	0.165NS	0.546**	0.534**	0.322**	0.147NS	0.068NS	0.516**	0.538**	0.147NS	-0.320**	-0.080NS	0.286*
7	0.024NS	0.157NS	-0.251*	-0.085NS	0.322**	0.166NS	1.000	0.368**	0.259*	0.328**	0.050NS	0.079NS	-0.158NS	-0.381**	-0.242NS	0.134NS	0.108NS	-0.125NS	-0.357**	0.105NS	-0.260*
8	0.380**	0.605**	0.280*	-0.394**	0.531**	0.604**	0.368**	1.000	0.518**	0.480**	0.363**	0.540**	0.093NS	-0.214NS	-0.305*	0.358**	0.524**	-0.009NS	-0.324**	-0.036NS	-0.076NS
9	0.410**	0.628**	0.276*	-0.368**	0.553**	0.594**	0.259*	0.518**	1.000	0.003NS	0.382**	0.272*	0.221NS	0.111NS	-0.219NS	0.487**	0.497**	-0.002NS	-0.500**	-0.089NS	0.070NS
10	0.030NS	0.184NS	0.088NS	-0.198NS	0.280*	0.165NS	0.328**	0.480**	0.003NS	1.000	0.066NS	0.105NS	0.088NS	-0.186NS	-0.195NS	0.067NS	0.131NS	-0.225NS	-0.177NS	-0.089NS	-0.183NS
11	0.488**	0.593**	0.225NS	-0.029NS	0.417**	0.546**	0.050NS	0.363**	0.382**	0.066NS	1.000	0.472**	0.356**	0.060NS	0.174NS	0.251*	0.476**	0.203NS	-0.162NS	0.118NS	0.167NS
12	0.361**	0.460**	0.209NS	0.047NS	0.413**	0.534**	0.079NS	0.540**	0.272*	0.105NS	0.472**	1.000	0.099NS	-0.255*	0.104NS	0.074NS	0.353**	0.293*	-0.038NS	0.168NS	0.048NS
13	0.351**	0.393**	0.127NS	0.024NS	-0.021NS	0.322**	-0.158NS	0.093NS	0.221NS	0.088NS	0.356**	0.099NS	1.000	0.266*	0.294*	0.114NS	0.128NS	0.302*	0.077NS	-0.131NS	0.174NS

14	0.337**	0.093NS	0.206NS	-0.234NS	-0.037NS	0.147NS	-0.381**	-0.214NS	0.111NS	-0.186NS	0.060NS	-0.255*	0.266*	1.000	0.261*	0.325**	0.054NS	0.167NS	0.021NS	-0.252*	0.399**
15	0.229NS	-0.065NS	-0.218NS	0.256*	-0.301*	0.068NS	-0.242NS	-0.305*	-0.219NS	-0.195NS	0.174NS	0.104NS	0.294*	0.261*	1.000	-0.088NS	-0.211NS	0.380**	0.249*	-0.062NS	0.433**
16	0.541**	0.600**	0.301*	-0.057NS	0.319**	0.516**	0.134NS	0.358**	0.487**	0.067NS	0.251*	0.074NS	0.114NS	0.325**	-0.088NS	1.000	0.684**	-0.159NS	-0.455**	-0.311*	0.300*
17	0.507**	0.653**	0.426**	-0.179NS	0.448**	0.538**	0.108NS	0.524**	0.497**	0.131NS	0.476**	0.353**	0.128NS	0.054NS	-0.211NS	0.684**	1.000	-0.065NS	-0.476**	0.009NS	0.125NS
18	0.567**	-0.035NS	-0.243*	-0.091NS	-0.098NS	0.147NS	-0.125NS	-0.009NS	-0.002NS	-0.225NS	0.203NS	0.293*	0.302*	0.167NS	0.380**	-0.159NS	-0.065NS	1.000	0.066NS	0.222NS	-0.069NS
19	-0.303*	-0.326**	0.046NS	0.279*	-0.407**	-0.320**	-0.357**	-0.324**	-0.500**	-0.177NS	-0.162NS	-0.038NS	0.077NS	0.021NS	0.249*	-0.455**	-0.476**	0.066NS	1.000	0.014NS	0.074NS
20	-0.021NS	-0.193NS	-0.156NS	0.120NS	-0.004NS	-0.080NS	0.105NS	-0.036NS	-0.089NS	-0.089NS	0.118NS	0.168NS	-0.131NS	-0.252*	-0.062NS	-0.311*	0.009NS	0.222NS	0.014NS	1.000	-0.269*
21	0.220NS	0.326**	0.159NS	-0.055NS	0.009NS	0.286*	-0.260*	-0.076NS	0.070NS	-0.183NS	0.167NS	0.048NS	0.174NS	0.399**	0.433**	0.300*	0.125NS	-0.069NS	0.074NS	-0.269*	1.000

Table No. 25. Pearson Correlation Matrix (Treatment)

1. Yield 2. Membrane stability index (MSI) 3. Photosynthetic rate (A) 4. Stomatal conductance (Gs) 5. Starch content 6. Soluble sugar content 7. Transpiration rate (E) 8.Chlorophyll fluorescence (CF) 9. Pollen viability (PV) 10. Total chlorophyll content 11. Titrable acidity (TA) 12. Total soluble solids (TSS) 13. Ascorbic acid content 14. Lycopene content 15. Plant height 16. Number of fruits 17. Fruit set % 18. Average fruit weight 19. Intensity of fruit drop 20.Intensity of flower drop 21. Total dry weight

Correlations @ * P <- 0.05, ** P <- 0.01, *** P <- 0.001

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.000	0.258*	0.235^{NS}	0.211^{NS}	0.180^{NS}	0.122^{NS}	0.103^{NS}	0.260*	0.252*	0.347**	0.005^{NS}	0.261*	0.161^{NS}	0.011^{NS}	0.044^{NS}	0.699**	0.936**	0.604**	0.227^{NS}	-0.656**	0.035^{NS}
2	0.258*	1.000	0.435**	0.508**	0.609**	0.613**	0.588**	0.682**	0.471**	0.685**	-0.031^{NS}	0.572**	0.246*	0.154^{NS}	0.132^{NS}	0.147^{NS}	0.314*	0.069^{NS}	-0.069^{NS}	-0.146^{NS}	0.267*
3	0.482**	0.435**	1.000	0.277*	0.401**	0.562**	0.166^{NS}	0.555**	0.229^{NS}	0.274*	-0.080^{NS}	0.492**	-0.018^{NS}	0.002^{NS}	0.070^{NS}	0.084^{NS}	0.242^{NS}	0.035^{NS}	-0.187^{NS}	-0.098^{NS}	0.189^{NS}
4	0.321*	0.508**	0.277*	1.000	0.569**	0.344**	0.529**	0.378**	0.567**	0.378**	0.052^{NS}	0.225^{NS}	0.209^{NS}	0.222^{NS}	0.175^{NS}	0.045^{NS}	0.232^{NS}	0.057^{NS}	-0.024^{NS}	-0.035^{NS}	-0.034^{NS}
5	0.414**	0.609**	0.401**	0.569**	1.000	0.433**	0.578**	0.680**	0.505**	0.517**	-0.175^{NS}	0.444**	0.333**	0.258*	0.202^{NS}	0.151^{NS}	0.245*	0.111^{NS}	-0.006^{NS}	-0.158^{NS}	0.309*
6	0.381*	0.613**	0.562**	0.344**	0.433**	1.000	0.442**	0.694**	0.184^{NS}	0.566**	0.118^{NS}	0.630**	-0.012^{NS}	-0.036^{NS}	0.010^{NS}	0.061^{NS}	0.186^{NS}	-0.060^{NS}	-0.070^{NS}	-0.084^{NS}	0.138^{NS}
7	0.103^{NS}	0.588**	0.166^{NS}	0.529**	0.578**	0.442**	1.000	0.532**	0.418**	0.561**	0.127^{NS}	0.397**	0.211^{NS}	0.034^{NS}	0.183^{NS}	0.085^{NS}	0.171^{NS}	0.046^{NS}	0.048^{NS}	-0.096^{NS}	0.203^{NS}
8	0.260*	0.682**	0.555**	0.378**	0.680**	0.694**	0.532**	1.000	0.422**	0.572**	-0.036^{NS}	0.556**	0.322**	0.213^{NS}	0.128^{NS}	0.154^{NS}	0.377**	0.064^{NS}	-0.017^{NS}	-0.158^{NS}	0.417**
9	0.252*	0.471**	0.229^{NS}	0.567**	0.505**	0.184^{NS}	0.418**	0.422**	1.000	0.302*	0.024^{NS}	0.181^{NS}	0.273*	0.264*	0.376**	0.227^{NS}	0.301*	0.241^{NS}	0.067^{NS}	-0.211^{NS}	0.142^{NS}
10	0.347**	0.685**	0.274*	0.378**	0.517**	0.566**	0.561**	0.572**	0.302*	1.000	0.136^{NS}	0.705**	0.331**	0.020^{NS}	0.012^{NS}	0.173^{NS}	0.358**	0.020^{NS}	0.081^{NS}	-0.162^{NS}	0.162^{NS}
11	0.005^{NS}	-0.031^{NS}	-0.080^{NS}	0.052^{NS}	-0.175^{NS}	0.118^{NS}	0.127^{NS}	-0.036^{NS}	0.024^{NS}	0.136^{NS}	1.000	-0.003^{NS}	-0.047^{NS}	-0.376**	-0.081^{NS}	-0.036^{NS}	0.007^{NS}	-0.153^{NS}	0.043^{NS}	0.020^{NS}	-0.001^{NS}
12	0.261*	0.572**	0.492**	0.225^{NS}	0.444**	0.630**	0.397**	0.556**	0.181^{NS}	0.705**	-0.003^{NS}	1.000	0.107^{NS}	-0.026^{NS}	-0.065^{NS}	0.116^{NS}	0.297*	0.004^{NS}	0.013^{NS}	-0.115^{NS}	0.208^{NS}
13	0.161^{NS}	0.246*	-0.018^{NS}	0.209^{NS}	0.333**	-0.012^{NS}	0.211^{NS}	0.322**	0.273*	0.331**	-0.047^{NS}	0.107^{NS}	1.000	0.426**	-0.017^{NS}	0.029^{NS}	0.184^{NS}	-0.017^{NS}	0.111^{NS}	-0.011^{NS}	0.184^{NS}
14	0.011^{NS}	0.154^{NS}	0.002^{NS}	0.222^{NS}	0.258*	-0.036^{NS}	0.034^{NS}	0.213^{NS}	0.264*	0.020^{NS}	-0.376**	-0.026^{NS}	0.426**	1.000	0.318**	-0.050^{NS}	0.007^{NS}	-0.005^{NS}	-0.108^{NS}	0.069^{NS}	-0.077^{NS}
15	0.044^{NS}	0.132^{NS}	0.070^{NS}	0.175^{NS}	0.202^{NS}	0.010^{NS}	0.183^{NS}	0.128^{NS}	0.376**	0.012^{NS}	-0.081^{NS}	-0.065^{NS}	-0.017^{NS}	0.318**	1.000	0.129^{NS}	0.034^{NS}	0.108^{NS}	0.017^{NS}	-0.131^{NS}	-0.162^{NS}
16	0.699**	0.147^{NS}	0.084^{NS}	0.045^{NS}	0.151^{NS}	0.061^{NS}	0.085^{NS}	0.154^{NS}	0.227^{NS}	0.173^{NS}	-0.036^{NS}	0.116^{NS}	0.029^{NS}	-0.050^{NS}	0.129^{NS}	1.000	0.747**	0.918**	0.483**	-0.995**	-0.042^{NS}

17	0.936**	0.314*	0.242NS	0.232NS	0.245*	0.186NS	0.171NS	0.377**	0.301*	0.358**	0.007NS	0.297*	0.184NS	0.007NS	0.034NS	0.747**	1.000	0.652**	0.291*	-0.712**	0.144NS
18	0.604**	0.069NS	0.035NS	0.057NS	0.111NS	-0.060NS	0.046NS	0.064NS	0.241NS	0.020NS	-0.153NS	0.004NS	-0.017NS	-0.005NS	0.108NS	0.918**	0.652**	1.000	0.445**	-0.903**	-0.065NS
19	0.227NS	-0.069NS	-0.187NS	-0.024NS	-0.006NS	-0.070NS	0.048NS	-0.017NS	0.067NS	0.081NS	0.043NS	0.013NS	0.111NS	-0.108NS	0.017NS	0.483**	0.291*	0.445**	1.000	-0.472**	-0.086NS
20	-0.656**	-0.146NS	-0.098NS	-0.035NS	-0.158NS	-0.084NS	-0.096NS	-0.158NS	-0.211NS	-0.162NS	0.020NS	-0.115NS	-0.011NS	0.069NS	-0.131NS	-0.995**	-0.712**	-0.903**	-0.472**	1.000	0.046NS
21	0.035NS	0.267*	0.189NS	-0.034NS	0.309*	0.138NS	0.203NS	0.417**	0.142NS	0.162NS	-0.001NS	0.208NS	0.184NS	-0.077NS	-0.162NS	-0.042NS	0.144NS	-0.065NS	-0.086NS	0.046NS	1.000

DISCUSSION

5. DISCUSSION

The global human population is currently growing at an alarming rate and will remain in such condition for at least 35 years. An increasing population is associated with an increase in demand of food but the food production is not sufficient to feed the growing population. Global warming and associated heat stress due to climate change is a major threat which affects the crop production adversely. The global climate change models predict an increase of 2°C daily mean temperature between the year 2046 and 2065 and 3.7°C by 2100 (IPCC, 2013). This climate change affects the world in many ways, including the extinction of species that cannot escape their adverse environment and a decrease in food productivity.

For tomato, the optimum daily temperature ranges from 25-30°C during day and 20°C during night at different growth stages; and this range of temperature is significant for maintaining normal net assimilation rate (Laxman *et al.*, 2013). At the same time, crossing the upper limit above optimum range (>30°C) can cause alterations in the major metabolic process required for the stable growth, development and yield (Sato *et al*., 2000; 2004; 2006; Islam, 2011; De Storme *et al.*, 2013; Alsamir *et al.*, 2017). Previous studies revealed that, like other crops, in tomato also day and night temperatures above optimum levels adversely affect the morphological, physiological and bio-chemical traits (Camejo *et al.*, 2005; Zhang *et al*., 2012; Laxman *et al.*, 2013; 2014; Alsamir *et al.*, 2017). Thus, the present experiment was conducted to examine the effects of high temperature on morpho-physiological and biochemical changes, fruit quality parameters and yield components and to identify the traits or parameters associated with heat stress tolerance.

5.1. EFFECT OF HIGH TEMPERATURE ON PHENOLOGICAL PARAMETERS

Duration of the crop gets extended when compared to plants grown under control conditions. All the genotypes showed delayed flowering and delayed fruiting under stress. Due to the over shaded environment and reduced sunlight intrusion into the polyhouse structure plants attained an increase in plant height and the enhanced temperature inside through greenhouse effect, resulted in flower burning and flower

dropping ultimately leading to extended flowering phase and delayed fruit initiation due to a phenomenon called stigma exertion.

