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ABIOTIC STRESSES IN COTTON: A PHYSIOLOGICAL APPROACH

Central Institute for Cotton Research
Nagpur

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1. INTRODUCTION

Prosperity of Indian economy wholesome depends upon positive strides in agricultural and industrial sectors. In the new millennium, sustainable agriculture will be the need of the hour in the context of global and liberalization trends. Crop production encounters various biotic and abiotic stresses particularly in the arid and semiarid regions. The micro and macro crop environments pave way for the natural formation of different agro-climatic zones and the quantum of deleterious and adverse stress factors become realistic in limiting yield realization in crops. In this context, plant physiological approaches in crop production assume importance to unravel the abiotic stress mechanisms and to identify explicit tolerance traits for countering the detrimental stress onslaught during ontogeny.

Cotton is the most important fiber crop and is the basic input to the textile industry. In India, cotton is grown in about 9 million ha. of which more than 70 per cent area is rainfed (Table 1). Maharashtra has an estimated area of 2.8 million ha under cotton, predominantly under rainfed cultivation. Rainfed cotton production has significant contribution towards productivity and an erratic cotton output trend may offset lint-fabric continuum and may upset our exim policies. It is obvious that growth and development of cotton has to face one or other stress entities under rainfed situation. Cotton physiology portrays unique indeterminate growth habits with longer crop duration which make cotton vulnerable to abiotic stress influences from emergence to senescence. The adverse effects on the ongoing physiological processes may affect yield projection trends leading to production lapses, inadequacies and may become the focal point of attention.

The various abiotic stress factors affecting cotton growth, development and yield mostly originate due to weather and soil constraints. Their occurrence may be erratic or specific and the intensity may be varying in their adversity. Consequently, stress imprints are marked in the altered plant traits. The major abiotic stress factors affecting cotton production are-

Table: 1. Rainfed cotton area in India

Regions	Area (m ha)
Gujarat	
South Gujarat cotton zone	0.1
Middle Gujarat	0.4
Wagad cotton zone	0.5
Mathio cotton zone	0.1
Madhya Pradesh	
Malwa region	0.25
Nimar region	0.33
Maharastra	
Marathwada region	0.7
Vidarbha region	1.4
Kandesh region	0.4
Andhra Pradesh	0.4
Tamil Nadu	0.2
Karnataka	0.9
Total	**5.7(71%)**

Source: Tripathi B.K., Munshi Singh and Narula A.M. Constraints in Productivity of Cotton in India and Future Strategies for Improvement. **Cotton Scenario in India- A souvenir 1990.**

Drought Low light High temperature Waterlogging Salinity

The stress factors are likely to develop independently or in selective combination depending upon the magnitude and severity of the problem. For instance, in Central India, cotton has to respond to low light stress during early growth phase. However, waterlogging may also simultaneously occur if the period and intensity of precipitation is high. Drought stress mostly commences during reproductive phase, whereas high temperature stress may co-develop under conditions of prolonged dry spell.

2. DROUGHT STRESS

Prolonged dry spell due to uneven and erratic monsoon particularly under rainfed condition will lead to rapid depletion in soil moisture. Drought stress gradually develops and intensifies during the course of soil moisture decline resulting in restricted growth and development in cotton. The current photosynthesis is impaired and sustainability of leaf turgor may not be adequate to display an efficient canopy. Cotton has to adapt or tolerate such adverse effects by various morpho-physiological traits. The most important physiological process is to possess higher water use efficiency. This is mostly achieved by stomatal regulation. Prevention of water loss by stomatal closure in restricting active transpiration from the leaf surface however tend to increase leaf temperature as a reflex action. Plant has to adapt the optimum physiological processes to ward off any harmful effects. Epicuticular wax on the leaf surface may act as a protective mechanism.

The critical crop stage encountering dry spell is important. Drought stress at early growth phase may lead to poor crop stand as the survival of the crop is at a great risk. Extension of dry spell duration at very early growth stage may become disastrous for cotton performance. Mid stage drought stress corresponding to peak flowering is critical as far as yield realization is concerned. Water requirement is relatively higher at this crop age to sustain developing squares and young bolls, whereas it is comparatively lower at pre-flowering and post-flowering stages. Continuous stress may enhance abscission of fruiting parts thus affecting sink strength. The water requirement of cotton pertaining to different stages of growth is given in Table 2.

