Management of Crops in Water-Logged Soil

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Abstract

Excessively water saturates the soil pores and creates waterlogging when there is indeed no or very thin coating of water present on the soil. Waterlogging typically causes changes in gene expression that affect a plant's physiology, metabolism, and anatomy. Crops respond to and adapt to waterlogging stress in a variety of ways, including the development of aerenchyma, adventitious root development, metabolism of energy, and plant-hormone signaling. One of the most damaging abiotic stresses that annually destroys 17 million km^2 of land, along with drought, is floods. Recent studies have found that increased extreme weather events, like flooding and soil waterlogging, brought on by climate change are having a substantial influence on agricultural productivity. Because of this, it is essential to understand how crops are impacted by flooding stresses and to develop better production methods that boost cropping systems' resistance and ability to endure extreme climate events. Potential management strategies that can be utilized to alleviate the stress brought on by soil waterlogging include the adoption of waterlogging-tolerant varieties, altering administration practices, improving permeability, and putting adaptive nutritional monitoring systems into

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place. These management approaches, which may be crop- or site-specific, should be assessed for their commercial feasibility before developing future implementation strategies that enable sustainable agricultural output from waterlogged soils.

Keywords

Soil waterlogging · Abiotic stress · Physiological response · Agronomic practices · Bio drainage

1 Introduction

Water facilitates plant development and functions, making it essential to a plant's life. However, plants are put in danger by flooding or waterlogging (Normile 2008). As seen in Fig. 1, the condition known as "waterlogging" occurs when a whole or a plant portion is completely under water (Bailey-Serres et al. 2012). As a result, air pockets in the earth are simply filled, leading to wet conditions. In many plant communities around the world, soil waterlogging is an abiotic (non-living) stress which impacts species composition as well as its production (Jackson and Colmer 2005). Seasonal precipitation as a whole, as well as the differences between and among seasonal precipitation events, have changed due to climatic variations. Extremes in the availability of water have grown more severe globally in farming areas during the past 50 years (Aderonmu 2015; Bailey-Serres et al. 2012). The main causes of waterlogging in Pakistan include inadequate irrigation management techniques, a scarcity of suitable infrastructure for drainage of soils, and the use of low-quality water for irrigation purposes (Hossain 2010). Due to the threat to food security, it is

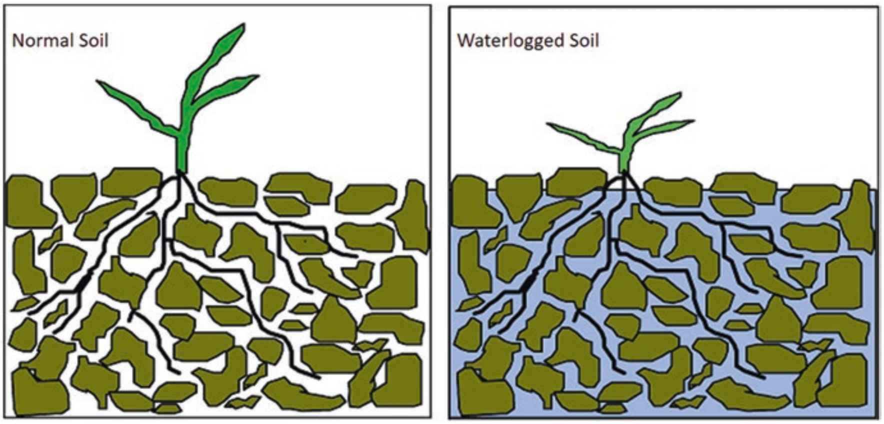

Fig. 1 Water logged condition illustration. [Source: Engineer Moid (2021), https://www.civil-click.com/waterlogging/ (source)]

urgent to find low-cost, ecologically friendly ways for managing and reclaiming these soils (Qadir and Oster 2002).