5.2. EFFECT OF HIGH TEMPERATURE ON PHYSIOLOGICAL PARAMETERS

The exerted style, stigma is elongated than the anther cone during reproductive stage reduces self-pollination (Faruq *et al.,* 2012). The elongation of style in flowers reduces the pollen proximity to stigma in heat sensitive genotypes and reduces fertilization (Alsamir *et al.,* 2017). Those genotypes which had no stigma exertion at high temperature are stable and produces high fruit yield (Aggarwal, 2002). Almost all the genotypes grown under stress condition showed stigma exertion. Hanna and Hernandez (1982) and Dane *et al.* (1991) observed that in tomato the elongated stigma tube of flowers had low pollination and thus reduced the yield per plant. Therefore, the previous studies and present experiment it may be suggested that those genotypes producing flowers with normal stigma tube under high temperature produces higher fruit yield. Stigma exertion rate was minimum for tolerant genotypes like Kashi Vishesh, Nandi, Anagha and was maximum in Arka Sourabh.

The varieties with the higher electrical conductivity (EC) average values are grouped as heat susceptible genotypes. In contrast, those varieties that had lower EC values are heat resistant ones. Similar results are also obtained from our study too. Nandi, Vellayani Vijay and Kashi Vishesh showed higher MSI and Arka Sourabh and Pusa Rohini showed lower rates of MSI under control conditions as well as under temperature stress conditions from our experiment. Saeed *et al.* (2014) carried out an experiment which showed that varieties with greater heat tolerance showed high membrane thermostability. The same results were obtained by Saadella *et al.* (1990), Kuo *et al.* (1993) and Ismail and Hall (1999) in cowpea and wheat. High temperature causes denaturation of the biological membrane with lipid bilayer composed of lipid and protein, or generation of fatty acids that are unsaturated in nature (Savchenko *et al.*, 2002). Heat stress changes membrane protein structures, tertiary and quaternary structures. Thus changes in the membrane permeability and cell leakage occurs under heat stress when

exposed to a longer duration. The primary symptom of heat stress is membrane collapse and the thermostability of plasmalemma is considered as a pointer of thermotolerance (Alsamir *et al.,* 2017). The varieties which are tolerant to high temperature had high membrane stability index (Saeed *et al.,* 2007).

Pollen viability and fertile pollen formation are susceptible to small hike in temperature higher than the optimum (Thomas and Prasad, 2003). A decrease in pollen production, release, viability, germination ability, fruit set and production of tomato at temperatures above optimum temperature has been mentioned by various scientists (Peet *et al.,* 1997; Sato *et al.,* 2001; Pressman *et al.,* 2002). Pressman *et al.* (2002) reported that the impact of heat stress on pollen viability is associated with carbohydrate metabolism during anther development. Reduced carbohydrate production and assimilation in the tomato anthers during heat stress results in defective pollen development and viability (Pressman *et al.,* 2002). From our observations also it is obvious that the pollen viability is reduced significantly for all tomato genotypes, but the reduction is less for tolerant genotypes (Nandi, IC-45, Vaibhav) and more for susceptible genotypes (Arka Vikas, Arka Sourabh).

From the study, it is reported that the plants when exposed to high temperature, a reduction of chlorophyll content is observed which are similar in trends of inferences from several studies (Balouchi, 2010; Reda and Mandoura, 2011) that is related either to impaired chlorophyll synthesis, due to an inhibition of various enzymes responsible for biosynthesis (Dutta *et al.,* 2009), and/or to accelerated chlorophyll degradation. This showed a reduction in the chlorophyll content and thereby decreases the photosynthetic rate. Tolerant genotypes showed a slight reduction in chlorophyll content but susceptible ones showed a drastic reduction.

Photosynthetic rate reduction under heat stress is associated with the decrease in chlorophyll content, lipid peroxidation of chloroplast and lipid peroxidation of thylakoid membrane (Camejo *et al.,* 2006). In tomato, varieties that had thermo-resistance enhances chlorophyll a: b proportion and decrease chlorophyll under high temperatures (Camejo *et al.,* 2005a; Wahid and Ghazanfar, 2006).

Photosynthesis is a physiological trait that is highly susceptible to heat stress and a rise in the CO_2 content in the atmosphere result in a hike in temperature and this marks remarkable effect on the yield and distribution of crops and genotypes in the future (Wahid *et al.,* 2007; Allakhverdiev *et al.,* 2008). Changes of the thylakoid membrane under heat stress are directly associated with a decrease in photosystem II activity which contributes to the photosynthetic rate (Yamamoto *et al.,* 2008). The Rubisco enzyme is sensitive to high temperature and causes a reduction in carboxylase activity (Morales *et al.,* 2003; Crafts-Brander and Salvucci, 2004) which also inhibit photosynthesis (Demirevska-Kepova and Feller, 2004) and thereby CO_2 fixation. Heat stress lowers the number of photosynthetic pigments (Todorov *et al.,* 2003), rubisco binding proteins (RBP), soluble proteins, and large and small subunits (SS) of rubisco in darkness but enhances these in light, exhibiting their functions as HSPs and chaperones (Kepova *et al.,* 2005).

Previous studies have shown that the increased temperature of 32°C at the flowering stage caused reductions not only in photosynthetic rate, but also in transpiration rate compared to ambient temperature (Islam, 2011). Studies on physiological responses of six tomato genotypes to high temperature stress under field and greenhouse conditions showed a reduction in photosynthesis, transpiration and stomatal conductance under temperature stress (Berova *et al.,* 2008). In another study, exposing tomato plants to a moderately high temperature of 35°C for eight hours caused a reduction in photosynthesis rate (Zhang *et al.,* 2012). One of the main reason for the decline of net photosynthesis at high temperature is due to the changes in the structural organisation of the photosynthetic apparatus (Zhang *et al.,* 2014). Photosynthetic apparatus is very susceptible and photosystem II and oxygen evolving complex are sensitive to high temperature (Mathur *et al.,* 2014). Our results supported the findings of Abdelmageed and Gruda (2009), that the tolerant cultivars showed higher photosynthetic rate under heat stress conditions at different growth stages in comparison to the heat sensitive ones. The reduction in photosynthesis rates of four tomato genotypes was observed under heat stress (Laxman *et al,* 2013); and the same trend was also observed in

different agricultural crops under elevated temperature such as sorghum (Sunoj *et al.*, 2017) and wheat (Sun *et al.*, 2018).

Under heat stress, a reduction in the transpiration rate was observed among genotypes. The reduction was minimum for the tolerant genotypes and maximum for the sensitive ones. Transpiration rate decreases with temperature up to 39°C (Bar-Tsur *et al.*, 1985). These findings are supported by earlier studies with other crops (Shaheen *et al.*, 2015). Stomatal opening increases in corn up to 50°C when the water supply is not limited, but a decrease in photosynthesis was found above 38°C (Raschke, 1979). Direct measurement of stomatal opening in crops including sunflower, corn, soybean, wheat and cotton indicate that stomata remain open at air temperatures up to 36°C, provided the leaves are not stressed (Hofstra and Hesketh, 1969).

From the present study, a decrease in the stomatal conductance was observed in all the genotypes, and a maximum reduction was observed for sensitive genotypes and minimum reduction for tolerant genotypes. The changes in stomatal conductance occur for the purpose of improving the capacity of mesophyll cells to perform photosynthesis (von Caemmerer *et al.*, 1981). High temperature decreases stomatal conductance and this reduction is caused by the partial closure of stomata, which increases resistance to carbon dioxide diffusion from external air to the chloroplasts (Nkansah *et al.*, 1994). Partial inhibition of the photosynthetic apparatus makes differences in leaf internal CO_2 or sub-stomatal CO_2 in different tomato genotypes under heat stress conditions (Camejo *et al.*, 2005b) and the findings of the present study also confirmed this. The results revealed that stomatal conductance decreased significantly in almost all the genotypes under stress condition compared to the control condition.

Chlorophyll fluorescence is the ratio of variable fluorescence to maximum fluorescence (Fv/Fm) and the base fluorescence (F_0) are physiological parameters used to correlate heat tolerance. Chlorophyll fluorescence used as a tool to study the alterations of photosystem I and photosystem II activity (Gerganova *et al.*, 2016). The ratio between variable fluorescence and maximum fluorescence i.e. chlorophyll fluorescence (Fv/ Fm)

will give an indication of the maximum quantum efficiency of PSII, and is the best tool to phenotype different tomato genotypes for heat tolerance (Zhou *et al.,* 2015).

Under abiotic stress condition especially heat stress, a decline in chlorophyll fluorescence is observed (Molina Bravo *et al.,* 2011; Sharma *et al.*, 2012). This supports our results too. Non-photochemical quenching under stress condition lead to decrease in Fm and the following increase in Fo, due to the photo-inactivation of PS II, is the main reason for the decline of Fv/Fm (Baker, 2008). It was observed that in tomato, Fv/Fm under control condition was higher than Fv/Fm under stress condition (Zhou *et al.*, 2015). The percentage decrease in the chlorophyll fluorescence is maximum for heat sensitive genotypes than that of heat tolerant genotypes.

5.3. EFFECT OF HIGH TEMPERATURE ON BIOCHEMICAL PARAMETERS

Assimilate partitioning, occur through apoplastic and symplastic pathways, under high temperatures, has significant effects on transport and transfer processes in plants (Taiz *et al.*, 2015). Heat stress reduces the accumulation of sucrose in the leaves of both heat tolerant and heat-sensitive tomato genotypes, indicating that carbohydrate translocation and partitioning to other plant organs are negatively affected at high temperatures, similar to results in wheat (Wahid *et al.,* 2007; Shanmugam *et al.,* 2013). A decrease in the starch content was observed in both short-term and long-term abiotic stress exposures (Vinocur and Altman, 2005). In our study also a drastic change in the starch content was observed for different varieties and this reduction was more in susceptible varieties and less in tolerant varieties.

The adverse effects of heat stress on pollen quality of tomato are associated with irregularities in starch accumulation in the pollen grains and a related decrease in soluble sugar content in the mature pollen (Pressman *et al.*, 2002). With the increase in temperature (32/26˚C) the amount of starch content in pollen grains was significantly lower than the control (28/22˚C) pollen grains (anther walls and inner fluid) (Pressman *et al.,* 2002). The heat-tolerant genotypes accumulate more starch before anthesis and soluble sugar at anthesis occur as a result of the ability of the pollen grains with an instant energy source for their germination (Srivastava *et al.,* 2012). Tolerant genotypes

(Anagha, Nandi, Kashi Vishesh) have ability to maintain a good amount of starch and soluble sugar in the leaves than compared to the susceptible genotypes (Arka Sourabh, Arka Rakshak, Arka Vikas).

Under heat stress, the concentration of starch and soluble sugar in the pollen grains was lower than that under control conditions (Kumar *et al.,* 2015). These findings are similar to those obtained that from rice (Sheoran and Saini, 1996) and wheat (Dorion *et al.,* 1996). The carbohydrate starvation in the pollen is not responsible for the stress-induced pollen sterility. Pollen of heat tolerant varieties have a high amount of glucose rather than sucrose and fructose and it can retain a high amount of carbohydrates (Firon *et al.,* 2006).

5.4. EFFECT OF HIGH TEMPERATURE ON QUALITY PARAMETERS

Under high temperature quality parameters like lycopene content was found to decrease, both titratable acidity, total soluble solid content and ascorbic acid content in tomato increased. Shi and Maguer (2000) reported the reduction of lycopene production at higher temperatures (38°C). The relatively heat tolerant genotypes showed a lesser decrease in lycopene content in the fruit at high temperature as compared to susceptible genotypes. The temperature plays an important role in lycopene biosynthesis than it does during the fruit growth and ripening period. High temperature lead to degradation of lycopene (Demiray *et al*., 2013), or to a reduced biosynthesis pathway (Helyes *et al*., 2007).

Shivashankara *et al*. (2015) observed variations in fruit quality parameters at high temperature among tomato genotypes through an experiment. An increase in temperature enhanced TSS and titrable acidity but decreased lycopene and total carotenoids concentration in five genotypes of tomato (Lokesha *et al.,* 2019). Sufficient literatures are available on fruit quality parameters of tomato genotypes (Valverde *et al*., 2002; Erge *et al*., 2011; Kavitha *et al*., 2014; Shivashankara *et al*., 2014) under temperature stress conditions. Hernandez *et al*. (2018) reported that vitamin C content was increased when the heat stress was induced at flowering and fruit set stages, showed that the plant metabolism are adapted to high temperature (Fleisher *et al.,* 2006).

The sugars content contribute to the total soluble solids content in tomato fruits (Selahle *et al*., 2014). The change in the glucose to fructose ratio and the content of organic acid in the tomatoes is the main cause for changes in the TSS. The taste of tomatoes, TSS was reported to be a crucial indicator (Klunklin and Savage, 2017). In our study, TSS increased in all the genotypes under temperature stress compared to control, which is supported by Shivashankara *et al*. (2015). Under high temperature stress conditions, increase in titrable acidity has been reported by Khanal (2012). The highest titrable acidity was recorded for Kashi Vishesh followed by Vaibhav and minimum for IC-45 and Arka Sourabh under control conditions and maximum for Kashi Vishesh and Nandi and minimum for IC-45 under high temperature conditions.

5.5. EFFECT OF HIGH TEMPERATURE ON YIELD PARAMETERS

The flowering traits like the number of trusses and flowers increased in stress conditions, the higher flower drop and flower drying resulted in a reduced number of fruits. The increased flower abortion under stress is an indication of disturbed source sink relationship on carbohydrate metabolism, which can adversely affect the temperature tolerance in tomato genotypes (Sato *et al.*, 2004; 2006). The sensitivity of reproductive development like flowering traits and microsporogenesis to temperature stress are reported in many other crops (groundnut; Prasad *et al.*, 2000, cotton; Kakani *et al.*, 2005, tomato; Sato *et al*., 2006, sorghum: Sunoj *et al.*, 2017).

Plants grown in the polyhouse were tallest irrespective of planting dates and culture conditions used in the experiment conducted by Dhaliwal *et al.* (2017). The plant height, number of branches per tomato plant, leaf area expansion rate and leaf area index were positively influenced by the warmer environment inside the polyhouse (Duhr and Dubas, 1990; Miah, 2001; Pandey *et al.*, 2004) irrespective of the lower amount of PAR (Parvej *et al.*, 2010). The amount of incident PAR under polyhouse is less when compared to the open field. The polyhouse permits easy entry of short-wave radiation but traps the outgoing long-wave radiation. The air temperature inside the polyhouse gradually increased due to the greenhouse effect. Thus, the inside of the polyhouse becomes warmer and temperature increases (Montero and Anton, 2003).

