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Effect of Waterlogging and Submergence on Crop Physiology and Growth of Different Crops and Its Remedies: Bangladesh Perspectives

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Abstract: This review assesses the impact of waterlogging and submergence on crop physiology and growth of important crops in Bangladesh along with its remedial measures. Waterlogging can take place because of heavy rainfall, inadequate drainage systems, natural flooding etc. Oxygen levels diminish very rapidly in waterlogged root environment. So, damage of crops depends on duration and severity of flooding. The oxygen deficient conditions hamper plant growth, development and survival based on their tolerance to excess water. Under such environment plants exhibit metabolic switch from aerobic respiration to anaerobic fermentation, resulting in reduced rate of energy production by 65-97%. Anaerobic roots may also die from self-poisoning byproducts of anaerobic metabolism. The flooding also impedes the diffusive escape and/or oxidative breakdown of gases such as ethylene or carbon dioxide resulting in its accumulations. The accumulated ethylene may slow root extension, while carbon dioxide can severely damage roots of certain species. Moreover, waterlogged plants often face the oxidative damage induced by the generation of reactive oxygen species. However, all the plants have the ability to detoxify the adverse effects of reactive oxygen species (ROS) by producing different types of antioxidants such as ascorbate peroxidase (APX), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), glutathione reductase (GR), ascorbic acid, glutathione, tocopherols and carotenoids. Prolonged exposure of plants to flooding conditions could result in root injuries which in turn restrict photosynthetic capacity by inducing certain alterations in biochemical reactions of photosynthesis. Waterlogging is also known to induce adverse effects on several physiological and biochemical processes of plants by creating deficiency of essential nutrients like nitrogen, magnesium, potassium, calcium. Species with inherently surface-inhabiting root systems are notably tolerant of prolonged waterlogging. There are several options for mitigation of submergence and waterlogging problems like breeding of waterlogging tolerant varieties, improvement of drainage systems and changing in crop husbandry. Providing adequate drainage, foliar spraying of fertilizers and hormones can alleviate waterlogging problems. Bed planting in waterlogged prone areas and floating beds in flooded areas are good options for high value crops.

Keywords: waterlogging, drainage systems, photosynthesis, aerobic respiration, fermentation.

INTRODUCTION

Water and oxygen are the indispensable components of every living being including plants. Plants operate photosynthesis in the leaves while securing water and minerals from the soil. There are more than 300,000 plant species worldwide. Many of them face waterlogging in certain part of their lifespan. The resulting effect of waterlogging is so severe that biochemical and morphological adaptations have emerged during evolution [1] to allow succession sporadically or permanently flooded areas in this green planet [2]. Although water is chemically benign, its certain physical properties interfere with free gas exchange and thus can injure and kill plants when they are totally submerged [3] or even when only the soil is waterlogged [4]. Vegetable crops are more sensitive to waterlogging than field crops in terms of yield.

It has been estimated that approximately 10% of all irrigated farmland in the world suffers from frequent waterlogging, which may decreases crop productivity by 20% [5]. Moreover, many rainfed regions are also susceptible to temporary flooding, like many parts in Bangladesh. About 10 million hectares of land in India and Bangladesh are regularly affected by flood in monsoon season [6]. Such flooding highly impairs crop productivity of much arable farmland. The effects of waterlogging on winter crops are usually seen as reduced growth and chlorosis of older leaves [7] because of impaired physiological activities. The inhibition of gas exchange within the root zone also has the potential to damage roots, resulting in restricted water and nutrient uptake by the plant. Chlorosis of older leaves is observed due to poor root development and slow uptake of nitrogen from the anaerobic soil [8].

The effect of waterlogging on crop yield depends on the frequency and duration of the waterlogging event(s) and timing with respect to growth stage of the crop [9]. Waterlogging has the greatest detrimental effect on crop yields when it occurs at germination or in the early vegetative stages [10]. All these findings suggest that crop plant show variable responses to water stress. Therefore, this review assesses the impact of waterlogging and submergence on crop physiology and growth of important crops in Bangladesh. Attention has been provided to responses that appear to enhance tolerance or survival along with remedies for crop production under such conditions.

OCCURRENCE OF WATERLOGGING AND SUBMERGENCE

Increasing Water Input

Waterlogging or submergence occurs when water enters soil surface faster than it can drain away under gravity. Water input is increasing in certain part of the world because of climate change. For example, flooding and rainfall has increased in much of northern and Western Europe during last century [11]. The frequency of flooding has also increased in lowland regions of the River Rhine in Europe and the Gangetic delta of Bangladesh. Flooding in such highly populated areas not only threatens the well-being of many people who depend on locally produced food but also can devastate vegetation of poorly adapted crop species.

Intensive and large-scale irrigation scheme can also increase the incidence of waterlogging because of rising water table. Change in land use pattern can also contribute to waterlogging. For example, conversion of meadow land to arable farming in Germany since 1950s has contributed to increased surface run-off and exacerbated flooding problems elsewhere in the landscape [12]. Under waterlogged conditions, aeration of the soil is reduced and loss of nitrogen by dentrification and leaching is increased [13, 8].