Table: 2. Water requirement of cotton (cubic m per ha)

Crop stage	Water requirement
Before flowering	700-800
During flowering	800-1000
During ripening	600-700

Cotton water requirement is about 5000 to 8000 cu.m during the season for obtaining a normal yield. Reduced water availability due to dry spell has telltale effect on growth and development due to adverse effect on the ongoing physiological processes. Studies conducted at Central Institute for Cotton Research, Nagpur indicated that leaf water potential beyond- 13 bars is more critical. Occurrence of terminal moisture stress, on the other hand may result in early age on yield may not be of great concern since contribution of late formed fruiting parts towards productivity is meager.

Among all critical stages, flowering phase is important as far as effective contribution of developing sink towards yield is concerned. The various adaptive and tolerant mechanisms in cotton in response to drought stress is given in Table.3.

Table: 3. Adaptive and tolerant morpho – physiological, biochemical and anatomical traits in cotton

- **Deep root system**
- **Higher root-shoot ratio**
- **Decrease in leaf area expansion**
- **Epicuticular waxiness**
- **Leaf rolling**
- **Maintenance of leaf turgidity at lower water potential**
- **Osmoregulation**
- **Increase in stomata per unit leaf area**
- **Stomatal regulation- closure of stomata**
- **Decrease in transpiration rate as a response to stomatal closure**
- **Early senescence and cut out**
- **Increase in abscission of fruiting parts**
- **Increase in praline content**
- **Increase in non- protein aminoacids**
- **Cellular adaptations-**
  - **Increase in cell wall thickness**
  - **Development of mechanical tissue**
  - **Decrease in cell size and intercellular space**

Deep root system and higher root- shoot ratio are adaptive mechanisms in response to water deficit. Roots may penetrate deep into the soil in search of moisture and in this context desi (diploid) cotton exhibits better adaptation to drought due to deep and efficient root system. Leaf surface in the canopy. As far as osmoregulation is concerned, accumulation of praline in response to water deficit acts as a better osmoregulant. Stomatal regulation in conserving moisture may enhance internal water potential to maintain optimum physiological efficiency. The various adaptive and tolerant traits in cotton as a response to inducted water deficit were studied in CICR, Nagpur and the results are presented in Table 4.

Table: 4. Morpho-physiological and biochemical parameters at flowering with drought stress induction (values given are mean over genotypes)

Plant Characters	Control	Drought
Biomass (g/pl)	33.6	30.9
Root-shoot ratio	0.17	0.18
Leaf temperature(^{o}C)	29.0	30.2
Stomatal resistance (s/cm)	0.9	1.8
Transpiration rate (µg H_2O)	13.8	7.7
Relative water content (%)	71.9	71.5
Leaf water potential (bars)	-13.6	-21.3
Praline content (µg/g)	21.0	25.5
Seed-Cotton yield (g/pl)	17.5	15.6

Pot experiments conducted at CICR, Nagpur indicated that the decline in soil moisture during induction of drought stress was rapid whereas the leaf relative water content showed a gradual decline in two elite cotton cultivars (Table.5) this signifies that irrespective of steep declining trends in soil moisture, cotton showed an adaptive and survival tendency by maintaining optimum leaf turgor during initial drought induction period.

Table: 5. Relationship between soil and plant moisture status

Date	Soil moisture Content (%)			Leaf relative water content (%)		
	LRA 5166	**LRK 516**	**Mean**	**LRA 5166**	**LRK 516**	**Mean**
21.09.98	23.2	23.3	23.3	87.5	87.5	87.5
23.09.98	20.6	19.4	20.0	92.5	88.6	90.6
25.09.98	16.1	14.6	15.4	92.4	91.7	91.2
28.09.98	8.1	6.7	7.4	70.6	77.4	74.0

In another study, it was noticed that the abscission of buds and bolls under rainfed condition had a significant negative relationship with stomatal resistance. This shows that a higher stomatal resistance as expected under rainfed condition may be useful in enhancing internal water status for sustainable productivity.