A significant decrease was observed in average fruit weight of tomato genotypes at high temperature. There was a decrease in the number of fruits per plant, percent fruit set and fruit yield per plant in all tomato genotypes under high temperature. The relatively tolerant tomato genotypes (Nandi, Kashi Vishesh, Anagha) showed a lesser magnitude of reduction in the above parameters as compared to relatively susceptible genotypes (Arka Sourabh, Pusa Rohini, PKM-1). The higher pollen viability, better pollen germination and high soluble sugar content in pollen grains at anthesis may be the reason for better number of fruits per plant, per cent fruit set and fruit yield in tolerant genotypes at high temperature. Pollen viability (Pressman *et al*., 2002, Stephenson *et al*., 2003) and fertility (Dane *et al*., 1991, Suzuki *et al*., 2001) are reported to be the reason for better plant productivity during heat stress. The fruit number, fruit set percentage and fruit weight per plant were decreased with increase in temperature. At high temperature, plants tend to transpire more, and hence yield reduction is caused by the impaired pollen, anther development, and reduced pollen viability. The temperature values higher than 35°C reduce the fruit set and delay the development of normal fruit colours (Sato *et al.*, 2006).

SUMMARY

6. SUMMARY

The thesis programme “Effect of high temperature on physiological, biochemical and yield parameters in tomato (*Solanum lycopersicum* L.)”) was conducted to study the effect of high temperature on physiological, biochemical, yield and quality parameters in tomato and the salient findings are given below.

All the tomato genotypes under heat stress showed delayed flowering and fruiting. Delay in flowering was found to vary between the varieties. Kashi Vishesh showed minimum delay in first flowering (10-12 days) than that of control whereas, Pusa Rohini showed maximum delay in flowering (25-30 days) than that of the control plants. Kashi Vishesh showed less delay in first fruiting (8-12 days) than that of control whereas, genotypes like Arka Rakshak, PKM-1, Pusa Rohini showed maximum delay (30-35 days) in fruiting under stress conditions. Under high temperature condition, Arka Sourabh showed the highest exerted stigma length and there is significant variation for flower burning and flower drop.

Under heat stress condition all tomato varieties showed a reduction in MSI showing the possibility of increased cell leakage. A decrease in MSI was observed for plants after 15 days and further reduction was observed for 25 days after stress induction when compared to control plants. Relatively tolerant genotypes showed significantly lesser decrease in percent pollen viability as compared to relatively susceptible genotypes. Similar results were obtained for physiological parameters like total chlorophyll content (mg g^{-1} fresh weight), photosynthetic rate (A) (µ CO_2 moles m^{-2} s^{-1}), transpiration rate (E) (mmol H_2O m^{-2} sec^{-1}), stomatal conductance (Gs) (mmol H_2O m^{-2} sec^{-1}) and chlorophyll fluorescence (CF-Fv / Fm).

Significant genotypic differences for starch content and soluble sugar content were observed in tomato plants under high temperature. Titrable acidity (TA) and total soluble solids (TSS) of tomato fruits were highest in concentration under high temperature conditions compared to low temperature regimes. The lycopene content

decreased with rise in temperature and the ambient condition recorded the highest lycopene content in fruits.

The yield attributes *viz*., number of fruits/plant, fruit set %, average fruit weight (g), yield per plant (g /plant) were significantly lower for varieties like Arka Saurabh, Arka Rakshak and Pusa Rohini. Under heat stress conditions only those genotypes that are tolerant as well as moderately tolerant, namely Nandi, Anagha, Akshaya, IIHR-2200, Vellayani Vijay, Kashi Vishesh, Arka Abha, Arka Alok, Vaibhav, Manuprabha, Manulakshmi, IC-45 and IIHR-26372 produced higher fruit yield per plant. But the varieties like Arka Saurabh, Arka Rakshak, PKM-1, Sakthi, Palam Pride, Arka Samrat recorded the maximum percent reduction in yield per plant and the minimum was recorded in Kashi Vishesh. In polyhouse conditions, all the genotypes showed an increment in the plant height and total dry weight because of the shaded environment, high temperature and enhanced CO_2 (570 ppm) conditions inside.

With respect to yield and physiological data the varieties sharing similar characteristics can be classified under three categories *viz,* tolerant varieties, moderately tolerant and susceptible varieties. Tolerant genotypes (Nandi, Kashi Vishesh, Vellayani Vijay) exhibited similar characteristics like yield (10-30 g^{-1} plant), MSI (60-70 %), PV (50-70%), starch content (190-200 mg g^{-1} fresh weight), A (17-22 µmol CO_2 m^{-2} sec^{-1}), Gs (47-68 mmol H_2O $m^{-2}sec^{-1}$), CF (Fv / Fm) (0.6-0.7). Moderately tolerant varieties (Akshaya, Manuprabha, IIHR-2200, Vaibhav) showed similar characteristics like yield (5-15 g^{-1} plant), MSI (40-50 %), PV (45-50 %), starch content (200 mg g^{-1} fresh weight), A (17-19 µmol CO_2 m^{-2} sec^{-1}), Gs (55-65 mmol H_2O $m^{-2}sec^{-1}$), CF(Fv / Fm) (0.6-0.7) and susceptible varieties (Arka Vikas, Pusa Rohini, Arka Sourabh, Arka Rakshak) showed similar features like yield (0.5-5 g^{-1} plant), MSI (25-40 %), PV (44-45 %), starch content (90-110 mg g^{-1} fresh weight), A (13-16 µmol CO_2 m^{-2} sec^{-1}), Gs (30-37 mmol H_2O $m^{-2}sec^{-1}$) and CF (0.4-0.5).

The correlation analysis revealed that under heat stress conditions yield showed positive and significant correlation with MSI, photosynthetic rate, stomatal conductance,

starch content, soluble sugar content, CF(Fv / Fm), pollen viability, total chlorophyll content, number of fruits per plant, fruit set %, average fruit weight and negatively correlated with intensity of flower drop. Hence this study has importance in identifying genotypes that possesses important physiological traits to increase the thermo-tolerance, so that they could give moderately higher yield even under high temperature.

REFERENCES

7. REFERENCES

Abdelmageed, A.H.A. and Gruda, N. 2009. Influence of high temperatures on gas exchange rate and growth of eight tomato cultivars under controlled heat stress conditions. *Eur. J. Hortic. Sci.* 74: 152–159.

Abdelmageed, A.H.A., Gruda, N., and Geyer, B. 2003. Effect of high temperature and heat shock on tomato (*Lycopersicon esculentum* Mill) genotypes under controlled conditions. Deutscher Tropentag, Gottingen, 8-10.

Abdulbaki, A.A. and Stommel, J.R. 1995. Pollen viability and fruit set of tomato genotypes under optimum and high temperature regimes. *Hortic. Sci.* 30(1): 115-117.

Ahmed, F.E., Hall, A.E., and DeMason, D.A. 1992. Heat injury during floral development in cowpea (*Vigna unguiculata*, Fabaceae). *Am. J. Bot.* 79: 784–791.

Ahmed, R., Iqbal, M.S., Ibrar, D., Mahmood, T., Naveed, M.S., and Naeem, M.K. 2013. A review on heat stress response in different genotypes of tomato crop (*Solanum lycopersicum* L.). *Int. J. Modern Agric.* 2: 64-71.

Ahmadi, A.B.E. and Stevens, M.A. 1979. Reproductive responses of heat tolerant tomatoes to high temperature. *J. Am. Soc. Hortic. Sci.* 104: 686-691.

Ahn, Y.J. and Zimmerman, J.L. 2006. Introduction of the carrot HSP into potato (*Solanum tuberosum* L.) enhances cellular membrane stability and tuberization in vitro. *Plant Cell Environ.* 29: 95–104.

Ainsworth, E.A and Ort, D.R. 2010. How do we improve crop production in a warming world? *Plant Physiol* 154:526–530.

Allakhverdiev, S., Kreslavskii, V., Klimov, V., Dmitry, L., Robert, C., Prasanna, M. 2008. Heat stress: An overview of molecular responses in photosynthesis. *Photosynth. Res.* 98. 541-550.

Allakhverdiev, S.I., Los, D.A., Mohanty, P., Nishiyama, Y., and Murata, N. 2007. Glycinebetaine alleviates the inhibitory effect of moderate heat stress on the repair of photosystem II during photoinhibition. *Biochem. Biophys. Acta* 1767: 1363–1370.

Alsadon, A.A., Wahb-allah, M.A., and Khalil, S.O. 2006. In vitro evaluation of heat stress tolerance in some tomato cultivars. *J. King Saud Univ. Agric. Sci.* 19(1): 13-24.

Alsamir, M., Ahmad, N.M., Keitel, C., Mahmood, T., and Trethowan, R. 2017. Identification of high-temperature tolerant and agronomically viable tomato (*Solanum lycopersicum*) genotypes from a diverse germplasm collection. *Adv. Crop. Sci. Technol*. 5(4): 299-309.

Anon, S., Fernandez, J.A., Franco, J.A., Torrecillas, A., Alarcon, J.J., and Sanchez-Blanco, M.J. 2004. Effects of water stress and night temperature preconditioning on water relations and morphological and anatomical changes of *Lotus creticus* plants. *Scientia Horticulturae* 101: 333–342.

Anza, M., Riga, P., and Garbisu, C. 2006. Effects of variety and growth season on the organoleptic and nutritional quality of hydroponically grown tomato. *J. Food Qual*. 29 (1): 16-37.

Arnon, D.I. 1949. Copper enzymes in isolated chloroplasts. Polyphenoloxidase in *Beta vulgaris*. *Plant Physiol.* 24: 1-15.

Ashraf, M. 1994. Breeding for salinity tolerance in plants. *Crit. Rev. Plant Sci.* 13: 17–42.

Asian Vegetable Research and Development Center (AVRDC). 2001. AVRDC Report 2000, Shanhua, Tainan, Taiwan, VII, 152p.

Association of official analytical chemists AOAC (Ed.). 1990. Official methods of analysis of the Association of official analytical chemists. 15th ed, AOAC Inc., Arlington, Virginia.

Awal, M.A. and Ikeda, T. 2002. Effects of changes in soil temperature on seedling emergence and phenological development in field-grown stands of peanut (*Arachis hypogaea* L.). *Environ. Exp. Bot.* 47 (2): 101-113.

Awal, M.A. and Ikeda, T. 2003a. Effect of elevated soil temperature on radiation-use efficiency in peanut stands. *Agric. Forest Meteorol.* 118 (1-2): 63-74.

Awal, M.A. and Ikeda, T. 2003b. Controlling canopy formation, flowering, and yield in field-grown stands of peanut (*Arachis hypogaea* L.) with ambient and regulated soil temperature. *Field Crops Res.* 81 (2-3): 121-132.

Ayyogari, K., Sidhya, P., and Pandit, M.K. 2014. Impact of climate change on vegetable cultivation - A review. *Int. J. Agric. Environ. Biotechnol.* 7(1): 145-155.

Bacci, L., Benincasa, F., and Rapi, B. 1996. Effects of growth temperature on the spectrocolorimetric characteristics of sorghum: Indices of stress. *Eur. J. Agron.* 5: 45-57. Conroy, J.P., Kuppers, M., Kuppers, B., Virgona, J., and Barlow, E.W.R. 1990. The influence of CO2 enrichment, phosphorus deficiency and water stress on the growth, conductance and water use of *Pinus radiata* D. *Plant Cell Environ.* 11: 91-98.

Baker, H.G. and Baker, I. 1979. Starch in angiosperm pollen grains and its significance. *Am. J. Bot.* 66(5): 127-136.

Baker, J.T. and Reddy, V.R. 2001. Temperature effects on phonological development and fruit yield of muskmelon. *Ann Bot.* 7: 605–613.

Baker, N.R. 2008. Chlorophyll fluorescence: a probe of photosynthesis *in vivo*. *Annu. Rev. Plant Biol.* 59: 659–668.

Baker, N.R. and Rosenqvist, E. 2004. Applications of chlorophyll fluorescence can improve crop production strategies: an examination of future possibilities. *J. Exp. Bot.* 55: 1607–1621.

Baldwin, E.A., Nisperoscarriedo, M.O., Baker, R. and Scott, J.W. 1991. Quantitative-analysis of flavor parameters in 6 florida tomato cultivars (*Lycopersicon esculentum* Mill). *J. Agric. Food Chem.* 39 (6): 1135-1140.

Balouchi, H.R. 2010. Screening wheat parents of mapping population for heat and drought tolerance, Detection of wheat genetic variation. *Int. J. Biol. Life Sci.* 7: 56-66.

Bar-Tsur A, Rudich J, and Bravdo, B. 1985. Photosynthesis, transpiration and stomatal resistance to gas exchange in tomato plants under high temperatures. *J. Hortic. Sci.* 60(3): 405–410.

Beckles, D. 2012. Factors affecting the postharvest soluble solids and sugar content of tomato (*Solanum lycopersicum* L.) fruit. *Postharvest Biol. Technol.* 63: 129–140.

Bell, G.D., Halpert, M.S., Schnell, R.C., Higgins, R.W., Lowrimore, J., Kousky, V.E., Tinker, R., Thiaw, W., Chelliah, M., and Artusa, A. 2000. Climate Assessment for *Am Meteorol. Soc.* Vol 81.

Berova, M., Stoeva, N., Zlatev, Z., and Daniela, G. 2008. Physiological response of some tomato genotypes (*Lycopersicon esculentum* L.) to high temperature stress. *J Cent. Eur. Agric.* 9(4): 9.

Berova, M., Stoeva, N., Zlatev, Z., Daniela, G. 2009. Physiological response of some tomato genotypes (*Lycopersicon esculentum* L.) to high temperature stress. *J. Cent. Eur. Agric.* 9(4): 9.

Bhandari, H.R., Srivastava, K., and Reddy, G.E. 2017. Genetic variability, heritability and genetic advance for yield traits in tomato (*Solanum lycopersicum* L.). *Int. J. Curr. Microbiol. App. Sci.* 6(7): 4131-4138.

Bhattarai, U., Sharma, A., Das, R., and Talukdar, P. 2016. Genetic analysis of yield and yield attributing traits for high temperature resistance in tomato. *Int. J. Veg. Sci.* 5260: 1-13.

Bita, C.E., and Gerats, T. 2013. Plant tolerance to high temperature in a changing environment: scientific fundamentals and production of heat stress-tolerant crops. *Frontiers Plant Sci. 4*: 273.

Blum, A and Ebercon, A. 1988. Cell membrane stability as a measure of drought and heat tolerance in wheat. *Crop Sci.* 21.

Blum, A. 1988. Plant breeding for stress environments. CRC Press, Florida, USA, 223p.

Bokszczanin, K.L. and Fragkostefanakis, S. 2013. Solanaceae pollen thermotolerance initial training network (SPOT-ITN) consortium perspectives on deciphering mechanisms underlying plant heat stress response and thermotolerance. *Front. Plant. Sci.* 4: 315.

Bray, E.A., Bailey-Serres, J., and Weretilnyk, E. 2011. Responses to abiotic stresses. *Biochem. Mol. Biol. Plants* In: Gruissem, W., Buchannan, B., Jones, R. (eds), *Am. Soci. Plant Physiologists* Rockville, pp 1158-1203.