Inadequate Drainage

The duration and severity of flooding can be influenced not only by the rate of water input but also by the rate of water flow out from the root zone and by the water absorbing capacity of soil. Topography plays an important role in determining the speed of lateral flow within and above the soil. It will be slower on the plain land than in the sloping one. Moreover, unplanned construction of roads and other infrastructures impede drainage systems in many parts of Bangladesh. The impact of rate of vertical drainage through the soil profile is strongly affected by soil structure. Total volume of spaces (pores), size of pores, their interconnectivity, stability and relative proportions of each size class have a major impact on how much water is held by the soil and how readily it drains through the profile. Adopting the classification of Greenland [14]; interconnected pores with a diameter larger than 50 µm (transmission pores) drain under gravity. This allows air to enter to support aerobic respiration and also gives space for root exploration. Pores with 50–0.5 µm diameters (storage pores) can hold water against the force of gravity but weak enough for roots to extract it. However, they are not large enough to allow roots to penetrate. Pores having less than 0.2 µm diameter hold water so strongly that neither gravity nor roots can extract its contents. These classifications are summarized in Table-1.

Table-1: Classification of soil pores showing their different water retention characteristics and relative abundance in a clayey and sandy soil

Residual	Storage	Transmission
Pores <0.5 µm diameter	50-0.5 µm diameter	Pores >50 µm diameter
Water not extractable	Extractable water	Drain under gravity
Always filled with water	Water or gas filled	Gas filled at field capacity
Clay soil (% filled by volume)*		
23%	38%	3%
*Remaining soil volume is occupied by soil particles		

WATERLOGGING/SUBMERGENCE AND CROP PHYSIOLOGY

Oxygen Shortage, Free Radicals and Its Damaging Effects

Plants exposed to flooding stress exhibit increased stomata resistance as well as limited water uptake leading to internal water deficit [15]. Low levels of O_2 may decrease hydraulic conductivity due to hampered root permeability [16]. Oxygen deficiency generally leads to the substantial decline in net photosynthetic rate [17]. This decrease in transpiration and photosynthesis is attributed to stomata closure 18]. However, other factors such as reduced chlorophyll contents, leaf senescence and reduced leaf area are also held responsible for decreased rates of photosynthesis [19].

In waterlogged plants, the concentration of reactive oxygen species (ROS) increases than normal plants. These ROS induce damage to a number of cellular molecules, metabolic reactions and metabolites such as proteins, lipids, pigments, photosynthesis, efficiency of PS II, DNA etc [20]. The elevated cellular levels of hydrogen peroxide result in inhibition of calvin cycle [21]. The ROS are free radicals possessing one or more unpaired electrons. This is not a stable configuration; therefore, the radicals react with other cellular molecules to produce more free radicals [22, 23].

Prolonged exposure of plants to flooding conditions could result in root injuries which in turn restrict photosynthetic capacity by inducing certain alterations in biochemical reactions of photosynthesis. These biochemical alterations include restricted activity of ribulose bisphosphate carboxylase (RuBPC), phosphoglycollate and glycollate oxidase [24], demolition of chloroplast membrane inhibiting photosynthetic electron transport and efficiency of photosystem II [25]. Flooding causes a marked reduction in photosynthetic capacity of a number of plants, for example, *Lolium perenne* [26], *Lycopersicon esculentum* [27, 28] *Pisum sativum* [29, 30] and *Triticum aestivum* [31]. However, plants exhibit certain adaptation under waterlogging stress to maintain photosynthetic capacity [32]. The flood induced destruction of chlorophyll has been investigated widely by a number of researchers [33, 34, 17]. This decrease in chlorophyll directly or indirectly affects the photosynthetic capacity of plants under waterlogged conditions [17].

In waterlogged soil, diffusion of gases through soil pores is strongly inhibited by water and thus fails to match the needs of growing roots. A slowing oxygen influx is the principal cause of injury to roots and the shoots they support [4]. The small amount of dissolved oxygen (about 3%) is quickly consumed during the early stages of flooding by aerobic micro-organisms and roots (Fig-1). The flooding also impedes the diffusive escape and/or oxidative breakdown of gases such as ethylene [35] or carbon dioxide, which is produced by roots and soil microbes resulting in its accumulations. The accumulated ethylene may slow root extension, while carbon dioxide can severely damage roots of certain species like soybean (*Glycine max*) but not rice crop [36]. Trapped carbon dioxide may form bicarbonate ions that can bring out the effect of high lime content, leading to iron unavailability and chlorosis [5]. Warm temperatures and adequate supplies of organic matter will accelerate the development of such potentially damaging soil conditions.

