**Waterlogged Soils: Causes, Challenges, and Management Strategies**

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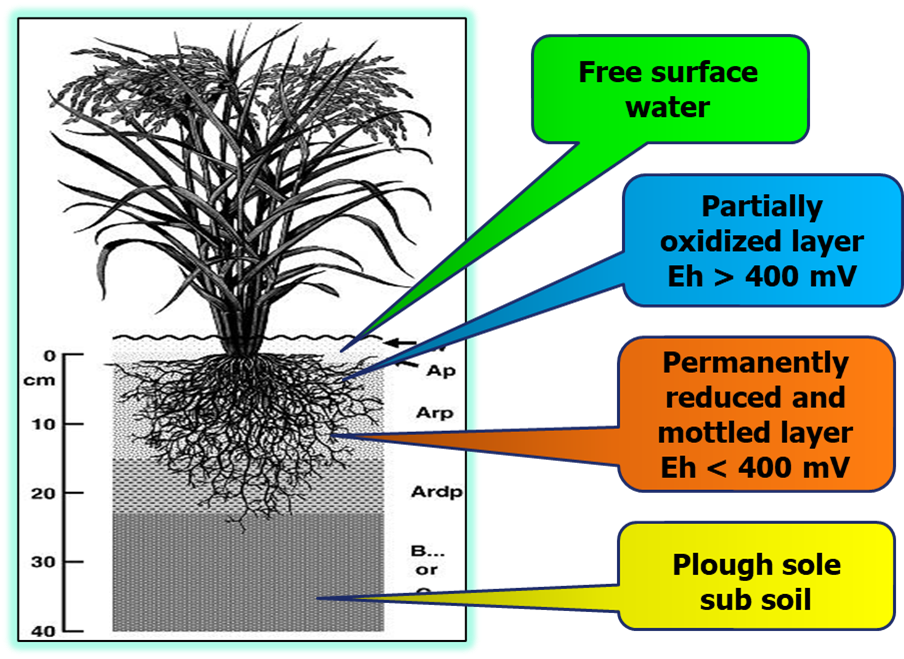
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**Introduction**

Waterlogging is simply the temporary or permanent soaking of soil with water. When there is an excess of water in a region, the soil is unable to absorb it as it should. Waterlogging due to rain or floods has long been a natural occurrence that has resulted in the largest loss of human life and economic devastation around the planet. In case of over irrigation, waterlogging occurs when the water table rises to the root zone - repeated incorrect irrigation creates a shallow impermeable layer that prevents water from infiltrating down. Waterlogging limits plant development and output under anaerobic circumstances, causing certain crops and plants to die (Najeeb *et al.* 2015). Furthermore, as a result of the excess water in the soil profile, plant roots become weak and die or fall (Pan *et al.* 2021). Thus, management of excess water either due to rain or over irrigation in agriculture is a major challenge globally as well as in India, where about 11.6 million ha area is waterlogged. Waterlogging or severe soil drainage restrictions impact an estimated 10-12% of agricultural land worldwide (Shabala 2011). Many forecasts indicate that flood risk for many river basins will grow significantly in the twenty-first century, owing not just to climate change but also to industrial expansion and land use changes (O’Donnell *et al.* 2020; Tariq *et al.* 2021). Waterlogging inhibits gaseous exchange with the atmosphere, and biological activity uses up available oxygen in the soil air and water – also called anaerobiosis, anoxia or oxygen deficiency. Such conditions have a number of effects on agricultural plants *e.g.,* toxicities or nutrition deficits, slow root death, in the winter it can cause deeper roots to die, resulting in spring dryness and early senescence of annual crops.

Most of the field crops such as wheat, rice, maize, and barley get affected by the waterlogging conditions. Waterlogging during the seedling, flowering, and grain filling phases of wheat reduced grain yield by 50-70% due to poor seed development and fewer spikes per unit area (Misra *et al.* 1992; Ding *et al.* 2020).