Flooding has a devastating effect on society and the environment. As terrestrial plant species including cultivated crops are susceptible to flood conditions, there is a decline in biodiversity of plants, natural species distribution, and production of food worldwide (Normile 2008). Each year, flooding damages about 17 million km^2 of land worldwide, resulting in losses in crop production and serious damage to plants (Voesenek and Sasidharan 2013). Waterlogging or serious soil drainage issues harm between 10% and 12% of the world's agricultural land (Shabala 2011). The projected annual cost of damage from severe floods that occur all over the world is much more than $74 billion (www.dartmouth.edu/~floods/Archives/2005sum.htm). According to existing fluctuations in changing climate globally, showing harsh climatic events, the National Aeronautics and Space Administration (NASA) simulation models estimated losses worth $3 billion annually in food production by 2030 (Rosenzweig et al. 2002). Pakistan has experienced exceptional monsoon conditions since June 2022, this month alone received rainfall which was 67% above average levels. As of August 27, the nation had received 2.9-fold as much rain as the 30-year average. A total of two million acres of crops and orchards have also been damaged at this point, including 1.54 million acres in Sindh, Baluchistan is 304,475 acres, and 178,186 acres in Punjab (OCHA 2022). Anatomical, physiological, and metabolic alterations are typically reported as plant responses to wet and flooding situations (Voesenek et al. 2006). Water diffusion, a mode of transportation in a biological system, is thought to be very low for terrestrial plants' survival for a long duration, which is why flooding causes damage. Essential nutrient deficits and toxicities from micronutrients like Copper (Cu), Iron (Fe), and Manganese (Mn) have an impact on plants (Setter et al. 2006). The primary source of potential energy for plant roots to absorb nutrients is aerobic respiration (Ferreira et al. 2008). These waterlogging effected roots resort to an ineffective anaerobic fermentation, using their present glucose reserves to produce the ATP they require to survive and operate. Continued hypoxia or anoxia impairs root growth and function due to reduced integrity of the membrane, hunger, and phytotoxic chemical diffusion into the root cells (Sauter 2013). Under hypoxic circumstances, the functions of shoots are compromised and may show apparent symptoms like senescence, wilting, and death because the roots are unable to transfer water and nutrients effectively (Sasidharan and Voesenek 2015). In addition, photosynthesis, carbohydrate partitioning, and the production and transport of growth regulators are all significantly impacted (Ferrer et al. 2005). Under waterlogged conditions, these physiological impedances ultimately result in a decreased crop yield.

To maintain root activity and plant survival in susceptible genotypes, waterlogged circumstances may induce and initiate crop tolerance traits or adaptation features that might enhance aeration and mitigate root hypoxia or anoxia. Plant tissues soaked with water produce ethylene (El-Esawi 2016a, b). The activation of genes related to aerenchyma production and adventitious root formation is crucial among the well-explained roles that ethylene plays in waterlogged conditions (Vidoz et al. 2010; Sasidharan and Voesenek 2015). In the shoot, the transport of auxin is reprogrammed by increased ethylene level in the stem, which causes a flow of auxin to be directed toward the submerged stem to start the growth of adventitious roots. Auxin transport inhibition reduces adventitious root development (Vidoz et al. 2010). The formation of suberin or lignin barrier, among other things, in roots in order to prevent loss of O_2, and direct its transportation to the tip of the root, were other adaptive traits displayed by resistant crops (Shiono et al. 2011).

Grain growers employ a wide range of crop management techniques to mitigate the impacts of waterlogging. Selection of crops, crop varieties that can withstand waterlogging, bio-drainage, and various agronomic techniques, like sowing season, nutrient application, engineering methods for surface and subsurface drainage, etc., and use of plant growth regulators (PGRs), are among them (Manik et al. 2019).

2 Causes of Soil Waterlogging

The oxygen concentration drops quickly in waterlogged soils because in water diffusion of a gas is several times slower than in air, causing a series of events that are detrimental to the survival of the majority of plant species (Colmer and Greenway 2011). In Asia and America, flooding is the main reason for yield losses, and waterlogging is thought to damage between 10% and 16% of the planet's cultivable soils (Yaduvanshi et al. 2012). In addition, in response to changing climate, flooding events are anticipated to occur more frequently and more intensely in every part of the planet (Westra et al. 2014). More than 21 Mha of Pakistan's 79.61 Mha total geographic area where agricultural practices take place. Almost 25% of irrigated area in Punjab province is seriously under waterlogging, but about 60% in Sindh (WAPDA 2007). Soil waterlogging in the plant-rooting zone can be caused by many variables, including the amount of water that enters the soil, the amount that flows over/through the soil's surface, and the amount of water that is absorbed by plants and other species (Kunkel 2003). Numerous factors, such as soil type, geography, meteorological circumstances, lateral ground water flows, and rising/perched water tables, can cause waterlogging (Fig. 2).