If root tips survive oxygen shortage, they may be injured or killed by subsequent changes in soil biochemistry [37]. These changes take place because microbes utilize inorganic ions as alternate electron acceptors to oxygen in order to sustain energy generation (Fig-1). Initially facultative anaerobes reduce nitrate to nitrite, nitrous oxide and nitrogen gas rendering nitrate unavailable to roots. As the reducing intensity of the soil increases, obligate anaerobes reduce oxides of Mn^{4+} and Fe^{3+} to highly soluble Mn^{2+} and Fe^{2+} [38] that may enter roots and interfere with enzyme activities and damage membranes. Ferrous ion toxicity can be a particular problem for rice farming on acidic soils. If flooding is prolonged further, anaerobic bacteria may then convert SO_4^{2-} to H_2S, a poison of respiratory enzymes and non-respiratory oxidases. Acidic soils that are low in iron are especially likely to contain free and undissociated H_2S [37]. In the most severely reducing soils, methogenic bacteria reduce carbon dioxide to methane.

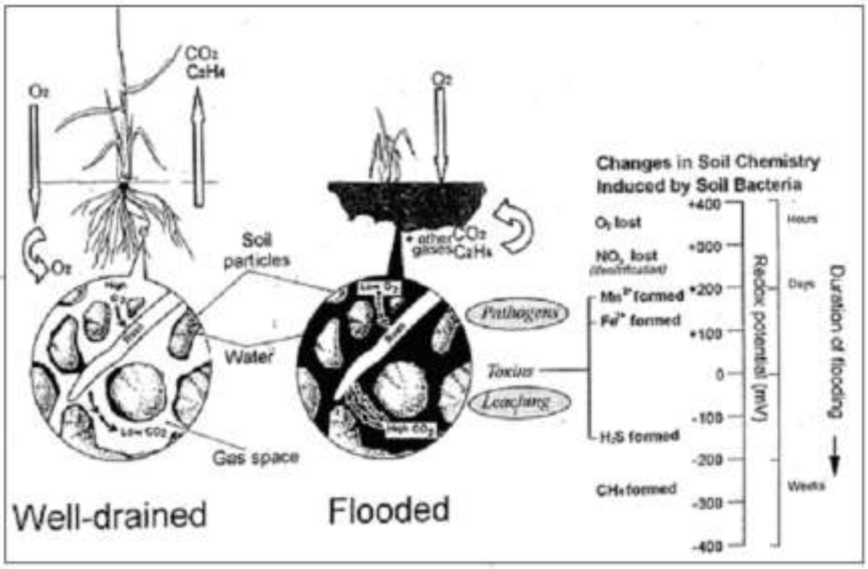

Fig-1: Effect of flooding on i) displacement and exclusion of aerial oxygen from the soil, entrapment of metabolically generated gases in the soil and ii) loss of free nitrate and generation of chemically reduced end-products [55].

Flooding may increase the incidence of soil-borne fungal diseases [39]. Germinating seeds are particularly vulnerable to fungal colonization like *Gliocladium roseum*. Infection of alfalfa, vegetables and trees by phytophthora (causing wilting), pythium (causing damping-off) takes place [40]. However it is not always clear whether injury is principally the result of the microbial infection or of the direct effects of flooding [41].

Mechanism of Root Tips Damage

Although an absence of oxygen is usually fatal to growing root tips, small amount of external oxygen (0.006–0.01 mol m^{-3} in solution) are able to keep them alive (water in equilibrium with air contains about 0.25 mol m^{-3} of oxygen at 25 ºC). Growth arrest and death of root tips arise primarily because of i) inadequate supply of ATP and ii) self-poisoning by products of anaerobic metabolism.

ATP Supply and Demand

Anoxia in plant tissues reduces the rate of energy production by 65–97% compared with the rate in air [42]. Anaerobic roots generate ATP mainly by glycolysis, the least efficient pathway. This pathway also feeds pyruvic acid into ethanolic fermentation and also into lactic acid fermentation, especially in the first hours of anoxia before the cytosol acidifies. Unless metabolic processes that consume ATP are simultaneously suppressed, the small yield of ATP in anaerobic cells is insufficient for survival beyond a few hours. Suppression can be brought about if the roots are 'trained' beforehand by a few hours of partial oxygen shortage (0.04 mol m^{-3} in solution or 3% v/v in the air phase) before the supply of oxygen is finally extinguished [43]. Greenway and Gibbs [43] concluded that early cell death can only be avoided if small amounts of available energy are successfully re-diverted to permit synthesis of certain critical 'anaerobic' proteins. A marked decrease of membrane integrity may well be one of the most critical consequences of ATP imbalance for the viability of root cells. It is a consequence of lipid hydrolysis that is probably mediated by lipolytic acyl hydrolase [44]. When membrane integrity is lost, the cell is irrecoverably damaged.

Sugar shortage caused by anaerobic arrest of starch breakdown and sugar unloading in roots can thus shorten the duration of survival. This is illustrated by the ability of rice seeds to germinate without oxygen. Such ability is due to activation of α-amylase coding gene under anaerobic conditions. The enzyme is principally responsible for degrading starch to a range of sugars [45]. In *in vitro* studies of anaerobic roots, hexose feeding is a prerequisite for long periods of anaerobic survival of the cultures. In hours or several days, seedling roots survive longer and ferment more vigorously when given external glucose [46]. However, they die eventually, indicating causes of death other than simply substrate-starved arrest of glycolysis**.** This may be because of glycolysis rates that cannot speed-up sufficiently to satisfy demand or because ATP demand is not sufficiently down-regulated. But other factors such as absence of molecular oxygen to support essential non-respiratory oxidative and oxygenation reactions play an important role in this regard [47].