Brenner, M.L. and Cheikh, N. 1995. The role of hormones in photosynthate partitioning and seed filling. In: Davies P.J. (ed): Plant Hormones: Physiology, Biochemistry and Molecular Biology. Kluwer Academic Publishers, Dordrecht, pp. 649–670.

Bukhov, N.G., Sabat, S.C., and Mohanty, P. 1990. Analysis of chlorophyll *a* fluorescence changes in weak light in heat treated Amaranthus chloroplasts. *Photosynth. Res.* 23: 81– 87.

Camejo, D. and Torres, W. 2011. 2001. High temperature effect on tomato (*Lycopersicon esculentum*) pigment and protein content and cellular viability *Cultivos Tropicales* 22(3): 13-17.

Camejo, D., Jimenez, A., Alarcon, J.J., Torres, W., Gomez, J.M., and Sevilla, F. 2006. Changes in photosynthetic parameters and antioxidant activities following heat-shock treatment in tomato plants. *Funct. Plant Biol.* 33: 177–187.

Camejo, D., Morales, M.A., Amico, J.M., Torrecillas, A., and Alarcon, J.J. 2005. High temperature effects on photosynthetic activity of two tomato cultivars with different heat susceptibility. *J. Plant Physiol*. 162: 281-289.

Carrico, G.C., Nepi, M., and Pacini, E. 2017. It is a matter of timing: asynchrony during pollen development and its consequences on pollen performance in angiosperms-a review. *Protoplasma* 254: 57-73.

Casey, B., Kopsell, D., and Carl, S. 2016. Abscisic acid improves tomato fruit quality by increasing soluble sugar concentrations. *J. Plant Nutr.* 40.

Chandola, A. 2016. Temperature induction response of tomato cultivars in mitigation of water and heat stress. Ph. D. (Ag) thesis. Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, 165p.

Cheema, D.S., Kaur, P., and Kaur, S. 2004. Off-season cultivation of tomato under net house conditions. *Acta Horticulturae* (ISHS), 659: 177-181.

Chen, T.H. and Murata, N. 2002. Enhancement of tolerance of abiotic stress by metabolic engineering of betaines and other compatible solutes. *Curr. Opinion Plant Biol.* 5: 250-257.

Chen, T.H. and Murata, N. 2008. Glycine betaine: An effective protectant against abiotic stress in plants. *Trends Plant Sci.* 13: 499-505.

Chen, T.H. and Murata, N. 2011. Enhancement of tolerance of abiotic stress by metabolic engineering of betaines and other compatible solutes. *Curr. Opinion Plant Biol.* 5: 250–257.

Chengkun, H., Suzhi, G., and Jiasen, L. 1996. Effect of drought stress on activated oxygen metabolism in tomato. *J. Fujian Agric. Univ.* 25: 307-311.

Chowdhury, R.S., Karim, M.D., Haque, M.M., Hamid, A., and Tetsushi, H. 2005. Effects of enhanced level of CO2 on photosynthesis, nitrogen content and productivity of mungbean (*Vigna radiata* L. Wilczek). *S. Pac. Stud.* 25(2): 97-103.

Crafts-Brandner, S.J. and Salvucci, M.E. 2002. Sensitivity of photosynthesis in a C4 plant maize to heat stress. *Plant Physiol.* 129: 1773-1780.

Dane, F., Hunter, A.G., and Chambliss, O.L. 1991. Fruit set, pollen fertility and combining ability of selected tomato genotypes under high temperature field conditions. *J. Am. Hort. Sci.* 116(5): 906-910.

De Storme, N. and Geelen, D. 2014. The impact of environmental stress on male reproductive development in plants: biological processes and molecular mechanisms. *Plant Cell Environ. 37*(1): 1–18.

Dekkers, B., Schuurmans, J., and Smeekens, S. 2008. Interaction between sugar and abscisic acid signalling during early seedling development in Arabidopsis. *Plant Mol. Biol.* 67: 151–167.

Demiray, E., Tulek, Y., Yilmaz, Y. 2013. Degradation kinetics of lycopene, β-carotene and ascorbic acid in tomatoes during hot air drying. *Food Sci. Technol.* 50: 172–176.

Dhaliwal 2017. Performance of sweet pepper (*Capsicum annuum* L.) cultivars and economics under protected structures in Punjab. (Ph.D) in Vegetable science Lovely professional university, Punjab, 106p.

Dinar, M. and Rudich, J. 1985. Effect of heat-stress on assimilate partitioning in tomato. *Ann. Bot.* 56: 239-248.

Dorion, S., Lalonde, S., Saini, H.S. 1996. Induction of male sterility in wheat by meiotic-stage water deficit is preceded by a decline in invertase activity and changes in carbohydrate metabolism in anthers. *Plant Physiol.* 111: 137–145.

Driedonks, N., Rieu, I., and Vriezen, W. H. 2015. Breeding for plant heat tolerance at vegetative and reproductive stages. *Plant Reprod*. 29: 67-79.

Dubois, M., Gilles, K.A., Hamilton, J.K., Robers, P.A. and Smith, F. 1956. *Anal. Chem.* 26: 350.

Duhr, E. and Dubas, A. 1990. Effect shading the soil with plastic film on the dynamics of plant development and yield of maize sown on different dates. Prce Kumisji Nouk Rolnicsy Ch-l-Kamiji-lesnych, 69: 9-18.

Dumas, Y., Dadomo, M., Di Lucca, G., and Grolier, P. 2003. Effects of environmental factors and agricultural techniques on antioxidant content of tomatoes. *J. Sci. Food Agr.* 83: 369-382.

Dutta, S., Mohanty, S., and Tripathy, B.C. 2009. Role of temperature stress on chloroplast biogenesis and protein import in pea. *Plant Physiol.* 150: 1050-1061.

El Ahmadi, A.B. and Stevens, M.A. 1979. Reproductive responses of heat-tolerant tomatoes to high temperatures. *J. Am. Soc. Hortic. Sci.* 104: 686-691.

Erge, H.S. and Karadeniz, F. 2011. Bioactive compounds and antioxidative activity of tomato cultivars. *Int. J. Food Properties* 14 (5): 968-977.

Faruq, G., Zaakaria, H.P., and Arasg, N. 2012. Heat tolerance in tomato. *Life Sci. J.* 9(4): 1936-1950.

Fierro-Cabo, A., Gosselin, A., and Tremblay, N. 1994. Supplemental carbon dioxide and light improved tomato and pepper seedling growth and yield. *HortScience* 29.

Firon, N., Shaked, R., Peet, M.M., Pharr, D.M., Zamski, E., Rosenfeld, K., Althan, L, and Pressman, E. 2006. Pollen grains of heat tolerant tomato cultivars retain higher carbohydrate concentration under heat stress conditions. *Scientia Horticulturae* 109: 212-217.

Fleisher, D.H., Logendra, L.S., Moraru, C., Both, A.J., Cavazzoni, J., Gianfagna, T., Lee, T.C. and Janes, H.W. 2006. Effect of temperature perturbations on tomato (*Lycopersicon esculentum* Mill.) quality and production scheduling. *J. Hortic. Sci. Biotechnol.* 81: 125-131.

Foolad, M.R. 2005. Breeding for abiotic stress tolerance in tomato. In: Ashraf and Harris (Eds.), Abiotic Stresses. Food Products Press, New York.

Fragkostefanakis, S., Röth, S., Schleiff, E., and Scharf, K.D. 2015. Prospects of engineering thermotolerance in crops through modulation of heat stress transcription factor and heat shock protein networks. *Plant Cell Environ.* 3: 1881–1895.

Frank, G., Pressman, E., Ophir, R., Althan, L., Shaked, R., Freedman, M., Shen, S., Firon, S. 2009. Transcriptional profiling of maturing tomato (*Solanum lycopersicum* L.) microspores reveals the involvement of heat shock proteins, ROS scavengers, hormones, and sugars in the heat stress response, *J. Exp. Bot.* 60(13): 3891–3908.

Fujita, Y., Fujita, M., Shinozaki, K., and Yamaguchi-Shinozaki, K. 2011. ABA-mediated transcriptional regulation in response to osmotic stress in plants. *J. Plant Res.* 124: 509–525.

Gabry, M. A. H. E., Solieman, T. I. H., and Abido, A. I. A. 2014. Combining ability and heritability of some tomato (*Solanum lycopersicum* L.) cultivars. *Scientia Horticulturae* 167: 153-157.

Gaikwad, A., Cheema, D., and Garg, N. 2009. Diallel analysis involving heat- tolerant lines of tomato. *Adv. Hortic. Sci.* 23: 87-93.

Gautier, H., Rocci, A., Buret, M., Grasselly, D., Causse, M. 2005. Fruit load or fruit position alters response to temperature and subsequent cherry tomato quality. *J. Sci. Food Agric.* 85: 1009 - 1016.

Gerganova, M., Antoaneta, V., Daniela, P.S., and Maya, V. 2016. Tomato plants acclimate better to elevated temperature and high light than to treatment with each factor separately. *Plant Physiol. Biochem.* 104**:** 234-241.

Giorno, F., Wolters-Arts, M., Mariani, C., and Rieu, I. 2013. Ensuring reproduction at high temperatures: The heat stress response during anther and pollen development. *Plants* 2: 489–506.

Giri, A., Heckathorn, S., Mishra, S., and Krause, C. 2017. Heat stress decreases levels of nutrient-uptake and assimilation proteins in tomato roots. *Plants* 6(6): 143-151.

Gómez, R., Costa, J., Amo, M., Alvarruiz, A., Picazo, M. and Pardo, J.E. 2001. Physicochemical and colorimetric evaluation of local varieties of tomato grown in SE Spain. *J. Sci. Food Agric.* 81 (11): 1101-1105.

Guendouz, A. and Maamari, K. 2012. Grain-filling, chlorophyll content in relation with grain yield component of durum wheat in a mediterranean environment. *Afr. Crop Sci. J.* 20(1): 31 - 37.

Guo, R., Shi, L., Jiao, Y., Li, M., Zhong, X., Gu, F., Liu, Q., Xia, X., and Li, H. 2018. Metabolic responses to drought stress in the tissues of drought-tolerant and drought-sensitive wheat genotype seedlings. *Plants* 10(2): 1-16.

Guo, Y.P., Zhou, H.F., and Zhang, L.C. 2006. Photosynthetic characteristics and protective mechanisms against photooxidation during high temperature stress in two citrus species. *Scientia Horticulturae* 108: 260–267.

Gupta, R. and Chakrabarty, S.K. 2013. Gibberellic acid in plant: still a mystery unresolved. *Plant Signal Behav*. 8(9): 25504.

Hall, A.E. 2001. Crop Responses to Environment. CRC Press LLC, Boca Raton, Florida, 248p.

Hamisu, H.S., Ado, S.G., Yeye, M.Y., Usman, I.S., Afolayan, S.O., Bala, M.G., Usman, A., Yaduma, J.J., Idris, B.A., Gwammaja, M.Y., and Muhammad, S.M. 2016. Genetic studies of agronomic and physiological traits in tomato (*Solanum lycopersicum* M.) under heat stress conditions. *Am. J. Exp. Agri.* 13(6): 1-8.

Hanna, H.Y. and Hernandez, T.P. 1982. Response of six tomato genotypes under summer and spring weather conditions in Louisiana. *Hortic. Sci.* 17: 758-759.

Haworth, M., Killi, D., Materassi, A., Raschi, A., and Centritto, M. 2016. Impaired Stomatal Control Is Associated with Reduced Photosynthetic Physiology in Crop Species Grown at Elevated [CO2]. *Front. Plant Sci.* 7: 1568.

Hayat, S., Hayat, Q., Alyemeni, M.N., Wani, A.S., Pichtel, J., and Ahmad, A. 2012. Role of proline under changing environments: a review. *Plant Signaling Behav.* 7(11): 1456–1466.

Hazra, P., Ansary, S.H., Dutta, A.K., Balacheva, E., and Atanassova, B. 2009. Breeding tomato tolerant to high temperature stress. *Acta Horticulturae* 830: 241-248.

Hazra, P., Ansary, S.H., Sikder, D.E., Peter, K.V. 2007. Breeding tomato (*Lycopersicon esculentum* Mill.) resistant to high temperature stress. *Int. J. Plant Breed.* 1(1): 31-40.

Hebbar, K., Rose, H., Nair, A., Kannan, S., Vittal, N., Manivannan, A., Gupta, A., Kukkamgai, S., Chandran, K.P., Chowdappa, P., Prasad, P., and Vara, V. 2018. Differences in *in vitro* pollen germination and pollen tube growth of coconut (*Cocos nucifera* L.) cultivars in response to high temperature stress. *Environ. Exp. Bot.* 153: 35-44.

Hedge, J.E. and Hofreiter, B.T. 1962. In: Methods in Carbohydrate Chemistry. Vol.17, (Eds.,) Whistler, R.L. and BeMiller, J.N., Academic Press, New York, 420p.

Helyes, L., Lugasi, A., and Pék, Zoltán. 2007. Effect of natural light on surface temperature and lycopene content of vine ripened tomato fruit. *Can. J. Plant Sci.* 87: 927-929.

Hernandez, V., Hellin, P., Fenoll, J., Molina, M.V., Garrido, I. and Flores, P. 2018. Impact of high temperature stress on ascorbic acid concentration in tomato. *Acta Horticulturae* 1194: 985-990.

Hofstra, G. and Hesketh, J.D. 1969. The effect of temperature on stomatal aperture in different species. *Can. J. Bot.* 47: 1307-1310.

Hortensteiner, S. 2009. Stay-green regulates chlorophyll and chlorophyll-binding protein degradation during senescence. *Trends Plant Sci.* 14: 155–162.

Howarth, C.J. 2005. Genetic improvements of tolerance to high temperature, in abiotic stresses: Plant resistance through breeding and molecular approaches, (eds). Ashraf, M. and Harris, P.J.C. Howarth Press Inc. New York, NY, pp. 277–300.

Hu, S., Wang, C., Sanchez, D.L., Lipka, A.E., Liu, P., Yin, Y., Lübberstedt, T. 2017. Gibberellins promote brassinosteroids action and both increase heterosis for plant height in maize (*Zea mays* L.). *Frontiers Plant Sci*. 8.

Aggarwal P K. 2003. Impact of climate change on Indian agriculture. *J. Plant Biol.* 30: 189-198.

Ibrahim, Z.E. 2016. Tomato breeding for heat stress conditions. *Eur. J. Acad. Essays.* 3(2): 87-93.

Ilan, N., Moran, N., and Schwartz, A. 1995. The role of potassium channels in the temperature control of stomatal aperture. *Plant Physiol.* 108: 1161–1170.

IPCC [Intergovernmental panel on climate change]. 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. In: Special report of the intergovernmental panel on climate change. Cambridge university press, Cambridge, pp. 1-19.