**Figure 1.** Different layers under waterlogged soils

Water logging in maize reduces output in tropical and subtropical areas. Waterlogging affects 15% of South-East Asia's maize growing regions, resulting in annual output losses ranging from 25-70% (Rathore *et al.* 2000; Tian *et al.* 2019). It promotes chlorophyll, protein, and RNA degradation in barley, as well as a decrease in the concentration of nutrients such as nitrogen, phosphorus, metal ions, and minerals in the shoot. After the commencement of flood leaf chlorosis (Wang *et al.* 1996; Buchanan *et al.* 2003), root and shoot development was also impaired, resulting in a drop in dry matter accumulation and, ultimately, yield (Malik *et al.* 2002). Based on plant damage, an average yield loss of 20-25% can occur; it may exceed 70% due to waterlogging (Setter *et al.* 1999). In present scenario, when climate is variable and incidences of flood have been increased, it is important to understand the mechanism of crop to be resilient towards this stress and other management practices that help the crops to perform better. With the above-mentioned aim, this review article has been designed in different sections that will discuss the problem, causes, and impact of waterlogging in major field crops with the future prospects and scope in water management for these crops.

**Causes of waterlogging**

***Climatological***

Excessive rainfall in a short span of time that exceeds the soil storage capacity and makes the area waterlogged. Climate change scenario has made such incidences more frequent and hence leading to frequent waterlogging situations. Higher air temperatures encourage evaporation of water in rivers and seas and, as a result, cloud formation. Higher temperatures allow the air to store more moisture and that may cause an increase in precipitation intensity, duration and/or frequency. As global warming raises the chance of additional extreme weather occurrences, dangers will spread beyond the established high-risk zones. More severe flooding is to be predicted, and for towns and cities where flooding has already occurred, it will no longer be a "once in a lifetime" risk, but will become considerably more often. The truth is that we live in a planet that is warming by 1.1o C. These record temperatures and floods are not anomalies; they represent the start of new standards, and the new records will be broken year after year.

***Irrigation***

Irrigation of soil without considering the soil infiltration capacity, soil storage ability and soil structure often leads to accumulation of water beyond desired, making the soil unsuitable for agricultural activity. Excessive irrigation often leads to accumulation of water above the soil surface creating anaerobic environment (Irmak *et al.* 2014).

***Drainage***

Drainage can be considered as the single most important factor that can lead to waterlogging (Balun 2020). Lack of proper drainage allows the excess water to remain on the soil surface for a longer period of time. The use of heavy machinery, a lack of organic matter addition, and other factors contribute to the formation of compacted layers in the subsurface region, resulting in poor drainage (Gurovich and Oyarce 2015; Kaur *et al.* 2020).