Self-poisoning

Anaerobic roots may also die from self-poisoning by products of anaerobic metabolism; the most notable toxin being excess protons that acidify the cytoplasm and vacuole [48]. For example, roots of pea (*Pisum sativum*) collapse quickly when anoxic; acidify their cytoplasm more rapidly than longer-lived anoxic maize, soybean or pumpkin root tips. The sources of the extra protons within the cell have proved difficult to identify [48]. Another possible toxin is acetaldehyde. In alcoholic fermentation, activity of the enzyme that converts acetaldehyde to ethanol usually exceeds the enzyme that promotes acetaldehyde production from pyruvic acid. Normally, this state of affairs ensures low sub-toxic concentrations of acetaldehyde in anoxic cells. However, after de-submergence excessive acetaldehyde production could be damaging [49]. Nitric oxide [50], which can be formed by the action of nitrate reductase has the ability to kill cells. However, the roles of this molecule are not clear and it has even been suggested that the beneficial impact of nitrate on survival of anoxia may be an outcome of increases in nitric oxide arising from the reduction of nitrate to nitrite [51]. The death of the root-tip caused by one or more of the above-mentioned factors threatens the vigor and survival of the entire plant. However, Subiah and Sachs [52] mention that rapid death of anoxic root tips is an adaptive response. They consider that loss of the root tip allows the remainder dormant lateral root primordia to survive for longer life of anaerobic maize seedlings.

Cell death arising from oxidative reactions following the aeration cannot be excluded as a cause of waterlogging injury and death. An absence of oxygen harms the ability of plant cells to protect themselves against the formation and action of active oxygen species when the floodwater recedes and free oxygen returns to the cells. Roots of soybean are thought to suffer in this way [53]. However, recent studies with cell cultures do not strongly support to the view that post-anoxic damage is a major cause of death from anoxia [54].

Root Survival Mechanism under Anaerobic Conditions

All the plants have the ability to detoxify the adverse effects of reactive oxygen species (ROS) by producing different types of antioxidants such as ascorbate peroxidase (APX), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), glutathione reductase (GR), ascorbic acid, glutathione, tocopherols and carotenoids [56]. When mungbean plants are subjected to waterlogging, the activities of glutathione reducatse (GR), superoxide dismutase (SOD), catalase (CAT) and ascorbate peroxidase (APX) decreased markedly [57]. They also stated that oxidative damage was not directly involved in the impairment of photosynthetic machinery of plants under waterlogged conditions. Waterlogging-induced reduction in the activity of oxygen processing enzyme SOD has also been reported in corn [58]. In contrast, increase in the activities of different enzymatic antioxidants was recorded in maize seedlings when subjected to varying degree of waterlogging [59]. Waterlogged pigeon pea showed increased activities of SOD, CAT, peroxidase (POD) and APX [60]. These examples indicate that waterlogged plants employ antioxidant defense system to get through the damaging effects of oxidative stress induced by ROS.

Biochemical Adaptations

Endogenous levels of plant growth regulators (PGRs) such as gibberellic (GA) and cytokinins (CK) are reduced in the roots. This has enhanced levels of ABA and ethylene in the shoots causing stomatal closure and early onset of senescence, respectively. It is also reported that levels of auxins are reduced and that of Aminocyclopropane-1-Carboxylic Acid (ACC), precursor for the ethylene biosynthesis are increased under flooding stress. Important roles played by these endogenous PGRs during high moisture (flooding) stress are summarized in Table-2.

Table-2: Effect of flooding stress on the endogenous levels of PGRs and their effect on plants

Level of PGR	Waterlogging effects on plants
Reduced Auxins	Swelling of stem base by collapse or enlargement of cells in cortex
Decreased GA	Reduction in cell enlargement and stem elongation
Decreased cytokinins	Early on-set of senescence and reduced rate of assimilate partitioning to the sinks
Increased ABA	Stomatal closure with consequential decrease in the rate of gas exchanges during photosynthesis, respiration and transpiration; results in efflux of K+ from the guard cells; decreases ion transport due to lower rate of transpiration; decrease the starch formation in the guard cells resulting in stomatal closure
Increased Ethylene	Epinasty of leaves (uneven growth of leaves due to more cell elongation on upper side than the lower side of the leaf); induces senescence and Hypertrophy in plants.

Source: http://agritech.tnau.ac.in/agriculture/agri_flood.html

Physiological systems of plants changes due to external stimuli. For example, six hour prior exposure to partial oxygen shortage (3-5%, v/v in the gas phase) can lengthen survival time of anoxic maize root tips from 8 h to 72 h [61]. One possibility is that sensing works through a binding of oxygen to non-leguminous haemoglobin, which is ubiquitous in plants. However, this mechanism has been ruled out because binding is too tight for sensitive detection of partial oxygen shortage [50]. Nonetheless, haemoglobin is undoubtedly important for anoxia tolerance in other as yet undiscovered ways [62] and petunia plants transformed with a Vitreoscilla haemoglobin gene, show remarkably enhanced tolerance to submergence [63].