IPCC. 2013. Summary of policymakers. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nouels, A., Xia, Y. (eds), Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK, 1535 p.

Islam, M.T. 2011. Effect of temperature on photosynthesis, yield attributes and yield of tomato genotypes. *Int. J. Expt. Agric.* 2(1): 8-11.

Ismail, A. and Hall, A. 1999. Reproductive-stage heat tolerance, leaf membrane thermostability and plant morphology in cowpea. *Crop Sci.* 39.

Ismail, A.M. and Hall, A.E. 1999. Reproductive-stage heat tolerance, leaf membrane thermo-stability and plant morphology in cowpea. *Crop Sci.* 39: 1762–1768

Iwahori, S. 1965. High temperature injuries in tomatoes development of normal flower buds and morphological abnormalities of flower buds treated with high temperature. *J. Jap. Soc. Hort. Sci.* 34: 33-41.

Jagadish, S.V.K., Craufurd, P., Shi, W., and Oane, R. 2014. A phenotypic marker for quantifying heat stress impact during microsporogenesis in rice (*Oryza sativa* L.). *Funct. Plant Biol.* 41: 48–55.

Jagadish, S.V.K., Muthurajan, R., Oane, R., Wheeler, T.R., Heuer, S., Bennett, J., and Craufurd, P.Q. 2010. Physiological and proteomic approaches to address heat tolerance during anthesis in rice (*Oryza sativa* L.). *J. Exp. Bot.* 61: 143–156.

Jain, M., Prasad, P.V., Boote, K.J., Hartwell, A.L., and Jr. Chourey, P.S. 2007. Effects of season-long high temperature growth conditions on sugar-to-starch metabolism in developing microspores of grain sorghum (*Sorghum bicolor* L. Moench). *Planta* 227: 67–79.

Jakobsen, I., Smith, S.E., Smith, F.A., Watts-Williams, S.J., Clausen, S.S., and Grønlund, M. 2016. Plant growth responses to elevated atmospheric CO2 are increased by phosphorus sufficiency but not by arbuscular mycorrhizas. *J. Exp. Bot.* 67(21): 6173-6186.

Janka, E., Körner, O., Rosenqvist, E., and Ottosen C.O. 2013. High temperature stress monitoring and detection using chlorophyll a fluorescence and infrared thermography in chrysanthemum (*Dendranthema grandiflora*). *Plant Physiol. Biochem.* 67: 87–94.

Kadam, G., Singh, K., and Singh, M.P. 2012. Effect of elevated carbon-dioxide levels on morphological and physiological parameters in gladiolus. *Ind. J. Hortic.* 69: 379-384.

Kakani, V.G., Reddy, K.R., Koti, S., Wallace, T.P., Prasad, P.V., Reddy, V.R. and Zhao D. 2005. Differences in in vitro pollen germination and pollen tube growth of cotton cultivars in response to high temperature. *Ann. Bot.* 96: 59–67.

Kang, B.S. and Sidhu, B.K. 2005. Studies on growing off-season tomato nursery under polyhouse. *Ann. Agric. Biol. Res.* 10 (1): 53-56.

Kang, H., Park, W., and Mikal, S. 2002. Elevated growing temperatures during the day improve the postharvest chilling tolerance of greenhouse-grown cucumber (*Cucumis sativus*) fruit. *Postharvest Biol. Technol.* 24: 49-57.

Kardivel, P. 2010. Molecular breeding in vegetable crops-challenges and opportunities. Paper presented at the 2nd national workshop on marker-assisted selection for crop improvement, Patancheru, AP.

Karim, Z., Chambrey, R., Chalumeau, C., Defontaine, N., and Warnock, D. 1999. Regulation by PKC isoforms of Na+/H+ exchanger in luminal membrane vesicles isolated from cortical tubules. *Am. J. Physiol.* 277: F773-F778.

Kaur, C. and Kapoor, H.C. 2008. Antioxidant in fruits and vegetables-The millennium's health. *Int. J. Food Sci. Technol.* 36: 703-725.

Kaushal, N., Bhandari, K., Siddique, K.H.M., and Nayyar, H. 2016. Food crops face rising temperatures: An overview of responses, adaptive mechanisms, and approaches to improve heat tolerance. *Cogent Food Agric.* 2: 1134380.

Kavitha, P., Shivashankara, K.S., Rao, V.K., Sadashiva, A.T., Ravishankar, K.V. and Sathish, G.J. 2014. Genotypic variability for antioxidant and quality parameters among tomato cultivars, hybrids, cherry tomatoes and wild species. *J. Sci. Food Agric.* 94: 993-999.

Kepova, D.K., Holzer, R., Simova, L., and Feller, U. 2005. Heat stress effects on ribulose-1, 5-bisphosphate carboxylase/oxygenase, RuBisCo binding protein and RuBisCo activase in wheat leaves. *Biol. Plant.* 49: 521-525.

Khan, M.M.A., Gautam, C., Mohammad, F., Siddiqui, M.H., Naeem, M., and Khan, M.N. 2006. Effect of gibberellic acid spray on performance of tomato. *Turk. J. Biol.* 30: 11–16.

Khanal, B. 2012. Effect of day and night temperature on pollen characteristics, fruit quality and storability of tomato. M. Sc. Thesis, Department of Plant and Environmental Sciences, Norwegian University of Life Sciences, Norway, 46p.

Killi, D., Bussotti, F., Raschi, A., and Haworth, M. 2017. Adaptation to high temperature mitigates the impact of water deficit during combined heat and drought stress in C3 sunflower and C4 maize varieties with contrasting drought tolerance. *Physiol Plant.* 159(2): 130-147.

Klunklin, W. and Savage, G. 2017. Effect of quality characteristics of tomatoes grown under well-watered and drought stress conditions. *Foods* 6 (8): 56-65.

Koh, E., Charoenprasert, S., and Mitchell, A.E. 2012. Effect of industrial tomato paste processing on ascorbic acid, flavonoids and carotenoids and their stability over one-year storage. *J. Sci. Food Agric.* 92: 23–28.

Kumar, M. and Dudi, B.S. 2011. Study of correlation for yield and quality characters in tomato (*Lycopersicon esculentum* Mill.). *Electr. J. Plant Breed.* 2(3): 453-460.

Kumar, S., Prakash, P., and Srivastava, K. 2015. Role of pollen starch and soluble sugar content on fruit set in tomato under heat stress. SABRAO *J. Breed. Genet.* 47 (4): 406-412.

Kuo, C.G., Chen, H.M., and Ma, L.H. 1986. Effect of high temperature on proline content in tomato floral buds and leaves. *J. Amer. Soc. Hortic. Sci.* 111: 734-750.

Kuo, C.G., Chen, H.M., and Sun, H.C. 1993. Membrane thermostability and heat tolerance of vegetable leaves. In: Kuo CG, (ed). Adaptation of food crops to temperature and water stress. Asian Veg Res Dev Center, Shanhua, Taiwan, 160-168.

Larkindale, J., Hall, J.D., Knight, M.R., and Vierling, E. 2005. Heat stress phenotypes of Arabidopsis mutants implicate multiple signaling pathways in the acquisition of thermotolerance. *Plant Physiol.* 138: 882–897.

Laxman, R.H., Srinivasa, R.N.K, and Bhatt, R.M. 2013. Response of tomato (*Lycopersicon esculentum* Mill.) genotypes to elevated temperature. *J. Agrometeorol.* 15: 38–44.

Levy, A., Rabinowitch, H.D., and Keder, N. 1978. Morphological and physiological characters affecting flower drop and fruit set of tomatoes at high temperatures. *Euphytica* 27: 211–218.

Li, L.L., Shao, T.Y., Yang, H., Chen, M.X., Gao, X.M., Long, X.H., Shao, H.B., Liu, Z.P. 2016. The endogenous plant hormones and ratios regulate sugar and dry matter accumulation in Jerusalem artichoke in salt-soil. *Sci. Total Environ.* 578: 40–46.

Li, X., Schmid, B., Wang, F., and Paine, C. 2016. Net assimilation rate determines the growth rates of 14 species of subtropical forest trees. Plos One. 11.

Lokesha, A.N., Shivashankara, K.S., Laxman, R.H., Geetha, G.A., and Shankar, A.G. 2019. Effect of high temperature on fruit quality parameters of contrasting tomato genotypes. *Int.J.Curr.Microbiol.App.Sci.* 8(3): 1019-1029.

Lu, K.X., Yang, Y., He, Y., and Jiang, D.A. 2008. Induction of cyclic electron flow around photosystem 1 and state transition are correlated with salt tolerance in soybean. *Photosynthetica* 46(1): 10–16.

Mamatha, H., Srinivasa R.N.K., Laxman, R. H., and Vijayalakshmi, T. 2015. Studies on effect of mild temperature increase on tomato (*Lycopersicon esculentum*) hybrid Arka Ananya. *Plant Arch.* 15(1): 171-175.

Manabendra D., and Baruah K.K. 2000. Comparable studies of rainfed upland winter rice (*Oryza sativa*). *Ind. J. Agric. Sci.* 70(3):135-139.

Marcum, K.B. 1998. Cell membrane thermostability and whole-plant heat tolerance of Kentucky bluegrass. *Crop Sci.* 38: 1214–1218

Marine, J.P., Haperen, P.V., Rieu, I., Richard, G.F.V., Yury, M.T., and Arnaud, G.B. 2017. Screening for pollen tolerance to high temperatures in tomato. *Euphytica* 213: 130-138.

Martineau, J.R., Specht, J.E., Williams, J.H., and Sullivan, C.Y. 1979. Temperature tolerance in soybeans. Evaluation of a technique for assessing cellular membrane thermostability. *Crop Sci.* 19: 75–78.

Martinez, V., Manuel, N.C., Maria, L.D., Reyes, R., Teresa, C.M., Francisco, G.S., Francisco, R., Pedro, A.N., Ron, M., and Rosa, M.R. 2018. Tolerance to stress combination in tomato plants: new insights in the protective role of melatonin. *Molecules* 23: 535-555.

Mathur, S., Jajoo, A., Mehta, P., and Bharti, S. 2011. Analysis of elevated temperature-induced inhibition of photosystem II using chlorophyll a fluorescence induction kinetics in wheat leaves (*Triticum aestivum*). *Plant Biol.* 13, 1–6.

Mathur, S., Jajoo, A., Mehta, P., and Bharti, S. 2014. Analysis of elevated temperature-induced inhibition of photosystem II using chlorophyll *a* fluorescence induction kinetics in wheat leaves (*Triticum aestivum*). *Plant Biol.* 13(1): 1–6.

Matsui, T., Omasa, K., and Horie, T. 2000. High temperature at flowering inhibits swelling of pollen grains, a driving force for thecae dehiscence in rice. *Plant Product Sci.* 3: 430–434.

Mesihovic, A., Iannacone, R., Firon, N., and Fragkostefanakis, S. 2016. Heat stress regimes for the investigation of pollen thermotolerance in crop plants. *Plant Reprod.* 29: 93-105

Miah, M.M. 2001. Performance of five winter vegetables under different light conditions for Agroforesty systems. M. Sc. Thesis, BSMRAU, Gazipur, Bangladesh, pp. 295-301.

Miller, P., Lanier, W., and Brandt, S. 2001. Using growing degree days to predict plant stages. Ag/Extension Communications Coordinator, Communications Services, Montana State University-Bozeman, Bozeman, MO, 35p.

Mitcham, E.J. and McDonald, R.E. 1992. Effect of high temperature on cell wall modifications associated with tomato fruit ripening. *Postharvest Biol. Technol.* 1 (3): 257-264.

Mittler, R., Finka, A., and Goloubinoff, P. 2012. How do plants feel the heat? Trends *Biochem. Sci.* 37: 118-125.

Mittler, R., Vanderauwera, S., Gollery, M., and Van Breusegem, F. 2004. Reactive oxygen gene network of plants. *Trends Plant Sci.* 9: 490–498.

Mittler, R., Vanderauwera, S., Suzuki, N., Miller, G., Tognetti, V.B., Vandepoele, K., Gollery, M., Shulaev, V., and Van Breusegem, F. 2012. ROS signaling: The new wave? *Trends Plant Sci.* 16: 300–309.

Mohammed, A.R. and Tarpley, L. 2010. Effects of high night temperature and spikelet position on yield-related parameters of rice (*Oryza sativa* L.) plants. *Eur. J. Agron.* 33: 117-123.

Molina-Bravo, R., Arellano, C., Sosinski, B., and Fernandez, G. 2011. A protocol to assess heat tolerance in a segregating population of raspberry using chlorophyll fluorescence. *Scientia Horticulturae* 130: 524-530.

Momcilovic, I. and Ristic, Z. 2007. Expression of chloroplast protein synthesis elongation factor, EF-Tu, in two lines of maize with contrasting tolerance to heat stress during early stages of plant development. *J. Plant Physiol.* 164: 90–99.

Montero, J.J. and Anton, A. 2003. Greenhouse characteristics and microclimatic conditions. *Acta Horticulturae* 614: 323-333.

Morales, D., Rodrıguez, P., Dell'amico, J., Nicolas, E., Torrecillas, A., and Sanchez-Blanco, M. J. 2003. High-temperature preconditioning and thermal shock imposition affects water relations, gas exchange and root hydraulic conductivity in tomato. *Biologia Plantarum* 47: 203–208.

Moraru, C., Logendra, L., Lee, T.C. & Janes, H. 2004. Characteristics of 10 processing tomato cultivars grown hydroponically for the NASA Advanced Life Support (ALS) Program. *J. Food Composition Anal.* 17 (2): 141-154.

Mortensen, A. and Skibsted, L.H. 1997. Importance of carotenoid structure in radical-scavenging reactions. *J. Agric. Food. Chem.* 45: 2970–2977.

Murchie, E.H. and Lawson, T. 2013. Chlorophyll fluorescence analysis: a guide to good practice and understanding some new applications, J. Exp. Bot. 64(13): 3983–3998.

Nafees, K., Kumar, M., and Bose, B. 2019. Effect of different temperatures on germination and seedling growth of primed seeds of tomato. *Russian J. Plant Physiol*. 66(5): 778–784.

Nagalakshmi, S.N., Nandakumar, D., Palanisamy, and Sreenarayanan, V.V. 2001. Naturally ventilated polyhouse for vegetable cultivation. *South Ind. Hortic.* 49: 345-346.

Nahar, K. and Ullah, S.M. 2012. Morphological and physiological characters of tomato (*Lycopersicon esculentum* Mill) cultivars under water stress. *Bangladesh J. Agric. Res.* 37(2): 355–360.

National Horticultural Board. 2018. Horticultural statistics at a glance. Ministry of Agriculture & Farmer's Welfare, Department of Agriculture, Govt. of India, 490p.

Nkansah, G.O. and Ito, T. 1994. Relationship between some physiological characters and yield of heat-tolerant and non-tolerant, and tropical tomato cultivars grown at high temperature. *J. Japan Soc. Hortic. Sci.* 62: 781–788.