2.1 Management

Physiological management approaches to mitigate drought stress mainly consist of enhancing drought tolerance in genotypes or use of antitranspirants, growth regulators and growth retardants. Studies conducted at CICR led to identification of following relatively higher drought tolerant genotypes – **COT 7, COT 10, Arabhavi, Arkansas 61 – 28, AP 18 – 1(1254), B 56 – 286 – CT, 7048, BT – 955, AR – 20, NIAB 72, LRA 5166, OK 2563, BBR IC 257, VAR 28, MHL 3, JBWR 35, JBWR 21, EG 3, JBWR 34, JBWR 25, VAR 20**

Use of antitranspirants reduce transpiration by 30-40 per cent by effective stomatal closure. The disadvantage of using antitanspirants is that induced closure of stomata may be useful in preventing water loss by transpiration but may also affect growth and developmental events due to the impediments in CO2 diffusion within the tissues. Kaolin 12 per cent spray one month after cessation of precipitation and pix 50 ppm spray at 50 per cent flowering period were found useful in enhancing yield under drought condition. It has been observed that Kaolin reduces leaf temperature 2-3 o C due to its light reflectance action. Growth retardants increase water use efficiency by improving root development and delaying senescence.

Adjusting planting dates to minimize the effect of drought during active reproductive phase may serve as an escape mechanism from the impact of depleted soil moisture. Drought condition coupled with low relative humidity may be more harmful and providing adequate irrigation and moisture conservative weeds may be beneficial in reducing the adverse effects. Moisture conservation practices will effectively reduce evapo-transpiration and the plant response in improving internal water status may be adequate for optimum growth and development. It is better to avoid drought by all available and possible means by the right selection and combination of genotypes and mitigation strategies.

2.2 Future line of work

- **Identification of physiological, biochemical and molecular trait/s which impart drought tolerance and could be useful in rapid screening of genotypes.**
- **Utilization of wild species in breading of drought tolerant genotypes.**

- **Identification of drought tolerant genes and their incorporation in evolving elite genetic material through molecular approaches.**

3. LOW LIGHT STRESS

Partial to full cloudy conditions pertaining to active monsoon season (July to September in Central India) cause low light stress affecting growth and development of cotton. The low light stress may also extend even in October, if the rainfed persists. The stress occurs due to reduction in light intensity and total sun shine hours. The stress occurs due to reduction in light intensity and total sun shine hours. The light intensity on a full cloudy day may fall below 400 µE and the sun shine hours may be drastically restricted, sometimes even reaching zero.

The morpho – physiological effects of low light stress on cotton are briefly mentioned below

- **Increase in cotyledonary leaf area**
- **Increase in leaf area expansion**
- **Increase in leaf chlorphyll content per unit area**
- **Increases in shedding of fruiting parts**
- **Increase in light interception**
- **Decrease in biomass production**
- **Decrease in specific leaf weight (SLW)**

Plants response to low light stress occurs mainly by persistent increase in source area and chlorophyll content for effective light interception. However, abscissions of fruiting parts occur due to lower biomass generation and reduction in SLW. The seed- cotton yield tend to decline under such situation.

Studies were conducted at CICR, Nagpur on the morpho- physiological characters in relation to normal and low light (30o% reduction in normal light) with AKH 4, H4, LRA 5166 and SRT 1 and the results are presented in Table 6.

Table: 6. Morpho- physiological characters and yield under normal and low light condition (Mean over genotypes)

Characters	Normal light	Low light
Cotyledenory area (cm^2)	12.3	15.6
Plant height (cm)	57.0	73.1
Leaf area (cm^2)	1413	2028
Specific leaf wt. (mg cm^2)	5.3	4.3
Stomatal resistance (s/cm)	1.7	3.6
Transpiration rate (µg H^2O)	13.0	5.9
Total chlorophyll content (mg/g)	1.02	1.13
Total biomass production (g)	42.8	42.2
Seed – cotton yield (g/pl)	23.1	20.8

Studies on low light induction brings into light the adverse effects of low light on yield realization particularly when the low light stress is extended for a longer duration.

Prevalence of low light duration reproductive phase leads to increase in physiological shedding of fruiting parts thus affecting final yield.

3.1 Management

Growing of low light stress tolerant genotypes. Studies conducted at CICR, Nagpur led to identification of following genotypes with relatively higher tolerance to inducted low light **JBWR 20, JBWR 34, TXORSC 78, VAR 13, JBWR 2, JK 97, IC 283, LRA 5166.** Avoiding high plant density and excessive vegetative growth facilitates increase in light interception into the canopy. Besides, adjusting planting dates to avoid intensive flowering phase coinciding with low light incidence may adequately increase canopy light use efficiency.