In partial oxygen deficiency, genes coding for anaerobic proteins (actually hypoxically-induced proteins or HIPs) are up-regulated at transcriptional and post-translational levels while others coding for many aerobic proteins remain expressed and translated up to the point when the cells finally become anoxic [64, 52, 65]. The anaerobic proteins or HIPs are necessary for adaptations. They play a major role in prolonging the life of anoxic roots that previously experience at least some hours of partial oxygen deficiency. If their synthesis is interfered with by applying protein synthesis inhibitors or through mutations, the effect of partial oxygen shortage on prolonging survival of subsequent anoxia is suppressed [3]. It is notable that translation mRNA of many 'aerobic' genes is suppressed in anoxic cells.

Survival Mechanisms of Above-ground Shoots

Stress on roots from soil waterlogging or submergence threatens shoot system because of the close functional relationship between them. For example, nitrate uptake is arrested due to absence of oxygen. Under such conditions, young leaves take this nutrient from older ones leading to their premature senescence [66]. A second example of this knock-on effect on shoots is the tendency of waterlogged plants to wilt severely in bright light [5].

Root to Shoot Communication and Shoot-water Conservation

The tendency for leaves to dehydrate irreversibly in response to increases in root hydraulic conductivity is ameliorated by rapid signalling from roots to shoots that results in a slowing of water loss from the foliage. This is achieved by a prompt decrease of stomatal apertures, leaf expansion and petiolar epinasty in tomato. Epinasty is the outcome of a downward re-orientation of whole leaves and leaflets that involves growth promotion on the upper surface. Epinasty reduces the amount of energy incident on the foliage and thus will slow the rate of water loss.

Severely hypoxic or anaerobic roots of tomato generate a positive message [27] to produce ethylene precursor 1-aminocyclopropane-1-carboxylic acid (ACC) for faster shoot ethylene production needed to induce epinasty [67]. The release of large amounts of ACC into xylem sap by anaerobic roots has two probable causes. The first is a blocking of ACC oxidation to ethylene by the absence of oxygen. This promotes a build-up of ACC. Some of this enters the transpiration stream and is drawn in to the shoot by transpiration steam as positive message. This enrichment has been shown in tomato and in xylem sap of *R. palustris*. Up-regulation occurs within 1 hr and takes place along with a rise in ACC concentration in roots and enhanced ethylene production in the leaves [68].

Fast stomatal closure is a usual phenomena in many species soon after waterlogging but difficult to explain. In tomato, many potential signalling messages such as increases in delivery of the hormone abscisic acid (ABA), sharp decreases in mineral nutrient delivery or increased xylem sap alkalinity have received little support, although in *Ricinus communis*, temporary dehydration of the leaves induced by severely decreased root hydraulic conductivity appears to trigger stomatal closure mediated by ABA [3]. Other less well-researched possibilities for root to shoot signalling in waterlogged plants involve decreases in pH and in the delivery of cytokinin or gibberellin hormones. In addition to possibly contributing to closing the stomata these changes may also help explain other shoot responses to waterlogging such as depressed stem elongation rates and faster leaf senescence.

Hormone Induced Replacement of Roots

Species with inherently surface-inhabiting root systems are notably tolerant of prolonged waterlogging [69]. These species must form replacement roots positioned near or at the better-aerated soil surface for survival. There are three mechanisms for generating these replacement root systems. One is a stimulation of the outgrowth of root primordia already present within the shoot base [5]. A second is the induction of a new root system that involves initiation of root primordia and their subsequent outgrowth. Ethylene seems to be involved in both these processes.

Hormone Induced Shoot Elongation

Flooding affects shoot extension and/or increased uprightness of submerged leaves [73]. Such events are seen with rice and maize plants. The elongation of shoot or leaf is primary responses to ethylene entrapped in the growing tissue by the floodwater [71]. The hormone is known to act in conjunction with gibberellins and/or with auxin to stimulate cell extension. In stems of deepwater rice [72] and petioles of *Rumex palustris* [70], faster underwater elongation is strongly dependant on a prior degradation of the growth-inhibiting hormone abscisic acid. Leaves of rice seedlings may also respond to a signal other than ethylene [73]. That signal may comprise of accumulated carbon dioxide or partial oxygen shortage since rice coleoptiles elongate faster underwater in response to their collaborative effects as well as to ethylene. In the stems of deepwater rice, these signals act more independently [74].

Young rice seedlings are readily submerged in water too deep for them to escape by means of fast upward elongation. In these circumstances, the expenditure of energy imposed by the faster growth rates may prejudice their survival. Survival is also challenged by more extensive leaf senescence that is promoted by accumulated ethylene [3, 73]. In lowland rice, the variety that elongate very little under submergence can maintain full set of green leaves. For example, BRRI dhan51 and BRRI dhan52 having *Sub1* gene can tolerate submergence for about two weeks [75].