Ogweno, J., Song, X., Shi, K., Hu, W., Mao, W., Zhou, Y., Yu, J., and Nogués, S. (2007). Brassinosteroids Alleviate Heat-Induced Inhibition of Photosynthesis by increasing carboxylation efficiency and enhancing antioxidant systems in *Lycopersicon esculentum*. *J. Plant Growth Reg.* 27: 49-57.

Oms-Oliu, G., Hertog, M., Van dePoel., A.J., Geeraerd, A., and Nicolaï, B. 2011. Metabolic characterization of tomato fruit during preharvest development, ripening, and postharvest shelf-life. *Postharvest Biol. Technol.* 62: 7-16.

O'Neill, D.P. and Ross, J.J. 2002. Auxin regulation of the gibberellin pathway in pea. *Plant Physiol. 130*(4): 1974–1982.

Pandey, V.K., Dwivedi, S.K., Pandey, A. and Sharma, H.G. 2004. Low cost polyhouse technology for vegetable cultivation in Chhattisgarh Region. *Plant Archiv.* 4 (2): 295-301.

Parvej, M.R., Khan, M.A.H., and Awal, M.A. 2010. Phenological development and production potentials of tomato under polyhouse climate. *J. Agric. Sci.* 5(1): 19-31.

Patel, P.K., Singh, U., Singh, A.K., Kumar, R., Singh, M. 2014. Identification of tomato gen otypes for better post-harvest attributes and high temperature tolerance. Poster at: National Conference on Pre-/Post-Harvest Losses & Value Addition in Vegetables. (July 12-13), IIVR, Varanasi, India, p 177.

Paupiere, M.J., Haperen, P.V., Rieu, I., Visser, R.G.F., Tikunov, Y.M., and Bovy, A. G. 2017. Screening for pollen tolerance to high temperatures in tomato. *Euphytica* 213: 130.

Peet, M., Sato, S., and Gardner, R. 1998. Comparing heat stress effects on male fertile and male sterile tomatoes. *Plant Cell Environ.* 21: 225-231.

Pervez, M.A., Ayub, C.M., Khan, H.A., Shahid, M.A., and Ashraf. I. 2009. Effect of drought stress on growth, yield and seed quality of tomato (*Lycopersicon esculentum* L.). *Pak. J. Agric. Sci*. 46(3): 174-178.

Prasad, P., Pisipati, S., Mutava, R., and Tuinstra, M. 2008. Sensitivity of grain sorghum to high temperature stress during reproductive development. *Crop Sci.* 48: 1911–1917.

Prasad, P.V.V. and Djanaguiraman, M. 2011. High night temperature decreases leaf photosynthesis and pollen function in grain sorghum. *Funct. Plant Biol.* 38: 993–1003.

Prasad, P.V.V., Boote, K.J. and Allen Jr., L.H. 2006. Adverse high temperature effects on pollen viability, seed-set, seed yield, and harvest index of grain-sorghum

[*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agric. Forest Meteorol.* 139: 237–251.

Prasad, P.V.V., Boote, K.J., Allen Jr., L.H. and Thomas, J.M.G. 2002. Effects of elevated temperature and carbon dioxide on seed-set and yield of kidney bean (*Phaseolus vulgaris* L.). *Glob. Change Biol.* 8: 710–721.

Prasad, P.V.V., Boote, K.J., Allen Jr., L.H. and Thomas, J.M.G. 2003. Super-optimal temperatures are detrimental to reproductive processes and yield of peanut under both ambient and elevated carbon dioxide. *Glob. Change Biol.* 9: 1775–1787.

Prasad, P.V.V., Boote, K.J., Allen, L.H.J.R., Sheehy, J.E., and Thomas, J.M.G. 2006b. Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. *Field Crops Res.* 95: 398–411.

Prasad, P.V.V., Craufurd, P.Q. and Summerfield, R.J. 2000. Sensitivity of peanut to timing of heat stress during reproductive development. *Crop Sci.* 39: 1352–1357.

Prasad, P.V.V., Pisipati, S.R., Ristic, Z., Bukovnik, U. and Fritz, A.K. 2008. Impact of night time temperature on physiology and growth of spring wheat. *Crop Sci.* 48: 2372–2380.

Pressman, E., Peet, M.M., and Pharr, D.M. 2002. The effect of heat stress on tomato pollen characteristics is associated with changes in carbohydrates concentration in the developing anthers. *Ann. Bot.* 90: 631-636.

Pushpalatha, P., Sharma-Natu, P., and Ghildiyal, M.C. 2008. Photosynthetic response of wheat cultivar to long-term exposure to elevated temperature. *Photosynthetica* 46: 552-556.

Qu, G.Q., Liu, X., Zhang, Y.L., Yao, D., Ma, Q.M., Yang, M.Y., Zhu, W.H., Yu, S., and Luo, Y.B. 2009. Evidence for programmed cell death and activation of specific caspase-like enzymes in the tomato fruit heat stress response. *Planta* 229: 1269–1279.

Rahbarian, R., Khavari-Nejad, R., Ganjeali, A., Bagheri, A. Najafi, F. 2011. Drought stress effects on photosynthesis, chlorophyll fluorescence and water relations in tolerant and susceptible chickpea (*Cicer Arietinum* L.) genotypes. *Acta Biologica Cracoviensia Series Botanica.* 53.

Rangana, S. 1976. Manual of analysis of fruits and vegetable products. McGraw Hill, New Delhi, 77p.

Raschke, K. 1979. Movements of stomata. In: Physiology of movements. Encyclopedia of Plant Physiology, (Haupt W and Feinleib ME. (eds.), Springer Verlag, Berlin, 383-441.

Reda, F., Mandoura, H.M.H. 2011. Response of enzymes activities, photosynthetic pigments, proline to low or high temperature stressed wheat plant (*Triticum aestivum* L.) in the presence or absence of exogenous proline or cysteine. *Int. J. Acad. Res.* 3: 108-115.

Regassa, M.D., Mohammed, A., and Bantte, K. 2012. Evaluation of tomato (*Lycopersicon esculentum* Mill.) genotypes for yield and yield components. *Afr. J. Plant Sci. Biotechnol.* 6(1): 45-49.

Reinert, R.A., Eason, G., and Barton, G. 1997. Growth and fruiting of tomato as influenced by elevated carbon dioxide and ozone. *New Phytol.* 137: 411-420.

Rhodes, D. and Hanson, A. 1993. Quaternary ammonium and tertiary sulfonium compounds in higher plants. *Annu. Rev. Plant Physiol*. 44: 357–384.

Rieu, I., Twell, D., and Firon, N. 2017. Pollen Development at high temperature: From acclimation to collapse. *Plant Physiol.* 173: 1967–1976.

Rosa, M., Rivero, T., Mestre, C., Mittler, R., Rubio, F., Garcia-Sanchez, F., and Martinez, V. 2014. The combined effect of salinity and heat reveals a specific physiological, biochemical and molecular response in tomato plants. *Plant Cell Environ.* 37: 1059–1073.

Ruan, Y.L., Jin, Y., Yang, Y.J., Li, G.J., and Boyer, J.S. 2010. Sugar input, metabolism and signaling mediated by invertase: roles in development, yield potential, and response to drought and heat. *Mol. Plant* 3: 942–955.

Rudich, J., Zamski, E., and Regev, Y. 1977. Genotypic variation for sensitivity to high temperature in the tomato: Pollination and fruit set. *Bot. Gaz.* 138(4): 448-452.

Saadella, M.M., Shanahan, J.F., Quick, J.S. 1990. Heat tolerance in winter wheat: hardining and genetic effects on membrane thermostability. *Crop Sci.* 30: 1243-1247.

Sadasivam, S. and Manickam, A. 2008. Biochemical methods. New Age International Pvt. Ltd, New Delhi, 270p.

Saeed A, Hayat K, Khan A.A, Iqbal S. 2007. Heat tolerance studies in tomato (*Lycopersicon esculentum* Mill.). *Int. J. Agric. Biol.* 9(4):200.

Saeed, A., Hayat, K., Khan, A.A., and Iqbal, S. 2014. Heat Tolerance studies in tomato (*Lycopersicon esculentum* M.). *Int. J. Agri. Biol.* 9(4): 649-652.

Saini, H.S., Sedgley, M., and Aspinall, D. 1984. Developmental anatomy in wheat of male sterility induced by heat stress, water deficit or abscisic acid. *Aust. J. Plant Physiol.* 11: 243–253.

Salem, M.A., Kakani, V.G., Koti, S., and Reddy, K.R. 2007. Pollen-based screening of soybean genotypes for high temperatures. *Crop Sci.* 47: 219–231.

Salvucci, M.E. and Crafts-brandner, S.J. 2004. Relationship between the heat tolerance of photosynthesis and the thermal stability of Rubisco activase in plants from contrasting thermal environments. *Plant Physiol.* 134: 1460-1470.

Sato, S., Kamiyama, M., Iwata, T., Makita, N., Furukawa, H., and Ikeda, H. 2006. Moderate increase of mean daily temperature adversely affects fruit set of *Lycopersicon esculentum* by disrupting specific physiological processes in male reproductive development. *Ann Bot* 97(5): 731–738.

Sato, S., Peet, M.M., and Gardner, R.G. 2004. Altered flower retention and developmental patterns in nine tomato cultivars under elevated temperature. *Scientia Horticulturae* 101: 95–101.

Sato, S., Peet, M.M., and Thomas, J.F. 2000. Physiological factors limit fruit set of tomato (*Lycopersicon esculentum* Mill.) under chronic, mild heat stress. *Plant Cell Environ.* 23: 719-726.

Sato, S., Peet, M.M., and Thomas, J.F. 2002. Determining critical pre and post anthesis periods and physiological processes in *Lycopersicon esculentum* Mill exposed to moderately elevated temperatures. *J. Exp. Bot.* 53: 1187-1195.

Savchenko, G., Klyuchareva, E., Abramchik, L., and Serdyuchenko, E. 2002. Effect of periodic heat shock on the inner membrane system of etioplasts. *Russian J. Plant Physiol.* 49. 349-359.

Scharf, K.D., Berberich, T., Ebersberger, I., and Nover, L. 2012. The plant heat stress transcription factor (Hsf) family: structure, function and evolution. *Biochem. Biophysica Acta* 1819: 104-119.

Schoffl, F., Prandl, R., and Reindl, A. 1999. Molecular responses to heat stress. In: Shinozaki, K., Yamaguchi-Shinozaki, K., (eds). Molecular Responses to Cold, Drought, Heat and Salt Stress in Higher Plants. R.G. Landes Co., Austin, Texas, pp. 81–98.

Seemann, J.R., Sharkey, T.D., Wang, J. and Osmond, C.B. 1987. Environmental effects on photosynthesis, nitrogen-use efficiency, and metabolite pools in leaves of sun and shade plants. *Plant Physiol.* 84: 796–802.

Selahle, M.K., Sivakumar, D., and Soundy, P. 2014. Effect of photo-selective nettings on post-harvest quality and bioactive compounds in selected tomato cultivars. *J. Sci. Food Agric.* 94: 2187–2195.

Shaheen, M.R., Ayyub, C.M., Amjad, M., and Waraich, E.A. 2015. Morpho-physiological evaluation of tomato genotypes under high temperature stress conditions. *J. Sci. Food Agric.* 96(8): 2698–2704.

Shamshiri, R.R., Jones, J.W., Thorp, K.R., Ahmad, D., Man, H.C., and Taheri, S. 2018. Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: A review. *Int. Agrophysics.* 32(2): 287-302.

Shanmugam, S., Kjaer, K.H., Ottosen, C.O., Rosenqvist, E., Sharma, D.K., and Wollenweber, B. 2013. The alleviating effect of elevated CO2 on heat stress susceptibility of two wheat (*Triticum aestivum* L.) cultivars. *J. Agron. Crop Sci.* 199: 340–350.

Sharma, A., Shahzad, B., Kumar, V., Kohli, S.K., Sidhu, G., Bali, A. S., Handa, N., Kapoor, D., Bhardwaj, R., and Zheng, B. 2019. Phytohormones regulate accumulation of osmolytes under abiotic stress. *Biomolecules 9*(7): 285.

Sharma, D.K., Andersen, S. B., Ottosen, C. O., and Rosenqvist, E. 2012. Phenotyping of wheat cultivars for heat tolerance using chlorophyll a fluorescence. *Funct. Plant Biol.* 39: 936— 947.

Sharma, D.K., Andersen, S. B., Ottosen, C. O., and Rosenqvist, E. 2014: Wheat cultivars selected for high Fv/Fm under heat stress maintain high photosynthesis, total chlorophyll, stomatal conductance, transpiration and dry matter. *Plant Physiol.* 153(2): 284-298.

Sharma, P., Bhushan, A.J., Shanker R.D., and Mohammad, P. 2012. Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions. *J. Bot.* 217037: 1-26.

Sharma, P.S., Sareen, M., Saini, A., Verma, B., Tyagi, S., and Sharma, I. 2014. Assessing genetic variation for heat tolerance in synthetic wheat lines using phenotypic data and molecular markers. *Aust. J. Crop Sci.* 8: 515—522.

Sharma, S.K. and Le Maguer, M. 1996. Lycopene in tomatoes and tomato pulp fractions. *Ital J. Food Sci.* 2: 107-113.

Sheila, C., Abrams, S., Stephen, A., Cutler, A., Mary, M., Andrew, R., Allison, K. 2003. A method for profiling classes of plant hormones and their metabolites using liquid chromatography-electrospray ionization tandem mass spectrometry: An analysis of hormone regulation of thermodormancy of lettuce (*Lactuca sativa* L.) seeds. *Plant J. Cell Mol. Biol.* 35: 405-417.

Sheoran, I.S. and Saini, H.S. 1996. Drought-induced male sterility in rice: changes in carbohydrate levels and enzyme activities associated with the inhibition of starch accumulation in pollen. *Sexual Plant Reproduction* 9: 161–169.

Shi, J. and Le Maguer, M. 2000. Lycopene in tomatoes: chemical and physical properties affected by food processing. *Crit. Rev. Food Sci. Nutr.* 40(1): 1– 42.

Shivashankara, K.S., Pavithra, K.C., Laxman, R.H., Sadashiva, A.T., Roy, T.K. and Geetha, G.A. 2015. Changes in fruit quality and carotenoid profile in tomato (*Solanum lycopersicon* L.) genotypes under elevated temperature. *J. Hortic. Sci.* 10(1): 38-43.

Sies, H. and Stahl, W. 1998. Lycopene: Antioxidant and Biological Effects and its Bioavailability in the Human. *Proceedings Soc. Experimental Biol. Medicine 218* (2), 121–124.

Singh, R., Singh, S., Cheema, D.S., and Dhaliwal, M.S. 2005. Screening for heat tolerance in tomato (*Solanum Lycopersicum* L.). *Veg. Sci.* 32(1): 90-91

Singh, S. and Sawhney, V.K. 1998. Abscisic acid in a male sterile tomato mutant and its regulation by low temperature. *J. Exp. Bot.* 49: 199–203.