2.1 Extreme Precipitation

The frequency of heavy precipitation events and several rains is a significant factor in an increase in waterlogging or flooding (Kunkel 2003). Extremely rainy years are distinguished from dry years by the amount, frequency, size, and spacing of precipitation events (Knapp et al. 2015). The Intergovernmental Panel on Climate Change (IPCC) predicts that rising emission of greenhouse gas will probably result in more instances of extreme precipitation ahead (Cubasch et al. 2001).

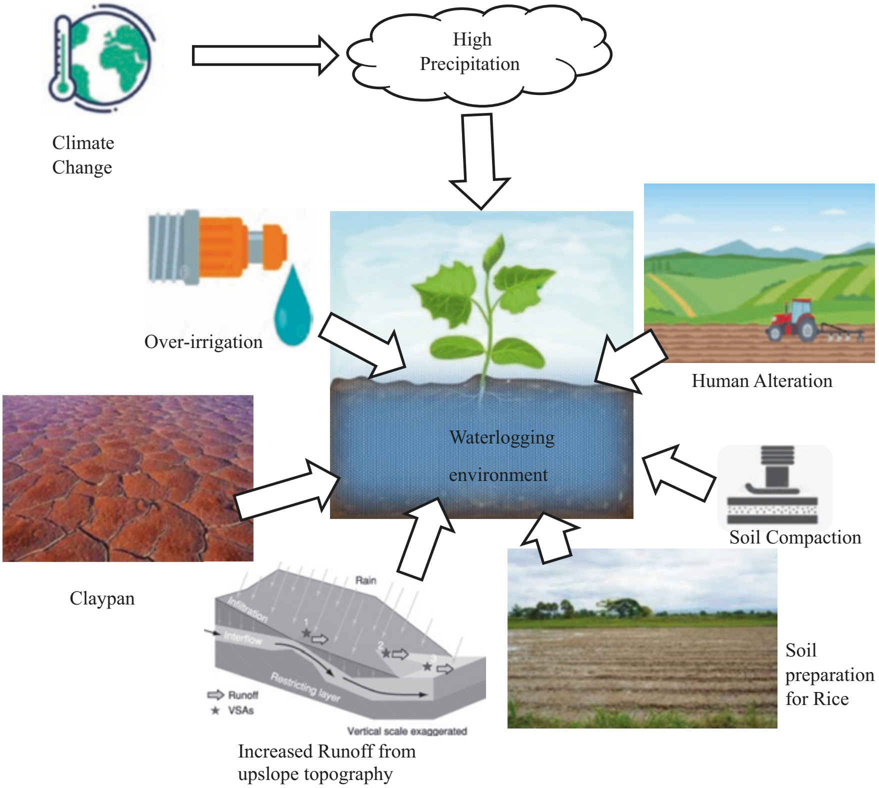

Fig. 2 Causes of waterlogging (Liu et al. 2020a)

2.2 Human Alteration in Land Use

In addition to rising precipitation frequency and severity, human modifications to stream channels, and land use are other factors contributing to rises in waterlogging (Kunkel 2003).

2.3 Over Irrigation/Rainfall after Irrigation

Soil waterlogging or floods may also be caused by over-irrigation or subsequent rains (Kirkpatrick et al. 2006). Shallow water table, compaction of soil, insufficient internal drainage as well as surface drainage are some of the issues (Kirkpatrick et al. 2006), in soils like heavy clay soils, clay pan, or duplex soil with coarse textured topsoil over compacted clay subsoil (Batey 2009).

2.4 Increased Runoff From Slope

Waterlogging in low-lying areas can result from excessive runoff from steep slope topographical regions, especially if soils there are inadequately drained (Singh et al. 2016).

2.5 Soil Compaction

Waterlogging is caused by poor soil structure resulting from natural processes or human activities, like compaction of soil due to puddling or heavy traffic, which results in shallow elevated ground water within the top few centimeters of soil or the subsurface (Batey 2009). Flooding can occur as a result of soil compaction brought on by tractor wheels movement in a field because it reduces water infiltration, permeability, and flow through the soil profile. Soil compaction can impact crop emergence, germination of seed, and its growth in addition to making roots more resistant to growth. Air movement inside the soil profile is affected by compaction because it rearranges soil particles, changes aggregate stability, bulk density, or arrangement, and affects the structure of soil (Samad et al. 2001).