EXCESS WATER STRESS AND CROP GROWTH

Waterlogging damage to crops may sometimes occur when crops are irrigated. For example, ponding on the soil surface for more than a day is harmful to wheat, pea and many other crops. The extent of damage to yield depends heavily on the stage of development as well as on duration of waterlogging and temperature (Table-3). For most crops, seed germination is probably the most vulnerable, reflecting both the fast metabolic rate of germinating seeds being coupled with complete inundation. Studied examples include peas [29] and temperate cereals [76, 77]. Seeds of rice are exceptional in being able to germinate in flooded soil without oxygen. But the germination is abnormal since only the coleoptile but not the root or the mesocotyl or leaves emerge from the embryo without oxygen. Elongation by the emerging coleoptile is stimulated under these conditions by a combination of lack of oxygen, carbon dioxide and ethylene.

Small cereal seedlings (e.g. wheat) with their shoots below ground are highly susceptible [83] but thereafter tolerance rises until early reproductive stages when susceptibility again increases as in soybeans [84]. Heightened vulnerability at or just before flowering has also been noted for several other crops including peas, wheat, sorghum, maize and cow peas [85] when inundated for one or more days. Symptoms of some waterlogged plants are provided in Table-4.

Table-3: Growth response as influenced by flooding duration and growth stages of certain crops.

Crop	Duration	Growth stage	Response	Reference
Bean	4 days	Vegetative	Reduced yield, rapid root development after stress removal	Nawata *et al*., [78]
	16 days		Restricted growth till adventitious root development	
Pea	3 days		Increased foliar hydration, 10-fold increase in endogenous ABA concentration	Jackson and Hall [79]
Soybean, peanut, mungbean	7 days	15 DAS	Stunted plants, reduced plant stand, delayed maturity	Herrera and Zandstra [80]
		30 DAS	Seed weight reduction	
Tomato	3 days	One month	Reduced stem growth	Kuo and Chen [81]
	3 days	Flowering	Increase in adventitious roots	Perez *et al*., [82]

DAS, days after sowing

Table-4: Symptoms of some waterlogged plants

Crops	Symptoms	Reference
Sweet potato	Flooding causes decreases in size and number of tuberous roots but increases fresh weight of the shoots	http://www.regional.org.au/au/asa/1989/contributed/irrigation/p-16.htm
Potato	The potato plant is sensitive to even short periods of moderate water stress. Water stress is usually reflected in slower growth, a smaller leaf canopy, early senescence and eventually in lower yields.	http://nbsystems.co.za/potato/index_27.htm
Wheat	Increased nodal root production and the proportion of aerenchyma within roots, but caused chlorosis and premature senescence of leaves, and decreased tillering	Belford [86]
Maize	Severely affect seed germination and seedling growth, fading of leaf colour immediately after flooding	Lone and Warsi [87]
Chickpea	Initial leaf chlorosis on the upper leaves. Reddish-brown anthocyanin pigmentation developed on midribs, stems and some leaflets. Unexpanded leaves had necrotic margins.	Cowie *et al*., [88]
Lentil	Lentil does not tolerate flooded or waterlogged soils	Oplinger *et al*., [89]
Mustard	Root cell die, premature bolting and floweing	http://www.canolawatch.org/2011/06/27/how-waterlogging-hurts-canola/
Tomato	Rapid development of downward growth of leaf petioles	Jackson and Cambell [90]
Eggplant	Yellowing of the bottom leaves and a brown discoloration in the stem interior. Prolonged periods of very wet conditions may also promote rapid growth of rot pathogens	*www.rma.usda.gov/pilots/feasible/pdf/eggplant.pdf*
Barley	Stomata closure	Yordanova *et al*., [91]
Pea	Prompt closure of stomata, wilting	Zang and Zang [92]
Okra	Decrease in photosynthetic rate, water use efficiency and intrinsic water use efficiency	Ashraf and Arfan [18]
Banana	Mats to float upon loosely rooted corms	http://agroforestry.net/tti/Musa-banana-plantain.pdf
Papaya	Within a day the plant dies. Net photosynthetic rate, transpiration rate and stomatal conductance decreases.	http://en.cnki.com.cn/Article_en/CJFDTotal-FRUI201103008.htm
Jackfruit	The tree does not tolerate waterlogging or poor drainage and will decline and die if roots become waterlogged for more than a day or two	http://informedfarmers.com/jack-fruit/
Chili	Leaf yellowing or fall off. Wilting can also be sign of poor drainage.	http://www.ehow.com/info_8279955_drainage-dying-chili-plants.html#ixzz2NV1ReROD
Pumpkin	Waterlogged soil with poor drainage can also lead to yellow, cupping pumpkin leaves	http://www.ehow.com/info_8764513_pumpkin-leaves-turning-yellow-cupping.html#ixzz2NVGMMZZW
Garlic	Waterlogged soils restrict the roots, cause misshapen bulbs and give poor results	http://www.agric.wa.gov.au/PC_92689.html?s
Onion	If the soil stays waterlogged, the onions will rot before they have a chance to grow	http://www.backyard-vegetable-gardening.com/growing-onions.html

Larger yield reductions result when flooding is imposed at reproductive stages than at vegetative growth stages of soybean [84], mungbean [93] and cowpea [94]. Wheat yield could be reduced by 51% in poorly drained soil compared to well-drained plots [95]. There was maximum yield reduction when corn field was waterlogged at vegetative stage [96]. Mid-season flooding in sweet potato caused 36-56% yield reduction. Continuous flooding of pepper plant for 4 weeks resulted in poor growth, yellowing of leaves and blackening of root tips [97].