Singh, U., Patel, P.K., Singh, A.K., Tiwari, V., Kumar, R., Rai, N., Bahadur, A., Tiwari, S.K., Singh, U., and Singh, B. 2015. Screening of tomato genotypes under high temperature stress for reproductive traits. *Veg. Sci.* 42 (2): 52-55.

Singh, U., Patel, P.K., Kashyap, S.P., Tiwari, S.K., Kumar, R., and Singh, M. 2014. Quantitative changes in antioxidant compounds of tomato fruits at different ripening stages under extreme temperature. Poster at: National Conference on Pre-/Post-Harvest Losses & Value Addition in Vegetables. (July 12-13), IIVR, Varanasi, India, p. 241-242.

Slama, I., Abdelly, C., Bouchereau, A., Flowers, T., and Savouré, A. 2015. Diversity, distribution and roles of osmoprotective compounds accumulated in halophytes under abiotic stress. *Ann Bot.* 115(3): 433-447.

Solankey, S.S., Singh, R.K., Baranwal, D.K., and Singh, D.K. 2015. Genetic expression of tomato for heat and drought stress tolerance: an overview. *Int. J. Veg. Sci.* 21(5): 496-515.

Solieman, T.H.I., Gabry, M.A.H.E. and Abido, A.I. 2013. Heterosis, potence ratio and correlation of some important characters in tomato (*Solanum lycopersicum* L.). *Scientia Horticulturae* 150: 25–30.

Somraj, B., Reddy, R.V.S.K., Reddy, K.R., Saidaiah, P., and Reddy, M.T. 2017. Genetic variability, heritability and genetic advance for yield and quality attributes in heat tolerant exotic lines of tomato (*Solanum lycopersicum* L.). *J. Pharmacol. Phytochemistry 6*(4): 1956-1960.

Song, Y., JoAnn, E., Manson, J.E., Buring, H.D., Howard D.S., and Liu, S. 2005. Association of dietary flavonoids with risk of type 2 diabetes, and markers of insulin resistance and systemic inflammation in women: a prospective study and cross-sectional analysis. *J. Am. Coll. Nutr*. 24(5): 376–384.

Song, Y.P., Ma, K.F., Ci, D., Zhan, Z.Y., and Zhang, D.Q. 2013. Biochemical, physiological and gene expression analysis reveals sex-specific differences in *Populus tomentosa* floral development. *Physiol. Plant* 150: 18–31.

Sonoike, K. 2011. Photoinhibition of photosystem I. *Physiol. Plantarum* 142: 56–64.

Srivastava, K., Kumar, S., Kumar, S., Prakash, P., Vaishampayan, A. 2012. Screening of tomato genotypes for reproductive characters under high temperature stress condition. *SABRAO J. Plant Breed. Genet.* 44(2): 263-276.

Srivastava, P., Srivastava, B.K., and Singh, M.P. 2002. Effect of date of planting and growing environment on the plant survival, growth and yield of early cauliflower in rainy season. *Veg. Sci.* 29 (2): 157-160.

Stevens, M.A. and Rudich, J. 1978. Genetic potential for overcoming physiological limitations on adaptability, yield and quality in the tomato. *Hortic. Sci.* 13 673-678. Stephenson, A.G., Travers, S.E., Mena-Ali, J.I., and Winsor, J.A. 2003. Pollen performance before and during the autotrophic-heterotrophic transition of pollen tube growth. *Philosophical Transactions Royal Soc. London Series B Biol. Sci.* 358: 1009-1018

Sullivan, C.Y. 1972. Mechanisms of heat and drought resistance in grain sorghum and methods of measurement. In: Rao, N.G.P., House, L.R., (eds). Sorghum in the seventies. Oxford and IBH publishing Co. New Delhi, pp. 247-264.

Sun, A., Impa, S., Sunoj V.S., Kanwardeep, S., Kulvinder, G., Prasad, P.V.V.S.V., Jagadish. K. 2018. Heat stress during flowering affects time of day of flowering, seed set, and grain quality in spring wheat. *Crop Sci. Metabol.* 58(1): 380-392.

Sun, A., Yi, S., Yang, J., Zhao, C., and Liu J. 2006. Identification and characterization of a heat-inducible ftsH gene from tomato (*Lycopersicon esculentum* Mill.). *Plant Sci.* 170:551–562.

Sunoj, V.S.J, Impa, M.S, and Chiluwal, A. 2017. Resilience of pollen and post flowering response in diverse sorghum genotypes exposed to heat stress under field conditions. *Crop Sci.* 57: 1-12.

Surender, K. 2013. Response of tomato (*Lycopersicon esculentum* M.) in heat stress. Ph. D. thesis, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi. 79p.

Suzuki, K., Takeda, H., Tsukaguchi, T., and Egawa Y. 2001. Ultrastructural study on degeneration of tapetum in anther of snap bean (*Phaseolus vulgaris* L.) under heat stress. *Sex. Plant Reproduction* 13: 293–299.

Swarup, R., Parry, G., Graham, N., Allen, T., and Bennett, M. 2002. Auxin cross-talk: integration of signalling pathways to control plant development. *Plant Mol. Biol.* 49: 411–426

Szabados, L. and Savouré, A. 2010. Proline: a multifunctional amino acid. *Trends Plant Sci.* 15: 89–97.

Taiz, L., Zeiger, E, Moller, I.M., and Murphy, A. 2015. Plant Physiology and Development. Sinauer Associates, Massachusetts, 761p.

Takatsuka, H. and Umeda, M. 2014 Hormonal control of cell division and elongation along differentiation trajectories in roots. *J. Exp. Bot.* 65(10): 2633–2643.

Takei, K., Yamaya, T., and Sakakibara, H. 2004. Arabidopsis CYP735A1 and CYP735A2 encode cytokinin hydroxylases that catalyze the biosynthesis of trans-zeatin. *J. Biol. Chem.* 279: 41866–41872.

Thomas, J.M.G. and Prasad, P.V.V. 2003. Plants and the environment /global warming effects. University of Florida, Gainesville, FL, USA, pp. 786-794.

Tigist, M., Workneh, T.S., and Woldetsadik, K. 2013. Effects of variety on the quality of tomato stored under ambient conditions. *J. Food Sci. Technol.* 50(3): 477-486.

Tikkanen, M., Greaco, M., Kangasja¨rvi, S., and Aro, E.M. 2010. Thylakoid protein phosphorylation in higher plant chloroplasts optimizes electron transfer under fluctuating light. *Plant Physiol.* 152: 723–735.

Todorov D., Karanov E., Smith A.R., and Hall M.A. 2003. Chlorophyllase activity and chlorophyll content in wild and mutant plants of *Arabidopsis thaliana*. *Biol. Plant.* 46: 125–127.

Toor, R.K. and Savage, G.P. 2006. Changes in major antioxidant components of tomatoes during post-harvest storage. *Food Chem*. 99: 724-727.

Toor, R.K., Savage, G.P., and Lister, C.E. 2006. Seasonal variations in the antioxidant composition of greenhouse grown tomatoes. *J. Food Comp. Anal.* 19: 1-10.

Vaktabhai, C.K. and Kumar, S. 2017. Seedling invigouration by halo priming in tomato against salt stress. *J. Pharmacol. Phytochem.* 6: 716–722.

Valverde, I.M., Periago, M.J., Provan, G. and Chesson, A. 2002. Phenolic compounds, lycopene and antioxidant activity in commercial varieties of tomato (*Lycopersicum esculentum*). *J. Sci. Food. Agric.* 82: 323-330.

Vassilevska-ivanova, R. and Tcekova, Z. 2002. Effect of temperature on seed germination and seedling growth of sunflower (*Helianthus annuus* L.). *Comptes Rendus de l Academie Bulgare des Sci*. 55: 10–67.

Vierling, E. 1991. The Roles of Heat Shock Proteins in Plants. *Ann. Rev. Plant Physiol. Plant Mol. Biol.* 42(1): 579-620.

Villareal, R.L., Lai, S.H. and Wong, S.H. 1978. Screening for heat tolerance in the genus *Lycopersicon, Hort. Sci.* 13: 479-481.

Vishwakarma, K., Upadhyay, N., Kumar, N., Yadav, G., Singh, J., Mishra, R.K., Kumar, V., Verma, R., Upadhyay, R.G., Pandey, M., and Sharma, S. 2017. Abscisic acid signaling and abiotic stress tolerance in plants: A review on current knowledge and future prospects. *Frontier Plant Sci.* 8:161.

von Caemmerer, S. and Farquhar, G.D. 1981. Some relationships between the biochemistry of photosynthesis and the gas exchange of leaves. *Planta* 153: 376–387.

Vollenweider, P. and Günthardt-Goerg, M. 2006. Diagnosis of abiotic and biotic stress factors using the visible symptoms in foliage. *Environ. Pollut.* 140: 562-571.

Wahid, A. and Ghazanfar, A. 2006. Possible involvement of some secondary metabolites in salt tolerance of sugarcane. *J. Plant Physiol.* 163:723–730.

Wahid, A. and Shabbir, A. 2005. Induction of heat stress tolerance in barley seedlings by pre-sowing seed treatment with glycine betaine. *Plant Growth Reg.* 46: 133–141.

Wahid, A., Gelani, S., Ashraf, M., and Foolad, M.R. 2007. Heat tolerance in plants: an overview. *Environ. Exp. Bot.* 61: 199–223.

Wang, S.Y. 2006. Effect of pre-harvest conditions on antioxidant capacity in fruits. *Acta Hortic*, 712: 299-305.

Wang, S.Y. and Zheng, W. 2001. Effect of plant growth temperature on antioxidant capacity in strawberry. *J. Agric. Food Chem.* 49: 4977-4982.

Wani, K.F.M., Shahid, M.A., Balal, R.M., Khan, M.W., Liaqat, M.R., and Akram, A. 2015. Morphological, physiological and nutritional responses of ten tomato genotypes at maturity stage under heat stress. *Res. J. Innovative Ideas and Thoughts* 4(2): 63-78.

Weerakkody, W. 2003. Nutritional value of fresh leafy vegetables as affected by pre-harvest factors. 511-515 pp.

Willits, D. and Peet, M. 2001. Measurement of chlorophyll fluorescence as a heat stress indicator in tomato: laboratory and greenhouse comparisons. *J. Am. Soc. Hortic. Sci.* 126.

Wollenweber, B., Porter, J.R., and Schellberg, J. 2003. Lack of interaction between extreme high temperature events at vegetative and reproductive growth stages in wheat. *J. Agron. Crop Sci.* 189: 142–150.

Woolf, A.B., Bowen, J.H., and Ferguson, I.B. 1999. Preharvest exposure to the sun influences postharvest responses of 'Hass' avocado fruit. *Postharvest Biol. Techno.* 15 (2): 143-153.

Wu, C.T., Zhou, B.L., and Zhang, T.Z. 2009. Isolation and characterization of a sterile-dwarf mutant in Asian cotton (*Gossypium arboreum* L.). *J. Genet. Genomics.* 36: 343–353.

Xu J., Li Y., Wang R.Z., Liu W., and Zhou P., 2015. Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates. Applied Energy, 138, 291-301,

Xu, J., Mieke, W.A., Celestina, M., Heidrun, H., and Ivo, R. 2017. Heat stress affects vegetative and reproductive performance and trait correlations in tomato (*Solanum lycopersicum*). *Euphytica* 213: 156-168.

Xu, Z., Qiao-Mei, W., Guo, Y., De-Ping, G., Ghazanfar, S., Hai-Lin, L., and Aining, M. 2008. Stem-swelling and photosynthate partitioning in stem mustard are regulated by photoperiod and plant hormones. *Environ. Exp. Bot.* 62: 160-167.

Yamashita, A., Nijo, N., Pospisil, P., Morita, N., Takenaka, D., and Aminaka, R. 2008. Quality control of photosystem II: reactive oxygen species are responsible for the damage to photosystem II under moderate heat stress. *J. Biol. Chem.* 283: 28380–28391.

Yang, Z., Li, Y., Li, P., Zhang, F., and Thomas, B.W. 2016. Effect of difference between day and night temperature on tomato (*Lycopersicon esculentum* Mill.) root activity and low molecular weight organic acid secretion. *Soil Sci. Plant Nutr.* 62(6): 423-431.

Yelle, S., Richard, B., Trudel, M., and Gosselin, A. 1989. Duration of CO2 enrichment influences growth, yield, and gas exchange of two tomato species. *J. Am. Soc. Hortic. Sci.* 115.

Yoshioka, M., Nakayama, Y., Yoshida, M., Ohashi, K., Morita, N., and Kobayashi, H. 2010. Quality control of photosystem II: FtsH hexamers are localized near photosystem II at grana for the swift repair of damage. *J. Biol. Chem.* 285: 41972–41981.

Yuan, X.K. and Yang, Z.Q. 2018. The effect of endogenous hormones on plant morphology and fruit quality of tomato under difference between day and night temperature. *Hortic. Sci.* 45: 131–138.

Zhang, J., Jiang, X.D., Li, T.L., and Cao, X.J. 2014. Photosynthesis and ultrastructure of photosynthetic apparatus in tomato leaves under elevated temperature. *Photosynthetica* 52: 430- 436.

Zhang, W.B., Jiang, H., Qiu, P.C., Liu, C.Y., Chen, F.L., and Xin, D.W. 2012. Genetic overlap of QTL associated with low-temperature tolerance at germination and seedling stage using BILs in soybean. *Can. J. Plant Sci*. 92: 1–8.

Zhou, R., Xiaqing, Y., Katrine, H.K., Eva, R., Carl-Otto, R., and Zhen, W. 2015. Screening and validation of tomato genotypes under heat stress using F v /F m to reveal the physiological mechanism of heat tolerance. *Environ. Exp. Bot.* 118: 1-11.

Zinn, K.E, Tunc-Ozdemir, M., and Harper, J.F. 2010. Temperature stress and plant sexual reproduction: uncovering the weakest links. *J. Exp. Bot.* 61: 1959–1968.

EFFECT OF HIGH TEMPERATURE ON PHYSIOLOGICAL, BIOCHEMICAL AND YIELD PARAMETERS IN TOMATO (*Solanum lycopersicum* L.).

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ABSTRACT OF THESIS

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ABSTRACT

Amrutha Vijayakumar **Date: 24-06-2020**

2018-11-095 **Time: 11-11:30 am**

EFFECT OF HIGH TEMPERATURE ON PHYSIOLOGICAL, BIOCHEMICAL AND YIELD PARAMETERS IN TOMATO (*Solanum lycopersicum* L.).

An experiment entitled "Effect of high temperature on physiological, biochemical and yield parameters in tomato (*Solanum lycopersicum* L.)" was conducted in the Department of Plant Physiology, College of Agriculture, Vellayani during Rabi 2019-2020 with the objective to study the effect of high temperature on physiological, biochemical, yield and quality parameters in tomato. Twenty two different tomato varieties were used for the study. The experiment was laid out in completely randomized design with two treatment levels i.e. control and high temperature stress (36+/-2^{o}C) with three replications each. The high temperature stress was induced from flower initiation to maturity stage by keeping the pots in a temperature controlled green house facility for 45 days. Phenological, physiological, biochemical parameters were taken at flowering stage. Also quality parameters and yield parameters were taken at harvesting stage.