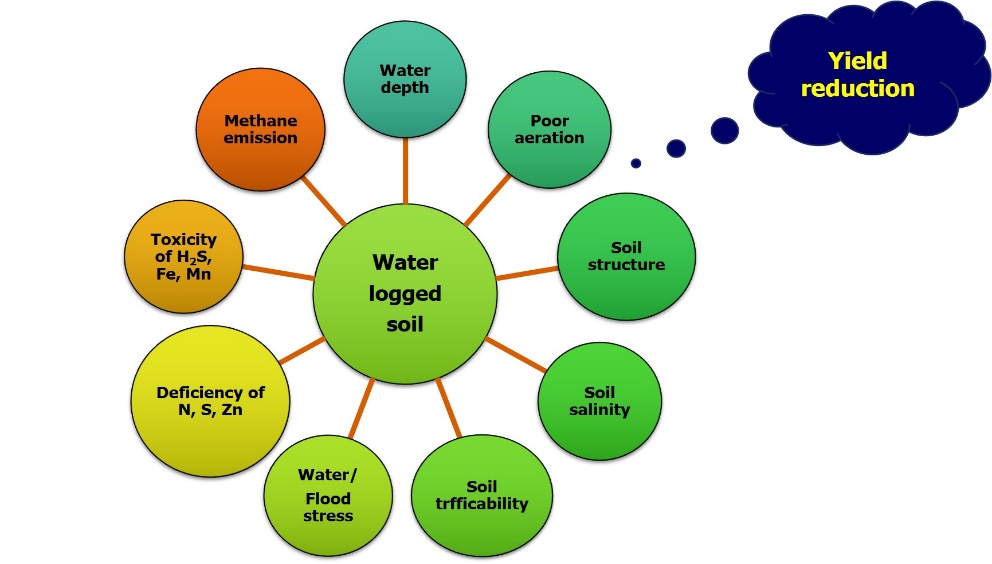
***Topography***

Topography has a significant effect on occurrence of flood in an area (Valeo and Rasmussen 2000; Sendek *et al.* 2021). Lowland soils are more prone to waterlogging than upland soil where free drainage is available. Uneven or unlevelled land creates waterlogged patches across the field as the water remains accumulated in small patches for longer period of time.

***Ground water table***

Shallow ground water table regions are more prone to waterlogging as high rainfall brings the water level close to the plant roots quickly resulting longer period of anaerobic environment around the root regions.

**Problems of waterlogging**

Waterlogging can cause multiple problems which have been discussed briefly under the following heads:

**Figure 2.** Effects of waterlogging on soil physicochemical and biochemical properties

***Poor crop performance***

Waterlogged soil causes anaerobic environment in the root zones which leads to lower root respiration. Lower root respiration generates less ATP, which is required for regular crop metabolic activity such as photosynthesis, absorption of nutrients etc. poor generation of ATP makes nutrient absorption poorer which leads to lower crop growth and productivity. Production of some toxic gases under anaerobic environment also lowers root permeability making both nutrient and water absorption increasingly difficult.

***Destruction of soil structure***

Excess soil moisture makes soil aggregates weaker. Tillage during excessive moisture as practiced by many farmers especially under paddy cultivation destroys the soil structure and creates subsurface compaction that restricts root movement of subsequent crops.

***Emission of greenhouse gas***

Anaerobic environment lowers redox potential that results in the formation of greenhouse gases such methane and nitrous oxide. Lowering redox potential also increases the toxicity of iron and manganese as their availability increases under reduced conditions.

**Table 1.** Different chemical species and their transformation under waterlogging condition and their redox potentials

|  |  |  |
| --- | --- | --- |
| **Reduction reactions under waterlogging** | | |
| **Oxidized species** | **Reduced species** | **Redox potential (mV)** |
| O2 | H2O | +380 to +320 |
| NO -3 | N2 | +280 to +220 |
| Mn4+ | Mn2+ | +280 to +220 |
| Fe3+ | Fe2+ | +180 to +150 |
| SO42- | S2- | -120 to -180 |
| CO2 | CH4 | -200 to -280 |
| H2O | H2 | -200 to -420 |