4. HIGH TEMPERATURE STRESS

The temperature range 26-32^{o}C is desirable during day time but the night should be cool during flowering and fruiting in cotton. This crop is able to tolerate short periods of high temperature upto 43-45 ^{o}C if soil moisture condition is favorable. High day temperature coupled with high night temperature delay flowering. The associative trend of high temperature low relative humidity is more harmful in desiccating the leaf surface due to sharp increase in leaf temperature. High temperature regimes affect plant metabolism by impairing membrane thermostability and photosynthetic process. Enzyme activity is more sensitive and proteins may be denatured at elevated temperatures. Plants tolerate high temperature by the accumulation of low molecular weight 70 kda heat shock proteins. The other heat avoidable mechanisms include light reflectance and transmittance to reduce the radiation load and to maintain active transpiration cooling. Thick cuticle and hairiness are desirable characters to minimize the heat stress effects.

The heat stress management includes – identifying plants with relatively higher tolerance or acclimatization to high temperature growing conditions. In this context, cotton possesses near xerophytic characters and wild cotton species have relatively more heat tolerance. High temperature effect may considerably be reduced by providing adequate irrigation at critical stages of growth which may lead to leaf cooling effects. Use of light reflectant material and soil moisture conservation at appropriate times may be useful in reducing the ill effects of elevated temperature. Such measures may enhance water use efficiency.

5. SALINTY STRESS

5.1 Types of salt affected soils

Salt affected soils are mainly confined to arid and semiarid regions of the world. Common ions contributing to this problem are **Ca. Mg, Na, C1, SO_4, HCO_3** and in some instances K and NO_3. As per USDA classification, the soils having EC of the saturated extract more than 4 dS m^{-1}, ESP more than 15 and pH more than 8.5 are categorized as alkali soils. Since most of the crops are very sensitive to salinity, recently the nomenclature committee of American Society of soil Science reduced the limits for saline soils to 2 dS m^{-1} from 4 dS m^{-1}.

5.2 Prevalence

Salt affected soils are found in almost all agro- ecological regions. In India, approximately 12m ha of cultivable land is under salty affect of which 3.6 m ha land is under alkali and rest is under saline soils (Table 7). The rainfed tract of Gujarat, Maharashtra, Karnataka and Andhra Pradesh has approximately 3m ha of salt affected soils of which nearly ¼ th of area is under alkali condition. Most of these areas belong to the cotton growing districts of Karnataka (Bijapur, Dharwad, Gulberga, Raichur), Maharastra (Akola, Amaravati, Buldana, Solapur, Dhule, Ahmednagar, Sangli), Andhra Pradesh (Guntur, Bapatla and other cotton growing district), and Gujarat (Some of the coastal districts).

Table: 7. Area of salt affected soils in states where cotton is grown

State	Type	Severity				Total (000 ha)
		Slight	Moderate	Strong	Extreme	
Gujarat	Salinity	-	147.9	146.4	-	294.3
	Salinity & water erosion	1160.5	162.3	42.9	-	366.0
	Salinity & Wind erosion	282.3	17.5	-	-	300.0
	Salinity & Flooding	70.4	156.1	103	194.0	524.0
Maharastra	Salinity & Alkalinity	-	887.6	-	169.0	056.0
A.P.	Salinity & Sodicity	42	16	156	204	517.0
Karnataka	Salinity	-	100	-	-	100
	sodicity	-	-	10	-	10
Rajasthan		-	-	-	-	958
Punjab		-	-	-	-	749
Haryana		-	-	-	-	636

Source: Soil Resource Management, **published by NBSS & LUP** and Salt affected soils of India by G.P.Bhargava 1989, **Oxford and IBM publishing Co. Pvt.Ltd.**

5.3 Causes

Soil degradation through salinisation and alkalization is seriously affecting the productivity of large areas of cultivated soils. Salinisation and alkalization causes poor plant growth and yield due to three major effects i) water stress caused by salt acting as an osmoticum ii) specific ion toxicity and iii) nutrient imbalances. In saline soils and saline sodic soils, all the 3 factors may contribute to reduced growth, whereas in alkaline soils ion toxicity and nutrient imbalances contribute to reduced growth.