Unlike other major crop species, rice can yield heavily when grown in waterlogged soil and specialized ecotypes are able to yield usefully even when partially submerged in water [98]. However, it is less widely recognized that these do not readily escape total submergence. Small vegetative deepwater rice plants if totally submerged for only a few days as a result of uncontrolled flooding in lowland areas, they are severely damaged or killed. Part of the problem is thought to be that stimulated leaf elongation and associated ethylene-promoted leaf senescence quickly deprive the young plants of starch and sugars, thus prejudicing their survival and re-growth potential [3].

STRATEGIES FOR COMBATING WATERLOGGING AND SUBMERGENCE

There are several options for mitigation of submergence and waterlogging problems. Breeding of waterlogging tolerant varieties, improvement of drainage systems and changing in crop husbandry could be some of the options.

Breeding Varieties

As with other major abiotic stresses, breeding and selecting successful tolerant varieties are only a few. Two submergence tolerant rice varieties have been released by BRRI which can tolerate about two weeks inundation [75]. Photograph of one variety is shown below. Waterlogging-tolerant accessions have identified in seven of the eight taxonomic sections in *Trifolium* when compared in terms of relative growth rates. Several lines of soybean and of winter wheat have also been shown to posses unusually high tolerance on the basis of injury levels and final yield [5]. Comprehensive tests in the glasshouse and in the field over several seasons and involving yield comparisons of over 20 cultivars [84] revealed notable tolerance in two lines of winter wheat.

Quimio *et al*., [99] reported improvements to submergence tolerance in rice by transforming rice with a gene (rice *pdc1*) coding for pyruvate decarboxylase the presumed rate-limiting step in ethanolic fermentation. A similar result has been obtained with arabidopsis. Petunia and arabidopsis transformed to over express a haemoglobin gene have also shown remarkable resilience to submergence stress [63] or severe hypoxia [62]. Neither species can be considered a major crop but similar transformations using important food crop species are anticipated.

Crop Husbandry

In areas where temporary flooding hazards are expected during the growing season, crops can be selected on their relative ability to tolerate excessive moisture (Table-5). Field crops are generally less sensitive than vegetable crops in terms of yield. So, some field crops would be more adaptable in flood prone areas than vegetable crops. In addition to choice of crops, planting dates could be shifted when possible by delaying dates of sowing or planting to avoid probable periods of flooding during the sensitive growth stages. Soil management practices like ridging and furrowing or making raised beds before planting is recommended. Amelioration with foliar application of chemicals like nutrients, growth hormones and fungicides is also recommended to overcome nutritional deficiencies, hormonal imbalances and disease infections. Every effort of amelioration should be exerted at the earliest opportunity, since water damage to crops becomes more severe with longer flooding duration.

Table-5: Susceptibility of some crops to waterlogging

Tolerant/moderately tolerant	Wheat, Barley*, Chickpeas, Maize, Jute, Sugarcane, Banana, Mango, Rice, Taro
Susceptible	Lentils, Pea, Tomato, Papaya, Jackfruit, Black gram, Green gram, Bean, Ladies finger, Gourd, Pineapple, Guava, Litchi, Lemon, Sapota, Onion, Pepper, Zinger
* Barley tolerates salt better than wheat in the absence of waterlogging, but is more sensitive to waterlogging in both saline and no-saline conditions.	

Vegetable Crops

Vegetable crops are more sensitive to waterlogging than field crops. So, gradual replacement of fertilizers is critical for recovery of a healthy root system. Heavy applications may cause further root damage. Foliar applications of soluble major and trace elements may help kick-start plants until their root systems re-establish. Vegetable can also be grown in raise beds or even in floating beds. Floating beds are made of water hyacinth, deep water rice straw and different types of aquatic vegetations like *Lemna trisulca, Azolla pinnata* and *Bluxa japonica* and bamboo poles. Initially farmers lay a bamboo pole on dense water hyacinth to stand on and then pile more water hyacinth to make it compact. The thickness depends on the duration of water logging, as it needs to float for the whole time of inundation. The bed is movable so the farmer can choose suitable locations for better management. After selecting a good location, the beds are usually fixed with bamboo poles. After 10-15 days, the farmers may transplant seedlings or broadcast vegetable seeds. More than 20 vegetable varieties like red amaranth, Indian spinach, coriander leaves, cauliflower, cabbage, tomato, lady's finger, cucumber, bitter, gourd, bottle gourd, snake gourd, ash gourd, sweet pumpkin, bean, radish, eggplant, potato, chilli, onion, garlic, turmeric and mustard are grown on floating beds in different locations of Bangladesh (http://www.coastalcooperation.net/part-III).

Tree Crops

Three of the important nutrients for tree crops- nitrogen, potassium and boron are prone to leaching from the soil and levels are likely to be low after high rainfall. Application of fertilizers is needed to make up for expected shortfalls. Typically rates are increased by up to 20% above the normal doses.