***Deficiency of nutrients***

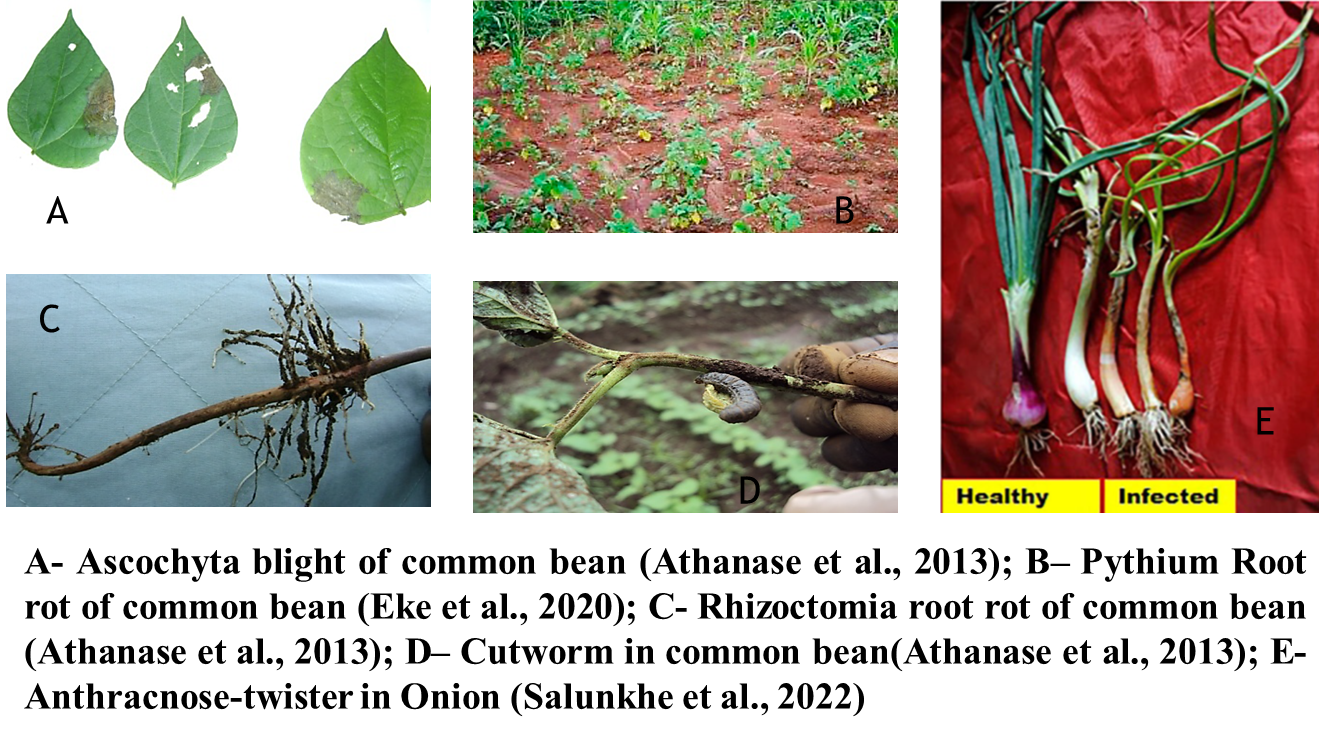
Waterlogging leads to deficiency of nutrients through different mechanism. Leaching of nutrient is one of the most common mechanisms of nutrient loss under waterlogged environment in which the soluble nutrients move beyond the root zone with water. Nutrients like nitrogen may also be lost through denitrification under waterlogged anaerobic environment. Zinc is the most limiting micronutrient under water logged condition as the availability is reduced because of the formation of sparingly soluble salt.

***Diseases and pest incidence***

Rising humidity developed under waterlogged condition provides congenial environment for development of diseases and pest incidence.

**Table 2.** Effect of waterlogging on different crops

|  |  |  |
| --- | --- | --- |
| **Crop** | **Effect due to waterlogging** | **References** |
| Corn | Cause of disease like Smut, Leaf spot and downy mildew | Urban *et al.* (2015) |
| Corn | Yield reduction | Singh *et al.* (2016) |
| Cotton | Effect on growth and yield attributes | Wang *et al.* (2017) |
| Cotton | Yield reduction | Zhang *et al.* (2016) |
| Wheat | Wheat scab disease | Urban *et al.* (2015) |
| Wheat | Yield loss | Arguello *et al.* (2016) |
| Soybean | Sudden death | Urban *et al.* (2015) |
| Soybean | Yield reduction | Singh *et al.* (2016) |
| *Arabidopsis* | Root cell death | Guan *et al.* (2019) |