5.4 Methodology followed to assess salinity tolerance

a) Screening for salt tolerance at germination stage:

Seeds of advanced germplasm lines, varieties and hybrids are germinated either in petriplates or germination papers. They are exposed to a sequence of NaC1 and $Na_2 CO_3$, during which the plants (seeding) are exposed to a optimum sublethal stress (induction), severe stress (lethal) and recovery in water for a known duration

Germinated Seedings ► Induction stress for16 hr (200 mM NaC1) ► Lethal Stress for 48 hr (400 mM NaC1) ► Recovery in H_2O for 48 hr

Observations

- Root and Shoot growth at all the 3 sets during stress and at the end of the recovery, both in induced and non- induced treatments.
- Protein/ isozyme studies in tolerant and susceptible genotypes
- Identification of tolerant and sensitive genotypes which can be utlised to understand the tolerant mechanisms.

b) Screening at whole plant level :

i) Field testing : Since salinity is more complex over space and time, evaluation for salinity tolerance in the field is difficult. Nevertheless, it is useful in screening large number of germplasm lines for their relative salinity tolerance.

ii) Pot culture : In pot culture, graded salinity levels can be created by irrigating the plants with known salinity solutions. Since the physical and chemical properties of the soil vary to a large extent it is difficult to ensure if the plant is growing under a desired level of salinity or not. Still pot culture is useful to screen large number of genotypes for relative salinity tolerance.

iii) Hydroponics (water culture): In hydroponics since the plant is grown with known level of salinity the absolute effect of salt on plant growth and the threshold concentration required to bring reduction in plant growth can be determined. Further, this technique is useful in identification of trait/s which impart tolerance to salinity. At CICR, the technique of growing the plants in hydroponics has been standardized (Plate.1) one week old seed grown in sand are transferred to plastic containers, containing one strength Hoagland solution. The nutrient solution is aerated regularly. The seedling which are established in hydroponics are treated with known salinity solutions.

Some of the physiological, biochemical and molecular observations which are found to be useful in understanding the tolerance mechanisms are listed below:

Physiological: Osmotic potential, root to shoot ratio, growth rates, chlorophyll stability, water potential, stomatal resistance.

Biochemical: K and Na content at different plant parts, qualification of enzymes viz. peroxidase (NR).

Molecular: identification and qualification of stress responsive proteins namely osmotins, LEA (late embryogenesis abundant) proteins.

5.5 Effects of salinity on growth and yield

A major difficulty associated with assessment and measurement of salt tolerance in cotton is variation in tolerance with growth stages or ontogeny.

5.5.1 Germination

Cotton is very sensitive to salinity germination and emergence. The germination percentage of most of the genotypes is not affected by salinity upto 10 dS m-1.Beyond 10 dS m-1 , however germination is drastically reduced. In one of the experiments, seed treatment with 15 and 20 dS m-1 NaCl reduced the germination percentage by 45 and 65 per cent of control plants respectively. More than the germination, cotton seeds are more sensitive to the emergence duration. The seedling emergence from the soil took 8 and 9 days at salinity concentrations of 15 and 20 dS m-1respectively in comparison to 4 days in control plants. By the time the seedling emerge from the soil all the nutrients are exhausted and resulted in poor crop stand at higher salinity levels.

5.5.2 Plant growth and yield

Cotton is relatively a salt tolerant crop however species as well as varietal variation exists for salt tolerance. Amongst the different crops viz. wheat, soybean, cotton and maize, cotton is the most tolerant and soybean is the most sensitive crop to salinity. Hydroponic experiments revealed that plant height, leaf area, square and boll number and plant biomass were not affected by salinity upto10 dS m^{-1} beyond which i.e., at 15 and 20 dS m^{-1} they were drastically reduced (Fig.1.). Early seedling stage is more sensitive to saline condition than later stages of growth. G.herbaceum and G.barbadense were found to be more tolerant than G.arboreum and G.hirsutum.

5.6 Mechanisum of tolerance

Although the mechanism of adaptation of plants salinity is not clear, many basic physiological attributes including direct modification of the influx and/ or efflux of ions such as K and Na across the plasma membrane and tonoplast, synthesis of compatible osmotica such as proline, other amino acids, soluble carbohydrates, and glycine betaines, and modification of membrane composition have been found to be important components of a salt tolerant phenotype. Sodium accumulation in roots and leaves showed a linear increase upto10 dS m^{-1} beyond which it was plateud. Contrarily, root K remained stable at all salinity levels and leaf K content declined sharply at 5 and 10 dS m^{-1}. Tolerant varieties had high K/Na ratio compared to susceptible varieties (Table 8).