Seeding

Sowing crops early and using long-season varieties help to avoid crop damage from waterlogging. Planting crops in the raised beds system is a good option for combating waterlogging problems [100]. Sorjon bed technique for crop establishment is very much useful for tidal flood prone area of Bangladesh. Since, damage to crops is particularly severe between germination and emergence, pre-treating seeds with an oxidizing coat has been tried as an insurance against such effects. Coatings include calcium hydroxide and calcium peroxide [101-104], although the effects on rice have not always been positive. If germinating seeds are likely to get contact with undegraded crop residues in wet conditions, it is better to plow down them or remove them before sowing. However, if waterlogging delays emergence and reduces cereal plant density to less than 50 plants/m^2, resowing would be better in case of early season damaged crops. Increase seeding rates in areas susceptible to waterlogging to give some insurance against uneven germination and to reduce the dependence of cereal crops on tillering to produce grain. High seeding rates will also increase the competitiveness of the crop against weeds, which take advantage of stressed crops.

Fertilizer

The crop will tolerate waterlogging better if it has a high nitrogen status before it becomes waterlogged. Applications of nitrogen at the end of a waterlogging period can be an advantage if nitrogen that was applied at or shortly after seeding has been lost by leaching or denitrification. Remedial effects can be observed after applying nitrogen fertilizers as foliar spray. Cotton yield could be improved by N spraying http://cotton.crc.org.au/Publicat/Agro/waterlog.htm). Application of 20 kg N/ha after two weeks of de-submergence followed by 20 kg N/ha and 7 kg K/ha improved yield of submerged rice crops [75]. Foliar and soil application of N as an ameliorant has been reported in cotton, corn, barley and soybean [105-107]. Foliar application of 3N-8P-15K @ 28.1 L/ha increased soybean yield having no leaf injury [106].

Weed Control

The number of weeds in the crop affects its ability to recover from waterlogging. The weeds compete for water and the small amount of remaining nitrogen; hence the waterlogged parts of a field are often weedy. Post-emergence herbicide can be used for controlling weeds.

Disease Control

Root diseases are often more severe in waterlogged crops because the pathogens tolerate waterlogging and low oxygen levels better than the crops. Leaf diseases are likely to be more severe in waterlogged crops because the crop is already under stress. Spraying may be an option after the site has dried, but only in crops with a high yield potential [108].

Use of growth regulators

Plant growth regulators can be utilized to offset waterlogging damaged symptoms. For example, spraying shoots with cytokinin (6-benzyl-aminopurine, BAP) reduced injury to shoots of dicotyledons in waterlogged soil [105]. Foliar application of BAP together with gibberellic acid (GA) can counteract waterlogged effects of pea [109] and tomato [110]. Foliar sprays of urea and mixtalol at flowering stage of *Brassica napus* and rice alleviated waterlogged symptoms [111].

Improving Drainage of Crop Land

Good drainage is essential for maintaining crop health in the field. However, for pot cultured plants certain special measure can be adopted. For example, the best ways to save waterlogged tomatoes is to uproot them from the pot, mix the wet soil with fresh or dry soil, then cut away the bad roots, vines, or leaves. Depending on the severity of water damage, a tomato plant needs to be dramatically reduced. When vegetables are waterlogged, it's important to remedy the situation quickly to avoid infection, fungi and root rot (http://www.ehow.com/info_8105105_treatments-waterlogged-tomatoes.html). There are several things that we can do to improve crop drainage, immediately and in the long term.

Drainage Problems after Flooding

After significant rain or flooding, inspection of crop field is essential to find out waterlogged areas by seeing crop symptoms. If possible, immediate steps should be taken to improve the drainage of these areas so that no damage done for sensitive crops.

Irrigation after Waterlogging

To avoid recurrence of waterlogging, irrigation water should be applied in small amounts often until the crop's root system has recovered.

Ways to Improve Drainage

In the long term, following options could be considered for ways to improve the drainage of the affected fields.

- re-shaping the layout of the field
- improving surface drainage
- installing subsurface drainage

Underground drainage systems including conventional mole and gravel mole systems, in combination with surface drainage, also have the potential to significantly increase grain production in many of the areas prone to waterlogging [9].

In a nutshell, following points may be considered for mitigation of waterlogging: (http://agritech.tnau.ac.in/agriculture/agri_flood.html):

- Provide adequate drainage around the root system.
- Spray growth retardant (e.g. 500 ppm cycocel) for arresting apical dominance
- Foliar spray 2% DAP + 1% KCl (MOP)
- Nipping terminal buds for arresting apical dominance
- Spray 40 ppm NAA for controlling excessive pre-mature fall of flowering/buds/young developing fruits and pods
- Spray 0.5 ppm brassinolide for increasing photosynthetic activity
- Foliar spray 100 ppm salicylic acid for increasing stem reserve utilization under high moisture stress
- Foliar spray 0.3 % Boric acid + 0.5 % $ZnSO_4$ + 0.5 % $FeSO_4$ + 1.0 % urea during critical stages of the stress

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