All the tomato genotypes under heat stress showed delayed flowering and fruiting. Delay in flowering was found to vary between the varieties. Kashi Vishesh showed minimum delay in first flowering (10-12 days) than that of control whereas, Pusa Rohini showed maximum delay in flowering (25-30 days) than that of the control plants. Kashi Vishesh showed less delay in first fruiting (8-12 days) than that of control whereas, genotypes like Arka Rakshak, PKM-1, Pusa Rohini showed maximum delay (30-35 days) in fruiting under stress conditions. Under high temperature condition, Arka Sourabh

showed the highest exerted stigma length and there is significant variation for flower burning and flower drop.

A decrease in Membrane Stability Index (MSI) was observed for varieties on 15^{th} day after stress induction and further reduction for 25^{th} day after stress induction when compared to control plants. Under heat stress conditions, Nandi (51.8%) and Arka Rakshak (25.13%) showed maximum and minimum MSI respectively. The percentage reduction in MSI was highest in Pusa Ruby (52%) and lowest in IIHR-2200 (11%). Under high temperature conditions pollen viability reduced significantly for all varieties with maximum viability for Nandi (87.38%) and minimum for Arka Vikas (36.31%). Similar results were obtained for physiological parameters like total chlorophyll content (mg g^{-1} fresh weight), photosynthetic rate (A) µ CO_2 moles m^{-2} s^{-1}), transpiration rate (E) (mmol H_2O m^{-2} sec^{-1}), stomatal conductance (Gs) (mmol H_2O m^{-2} sec^{-1}) and chlorophyll fluorescence (CF-Fv / Fm). The percentage reduction in photosynthetic rate under high temperature condition was highest in Palam Pride (30%) and minimum for Manulakshmi (9%). The percent reduction in transpiration rate was maximum for Arka Sourabh (67%) and minimum for Kashi Vishesh (12%).

Significant genotypic differences for starch content and soluble sugar content were observed in tomato plants under high temperature. Among the genotypes, Vaibhav (312.97 mg g^{-1} fresh weight) recorded the maximum starch accumulation while the minimum starch content was recorded in Arka Vikas (209.70 mg g^{-1} fresh weight) under control conditions. Under heat stress condition, the highest starch content was observed in Anagha (235.67 mg g^{-1} fresh weight), while the lowest was observed in Arka Sourabh (84.37 mg g^{-1} fresh weight). The percent decrease in soluble sugar content was more in Arka Rakshak (31.2%) and less in IIHR-2200 (3%) under high temperature condition.

Titrable acidity (TA) and total soluble solids (TSS) of tomato fruits were highest in concentration under high temperature conditions compared to low temperature regimes. The percent increase in titrable acidity under heat stress was highest for Arka Alok (27%) and minimum for Pusa Rohini (2%). Highest TSS was recorded for Arka

Samrat (5.72%) and lowest for IC-45 (2.32%) under control ambient condition. But under high temperature conditions highest TSS was recorded for Kashi Vishesh (6.23%) and lowest for IC-45 (2.57%). The lycopene content decreased with rise in temperature and the ambient condition recorded the highest lycopene content in fruits. The percent reduction in lycopene content under heat stress conditions was maximum for IIHR-2200 (52%) and minimum for Kashi Vishesh (3%).

The yield attributes *viz*., number of fruits/plant, fruit set %, average fruit weight (g), yield per plant (g /plant) were significantly lower for varieties like Arka Saurabh, Arka Rakshak and Pusa Rohini. Under heat stress conditions only those genotypes that are tolerant as well as moderately tolerant, namely Nandi, Anagha, Akshaya, IIHR-2200, Vellayani Vijay, Kashi Vishesh, Arka Abha, Arka Alok, Vaibhav, Manuprabha, Manulakshmi, IC-45 and IIHR-26372 produced higher fruit yield per plant. But the varieties like Arka Saurabh, Arka Rakshak, PKM-1, Sakthi, Palam Pride, Arka Samrat recorded the maximum percent reduction in yield per plant (99%) and the minimum was recorded in Kashi Vishesh (69%). In polyhouse conditions, all the genotypes showed an increment in the plant height and total dry weight because of the shaded environment, high temperature and enhanced CO_2 (570 ppm) conditions inside.

With respect to yield and physiological data the varieties sharing similar characteristics can be classified under three categories *viz,* tolerant varieties, moderately tolerant and susceptible varieties. Tolerant genotypes (Nandi, Kashi Vishesh, Vellayani Vijay) exhibited similar characteristics like yield (10-30 g^{-1} plant), MSI (60-70 %), PV (50-70%), starch content (190-200 mg g^{-1} fresh weight), A (17-22 µmol CO_2 m^{-2} sec^{-1}), Gs (47-68 mmol H_2O $m^{-2}sec^{-1}$), CF (Fv / Fm) (0.6-0.7). Moderately tolerant varieties (Akshaya, Manuprabha, IIHR-2200, Vaibhav) showed similar characteristics like yield (5-15 g^{-1} plant), MSI (40-50 %), PV (45-50 %), starch content (200 mg g^{-1} fresh weight), A (17-19 µmol CO_2 m^{-2} sec^{-1}), Gs (55-65 mmol H_2O $m^{-2}sec^{-1}$), CF(Fv / Fm) (0.6-0.7) and susceptible varieties (Arka Vikas, Pusa Rohini, Arka Sourabh, Arka Rakshak) showed similar features like yield (0.5-5 g^{-1} plant), MSI (25-40 %), PV (44-45 %), starch content (90-110 mg g^{-1} fresh weight), A (13-16 µmol CO_2 m^{-2} sec^{-1}), Gs (30-37 mmol H_2O m^{-}

$^{2}sec^{-1}$) and CF (0.4-0.5). The correlation analysis revealed that under heat stress conditions yield showed positive and significant correlation with MSI, photosynthetic rate, stomatal conductance, starch content, soluble sugar content, CF(Fv / Fm), pollen viability, total chlorophyll content, number of fruits per plant, fruit set %, average fruit weight and negatively correlated with intensity of flower drop. Hence this study has importance in identifying genotypes that possesses important physiological traits to increase the thermo-tolerance, so that they could give moderately higher yield even under high temperature.

സംഗ്രഹം

തക്കാളിയിലെ ഫിസിയോളജിക്കൽ, ബയോകെമിക്കൽ, വിളവ് പാരാമീറ്ററുകളിൽ ഉയർന്ന താപനിലയുടെ പ്രഭാവം" എന്ന തലക്കെട്ടിൽ ഒരു പരീക്ഷണം നടന്നു. തക്കാളിയിലെ ഫിസിയോളജിക്കൽ, ബയോകെമിക്കൽ, വിളവ്, ഗുണനിലവാര പാരാമീറ്ററുകൾ എന്നിവയിലെ ഉയർന്ന താപനില. ഇരുപത്തിരണ്ട് വ്യത്യസ്ത തക്കാളി ഇനങ്ങൾ പഠനത്തിനായി ഉപയോഗിച്ചു. പൂർണ്ണമായും ക്രമരഹിതമായ രൂപകൽപ്പനയിൽ രണ്ട് ചികിത്സാ തലങ്ങളോടെ പരീക്ഷണം നടത്തി, അതായത് നിയന്ത്രണവും ഉയർന്ന താപനില സമ്മർദ്ദവും (36 +/- 2oC) മൂന്ന് തനിപ്പകർപ്പുകൾ വീതം. 45 ദിവസത്തേക്ക് താപനില നിയന്ത്രിത ഹരിതഗൃഹ കേന്ദ്രത്തിൽ കലങ്ങൾ സൂക്ഷിച്ചുകൊണ്ട് പുഷ്പത്തിന്റെ തുടക്കം മുതൽ പക്വത ഘട്ടത്തിലേക്ക് ഉയർന്ന താപനില സമ്മർദ്ദം സൃഷ്ടിച്ചു. പൂച്ചെടികളുടെ ഘട്ടത്തിൽ ഫിനോളജിക്കൽ, ഫിസിയോളജിക്കൽ, ബയോകെമിക്കൽ പാരാമീറ്ററുകൾ എടുത്തിരുന്നു. വിളവെടുപ്പ് ഘട്ടത്തിൽ ഗുണനിലവാരമുള്ള പരാമീറ്ററുകളും വിളവ് പാരാമീറ്ററുകളും എടുത്തിട്ടുണ്ട്.

സ്ട്രെസ് ഇൻഡക്ഷന് ശേഷം 15-ആം ദിവസം മെംബ്രൻ സ്റ്റെബിലിറ്റി ഇൻഡെക്സിൽ (എം.എസ്.ഐ) കുറവും കൺട്രോൾ പ്ലാന്റുകളുമായി താരതമ്യപ്പെടുത്തുമ്പോൾ സ്ട്രെസ് ഇൻഡക്ഷന് ശേഷം 25-ാം ദിവസത്തേക്ക് കുറവുണ്ടായി. ഉയർന്ന താപനിലയുള്ള സാഹചര്യങ്ങളിൽ നന്ദി (87.38%), അർക്ക വികാസിന് (36.31%) പരമാവധി പ്രവർത്തനക്ഷമതയുള്ള എല്ലാ ഇനങ്ങൾക്കും തേനാണ് പ്രവർത്തനക്ഷമത ഗണ്യമായി കുറഞ്ഞു. മൊത്തം ക്ലോറോഫിൽ ഉള്ളടക്കം (mg g-1 പുതിയ ഭാരം), ഫോട്ടോസിന്തറ്റിക് നിരക്ക് (A) μ CO2 മോളുകൾ m-2 s-1), ട്രാൻസ്പിറേഷൻ നിരക്ക് (E) (mmol H2O m-2 sec-1) പോലുള്ള ഫിസിയോളജിക്കൽ പാരാമീറ്ററുകൾക്കും സമാന ഫലങ്ങൾ ലഭിച്ചു. ഉയർന്ന താപനിലയിൽ തക്കാളി ചെടികളിൽ അന്നജം, ലയിക്കുന്ന പഞ്ചസാര എന്നിവയുടെ ഗണ്യമായ ജനിതക വ്യത്യാസങ്ങൾ കണ്ടെത്തി. കുറഞ്ഞ താപനില വ്യവസ്ഥകളെ അപേക്ഷിച്ച് ഉയർന്ന താപനില സാഹചര്യങ്ങളിൽ ടൈറ്ററബിൾ അസിഡിറ്റി (ടിഎ), തക്കാളി പഴങ്ങളുടെ മൊത്തം ലയിക്കുന്ന സോളിഡുകൾ (ടിഎസ്എസ്) എന്നിവ ഉയർന്ന സാന്ദ്രതയിലാണ്. താപ സമ്മർദ്ദത്തിൽ ടൈറ്റബിൾ അസിഡിറ്റിയുടെ ശതമാനം വർദ്ധനവ് അർക്ക അലോക്കിന് (27%) ഏറ്റവും കുറഞ്ഞത് പുസ രോഹിണിക്ക് (2%). നിയന്ത്രണ ആംബിയന്റ് അവസ്ഥയിൽ ഏറ്റവും

ഉയർന്ന ടിഎസ്എസ് അർക്ക സാമ്രാട്ടിന് (5.72%), ഐസി -45 (2.32%) ന് ഏറ്റവും കുറവ് രേഖപ്പെടുത്തി. ഉയർന്ന താപനിലയിൽ ഏറ്റവും ഉയർന്ന ടിഎസ്എസ് രേഖപ്പെടുത്തിയത് കാശി വിശേഷിന് (6.23%) ഏറ്റവും താഴ്ന്ന ഐസി -45 (2.57%). താപനില ഉയരുന്നതോടെ ലൈക്കോപീൻ അളവ് കുറയുകയും അന്തരീക്ഷ അവസ്ഥയിൽ പഴങ്ങളിൽ ഏറ്റവും ഉയർന്ന ലൈക്കോപീൻ ഉള്ളടക്കം രേഖപ്പെടുത്തുകയും ചെയ്തു.

വിളവും ഫിസിയോളജിക്കൽ ഡാറ്റയും സംബന്ധിച്ച്, സമാന സ്വഭാവസവിശേഷതകൾ പങ്കിടുന്ന ഇനങ്ങളെ മൂന്ന് വിഭാഗങ്ങളായി തരംതിരിക്കാം, അതായത് സഹിഷ്ണുതയുള്ള ഇനങ്ങൾ, മിതമായ സഹിഷ്ണുത, സാധ്യതയുള്ള ഇനങ്ങൾ. ടോളറന്റ് ജനിതകരൂപങ്ങൾ (നന്ദി, കാശി വിഷേഷ്, വെല്ലയാനി വിജയ്) വിളവ് (10-30 ഗ്രാം -1 പ്ലാന്റ്), എംഎസ്ഐ (60-70%), പിവി (50-70%), അന്നജം (190-200 മില്ലിഗ്രാം ഗ്രാം) -1 പുതിയ ഭാരം), A (17-22 µmol CO2 m-2 sec-1), Gs (47-68 mmol H2O m-2sec-1), CF (Fv / Fm) (0.6-0.7). മിതമായ സഹിഷ്ണുത പുലർത്തുന്ന ഇനങ്ങൾ (അക്ഷയ, മനുപ്രഭ, IIHR-2200, വൈഭവ്) വിളവ് (5-15 ഗ്രാം -1 പ്ലാന്റ്), എംഎസ്ഐ (40-50%), പിവി (45-50%), അന്നജം (200 മില്ലിഗ്രാം) g-1 പുതിയ ഭാരം), A (17-19 olmol CO2 m-2 sec-1), Gs (55-65 mmol H2O m-2sec-1), CF (Fv / Fm) (0.6-0.7), വരാൻ സാധ്യതയുള്ള ഇനങ്ങൾ (അർക്ക വികാസ്, പൂസ രോഹിണി, അർക്ക സൗരഭ്, അർക്ക രക്ഷക്) വിളവ് (0.5-5 ഗ്രാം -1 പ്ലാന്റ്), എംഎസ്ഐ (25-40%), പിവി (44-45%), അന്നജം (90-110) mg g-1 പുതിയ ഭാരം), A (13-16 µmol CO2 m-2 sec-1), Gs (30-37 mmol H2O m-2 sec-1), CF (0.4-0.5). അതിനാൽ, തെർമോ-ടോളറൻസ് വർദ്ധിപ്പിക്കുന്നതിന് പ്രധാന ഫിസിയോളജിക്കൽ സ്വഭാവങ്ങളുള്ള ജനിതകശാസ്ത്രത്തെ തിരിച്ചറിയുന്നതിൽ ഈ പഠനത്തിന് പ്രാധാന്യമുണ്ട്, അതിനാൽ ഉയർന്ന താപനിലയിൽപ്പോലും അവർക്ക് മിതമായ വിളവ് ലഭിക്കും