Table: 8. Comparison between a salinity tolerant and susceptible variety

	0 EC	5EC	10EC	15EC
Biomass (g plant^{-1})				
Tolerant	29.14	28.52	23.89	21.50
Susceptible	28.62	21.46	5.50	-
NAR (mg cm-^{2} day-^{1})				
Tolerant	0.26	0.12	0.091	0.032
Susceptible	0.35	0.19	0.10	-
RGR(gg-^{1}day-^{1})				
Tolerant	0.085	0.074	0.077	0.075
Susceptible	0.079	0.045	0.04	-
K/Na ratio				
Tolerant	6.5	5.2	5.3	0.5
Susceptible	7.4	3.0	1.8	-

5.7 Management

Two broad approaches viz. reclamation and adoption of appropriate management practices can be utilized to overcome the salt effect. Under rainfed condition however, reclamation of the soil is very difficult mainly because of the scarcity of water to leach out the salts. Management practices that can aid in obtaining better crop production include choice of crops that are more tolerant to salt affected condition and other practices that minimize the salt concentration in the root zone of growing crops. Screening of popularly cultivated varieties at CICR has identified the following varieties as tolerant to salinity viz. **LRA 5166, PKV 081, Khandwa 2, 3, Acala 44, CNH 36, LD, 327, Dhumad.** Amongst the various amendments used for improvement for alkali soils gypsum along with improved package of practices altered the physico- chemical characteristics of soil. Application of gypsum decreased pH, ECe and ESP and also enhanced the yield.

Organic residue incorporation improved the physical conditions of the soil. A close relationship between aliphatic component of soil organic matter and microbial biomass and soil aggregation has been reported. Various cultural and mechanical measures like tillage operations, opening of furrows can help in in – situ moisture conservation and improve the soil moisture storage by way of reducing the surface run off. Improved physical properties of soil increased yield of salt affected soils.

5.8 Future line of work

- **Gradual improvement in salinity tolerance through conventional breeding and selection**
- **Introgression with wild progenitors, which may already posess salinity tolerance**
- **Domestication of wild species that currently inhabit saline environments by breeding and selection for improved agronomic characteristics**
- **Identification of salt tolerant genes, clone it and its manipulation across conventional genetics barriers using the advanced techniques of molecular biology**

6. WATERLOGGING

Cotton in India is grown in different agroclimatic zones. In North India more than 95 per cent of the crop is irrigated. Due to excessive canal irrigation, the water table in parts of Haryana, Rajasthan and Punjab had risen to such a high level that it is becoming difficult to grow cotton crop. In due course, rice or other crops may replace cotton in these areas. In Central India, more than 70 per cent of the crop is grown under rainfed conditions and often it suffers from waterlogging duration early and mid vegetative growth stages. Even in South India where part of the crop is cultivated under irrigated condition and rest under rainfed condition cotton experiences waterlogging at one or other stages of its life cycle.

Flooding or submerging an air dry soil in water sets in motion a series of physical, chemical and biological processes that profoundly influence the quality of soil as a medium for plant growth. Flooding a dry soil destroys soil structure by disrupting the aggregates. The soil pore space is totally water filled, and gas exchanges between soil and atmosphere is virtually eliminated. Drastic restriction of gas exchange between flooded soil and the atmosphere leads to depletion of molecular oxygen and accumulation in the soil of CO2, methane and hydrogen. Deoxygenation and accumulation of the above gases in the rooting medium cause either root damage or death of the plant. Thus, growth and productivity of the plant will be affected.

Cotton has been classified as a susceptible crop for waterlogging. However, the occurrence and extent of any particular response depends on many interrelated factors such as the species or the cultivar, its age and stage of development, duration depth and timing of flooding, soil type.

6.1 Effect on root growth

The imposition of excess water around roots affected its development. Root elongation has been inhibited under anaerobic condition. The deeper roots die and quite often there is proliferation of surface roots and hence, waterlogged plants will have a smaller and more superficial root system. The severity of the effect of transient flooding on root system depends on growth stage of the plant (Table 9). Those roots that became submerged during the early seedling growth immediately ceased extension. With flooding immediately after flowering, roots below the water table ceased extension and new roots compensated for this by growing from roots located in the upper part of the soil.