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**Figure 3.** Incidence of diseases and pest under waterlogging in crops (A) Ascochyta blight of common bean (Athanase *et al.* 2013), (B) Phythium root rot of common bean (Eke *et al.* 2020), (C) Rhizoctonia root rot of common bean (Athanase *et al.* 2013), (D) Cutworm in common bean (Athanase *et al.* 2013), and (E) Anthracnose twister in onion (Salunkhe *et al.* 2022)

***Effect of water logging on plant physiological parameters***

Plants can suffer significant damage from the excessive synthesis of several ROS (reactive oxygen species) in waterlogged conditions, such as superoxide radicals, hydroxyl radicals, hydrogen peroxide, and singlet oxygen observed in hypoxia-stressed leaf and root tissues. In wet soil, ethylene is a potentially hazardous compound that inhibits root extension development. Additionally, the leftover ethanol in anoxic cells will be converted into acetaldehyde during the reintroduction of oxygen during the recovery phase, which may result in cell damage. All of them result in constrained root development, early leaf withering, and the formation of sterile florets, which all reduce yield. Due to a combination of factors including a decreased photosynthetic rate, a decreased stomatal conductance, a decreased root hydraulic conductivity, and a decreased translocation of photo assimilates, carbohydrate production was drastically reduced during complete submersion or subsequent de-submergence. The decrease in stomata conductance is one of the earliest reactions of plants to waterlogging. Abscisic acid (ABA) transit from older to younger leaves or the hormone’s de novo synthesis was suggested as the causes of the stomata closing. Waterlogging also lowers the chlorophyll concentration of leaves (Manik *et al.* 2019). The capacity of plants to photosynthesize is either directly or indirectly impacted by this decrease in chlorophyll. Stomata closure, which limits CO2 flow, is to blame for the decline in transpiration and photosynthesis.

**Management practices**

***Alternate crop***

Growing crop suitable under waterlogged condition can be the single most effective strategy to tackle issue of yield reduction under waterlogged environment. Varieties of particular crop suitable for waterlogged condition can be further effective in reducing the negative impact of waterlogging.

***Alteration in cropping pattern***

Developing cropping pattern that facilitates growing water logging tolerant crops or growing crops in such a time that can escape waterlogging at critical stages can be an effective strategy in alleviating waterlogging issue.

***Sowing time***

Adjusting the sowing time can be useful in escaping waterlogging. Sowing rice in late April or early may can help rice in escaping early season flood. Moreover, this facilitates the early sowing of wheat. Adjusting the planting time should be done in such a way that, the most susceptible stage of the crop does not coincide with the peak waterlogging period.

***Raised bed planting***

Growing crop such as maize, wheat, mustard etc. on raised bed has been found effective in minimizing the negative effect of waterlogging to a great extent. Crop planted on raised bed are less exposed to waterlogging. Moreover, the furrows formed between the raised bed serves as a channel for the drainage of excess water.

***Drainage***

Provision of surface and subsurface drainage can help minimizing waterlogging issue. Subsurface drainage is especially useful in alleviating the issue of rising water table. Surface drainage can be useful for condition where excess water accumulates over the soil surface. Bio-drainage can also be effective in lowering the water table. This can especially useful where the water table is shallow resulting in frequent issues of waterlogging.

***Genetic approach***

Breeding for water logging tolerance can be an effective strategy for better adaptation under waterlogging condition. Varieties such as Sarjoo – 52 and Swarna sub 1 have been highly effective under waterlogged condition. Finding land races or germplasm and screening for their waterlogging tolerance ability can be the first step in developing such varieties. Bringing water logging tolerant genes from wild parents can also be useful in this aspect.

**Conclusion**

Flood/waterlogging is an important and serious threat to agriculture as it is evident with many research works. These are need to develop a comprehensive and spatially explicit risk evaluation framework to predict and investigate how floods impact crop production. Also, it is required to develop climate resilient agriculture techniques that not only save the crops but also protect soil from erosion. A risk-based approach should be frame that would lead to an economic, social, and environmental balance between gains and losses.

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