6.2 Effect on shoot growth

Waterlogged plants had a stunted growth compared to normal well aerated plants (Table 9). Plants are more sensitive at early seedling stage and waterlogging the plants at or after flowering had no significant effect on plant height. Leaf growth is extremely sensitive to flooding and root anoxia. Leaf area per plant has been reduced by inhibiting leaf initiation and expansion as well as by inducing leaf abscission. The above ground plant growths as well as root growth were very sensitive to waterlogging at early growth stages. Through, withdrawing the waterlogging treatment after 45 days resulted in a gradual recovery of plant growth in 45 day old waterlogged plants, but it failed to produce any yield. On the country, there was only a marginal reduction in yield when plants were waterlogged at 90 days after sowing. This suggests that plants subjected to waterlogging at flowering or later stages are getting adapted and maintain their growth.

Table: 9. Impact of continuous waterlogging (45 days) at different growth stages (45 and 90 DAS)

Characters	Waterlogging at			
	45 DAS		90 DAS	
	Normal	Waterlogged	Normal	Waterlogged
Plant height (cm)	79	28	140	135
Leaf area(cm^2)	1192	265	2728	2514
Above ground biomass(g)	19.5	6.2	41.0	36.5
Root biomass (g)	5.2	0.9	12.0	7.1
Seed- cotton yield (g/plant)	19.0	0.0	19.0	15.4

6.3 Adaptation to waterlogging

Species as well as varieties vary in their tolerance to flooding. Cotton plants exhibit metabolic adaptation to tolerant anoxia (truly anoxia tolerant plant), as well as morphological and physiological adaptation to avoid anoxia (apparently anoxia tolerant) and few do not adapt and succumb very quickly to anoxia (anoxia intolerant).

6.3.1 Morphological adaptation

Work carried out at CICR, Nagpur showed that waterlogged cotton plants at the zone of submergence produced specialized cells called as 'lenticels' (Plate 2). Lenticels were formed few centimeters above and at the zone of submergence within 3 days of waterlogging. Further it was observed that when only bottom half of the roots were submerged, there was no formation of lenticels and all the roots became apparently negatively geotropic. Similarly, once the waterlogging treatment was withdrawn the lenticels gradually disappeared. This indirectly suggested the involvement of lenticel in oxygen uptake and its transfer from shoot to roots and thus helped the waterlogged plants to maintain stable root activity. Since the stem girth was very less at early growth stages, waterlogging of these plants produced only few lenticels and thus they were very sensitive to waterlogging. Tolerant varieties **Viz. LRA 5166, LRK 516, F414, F505** formed lenticels immediately after waterlogging, while susceptible varieties took more time.

6.3.2 Metabolic adaptation

Cotton plats exhibit metabolic adaptation in addition to morphological adaptation to withstand adverse affect of waterlogging. Anaerobiosis induced alteration in protein synthesis has been reported in cotton. Fourteen major polypeptides are shown to be selectively synthesized under anaerobiosis in cotton and designated as cotton anaerobic polypeptides (ANPs), of which 3 of the major ANPs are alcohol dehydrogenase (ADH) enzymes. Alcohol dehydrogenase plays a major physiological role plants during anaerobic stress when carbohydrate metabolism must switch from an oxidative to a fermentative pathway. ADH is a terminal enzyme in the ethanolic fermentation pathway converting acetaldehyde to ethanol and regenerating NAD^+ in the process. Removal of acetaldehyde is important because of its phytotoxic effects and the regeneration of NAD^+ is essential for the continuation of anaerobic glycolysis, which is the major source of cellular ATP during periods of anaerobiosis. The ongoing work at our laboratory showed that waterlogged cotton plants had higher ADH activity in the roots compared to leaves and shoot (Table 10) thus enabling the plant to continue anaerobic glycolysis and the ATP synthesis.

Table: 10 The ADH activity of roots and shoots of LRA 5166 after 5 days of waterlogging.

Treatment	Specific activity of ADH (units / mg of protein)	
	Root	Shoot
Control	1.3±0.2	1.7±0.3
Waterlogged	6.8±1.1	5.2±0.9

6.4 Future line of work

- **Mechanism of lenticel formation and reasons for genotypic variation in lenticel formation**
- **The biochemical and molecular attributes that enable few genotypes to survive without oxygen for considerable time.**
- **Role of plant hormones in adaptation to waterlogging.**

Detailed elucidation of the mechanism which impart tolerance to various abiotic stresses at physiological, biochemical and molecular level is a pre-requisite in improving crop productivity. The anticipated global environmental changes in the near future may further aggravate the abiotic stress related plant responses. This necessitates intensive research efforts so as to better understand and manage cotton from adverse effect of biotic stresses.