2.6 Claypan

In situations of heavy precipitation or irrigation, soils with swelling–shrinking clay kinds (heavy clay soils) are vulnerable to soil waterlogging. Heavy clay soils with a high-water retention capacity and poor drainage may swell as the soil reaches its maximum water retention capacity, preventing penetration into the soil profile (Blessitt 2007). Constrictive clay subsoil horizons can be found on over 290 million ha of soil worldwide (USDA-NRCS 2006). In soils with clay pans, the subsoil horizon often suffers a fast, 100% rise in clay concentration in comparison to the soil layers above it over a small vertical distance (Motavalli et al. 2003). Depending on the topography, the claypan layer's depth could range, from 10 cm at the back slope locations to 40 cm at the front slope locations (Jiang et al. 2007).

2.7 Soil Preparation for Rice

The yield of successive non-rice crops in the rotation is negatively impacted by the breakdown of aggregates of soil also the creation of a hardpan during puddling, and these crops also demand more effort for land preparation (Kumar and Ladha 2011). Additionally, where the field had been puddled for rice, the soil infiltration rates during the wheat season are lower than they were whenever the land had been dry-drilled or maintained in no (Singh et al. 2011). Preparation of soil for rice (*Oryza sativa* L.) cultivate causes compaction of subsurface, leading to low drainage, as a result, waterlogging issues in crops like wheat in Asian countries (Samad et al. 2001).

3 Why Did Waterlogging Conditions Develop in Pakistan?

Pakistan is blessed with an abundance of water sources, including enormous rivers, tributaries, rivulets, and hill torrents, as well as significant underground water reservoirs that are known for their tall snow- and ice-covered mountain summits. The Indus irrigation system utilizes a large river and rainwater, which may help irrigate vast amounts of potentially fertile agricultural land (Aslam et al. 2015). Pakistan's economy is largely agrarian just because of that. Major crop yields, however, are much lower than any of those attained by other developing nations worldwide. Table 1 provides information on crop output (year) deficiency in the Indus Basin. Various soil, water, and management techniques, inadequate floods and spoor water management procedures, inadequate irrigation inputs of good quality water, and an insufficient drainage system could all be to blame for this (Aslam et al. 2015).

In Pakistan, irrigated agriculture is primarily limited to the Indus plains, where it has grown as a result of utilizing the main water resources the nation has to offer. Adjoining Indus Basin irrigates a total of 16 million acres. In the 1960, Indus Water Treaty, Pakistan has access to $181 \times 109\ m^3$ of water, or around 75% of the yearly available flow, from the Indus River system (Reinsch and Pearce 2005). Due to the rising depth of groundwater levels (>15 m), growers must transition, from tiny tubewells operated by diesel to powerful engines run by electricity or diesel. The majority of tubewell was driven by electricity, installations took place in the 1970s and 1980s, a time when the government offered installation cost incentives. Early in the 1990s, the government stopped providing subsidies due to rising energy costs, which caused the development of electric tubewells to stop and the number of diesel-powered tubewells to rise. Recent estimates indicate that tubewells powered by electricity are just 13%, with the remaining 85% being powered by diesel engines of various sizes (Qureshi et al. 2003). Fresh groundwater is readily available on demand, which has helped farmers attain stable and predictable yields while coping with the fluctuations in surface water supply (WAPDA 2003). To prevent a rise in the groundwater table in semiarid and arid areas, draining is seen as a complementary activity to irrigation. However, even though irrigation development has advanced significantly, Pakistan has never prioritized the building of drainage infrastructure. Due to the constant seepage over time from unlined clay canals, a wide

Table 1 Water resource draft report for the strategy study vol. 1. Islamabad (ADB 2002)

Crops	Demand	Yield	Shortage
Vegetables	14.3	9	5.3
Fruits	16.1	9	7.1
Cotton (lint)	3.5	2.7	0.8
Pulses	1.9	1.4	0.5
Sugarcane	82	46.4	35.4
Oilseed	3.3	1.5	1.8
Food-grain	50	31.5	18.5
Total	171	102.8	69.4

number of distributing channels, irrigated fields infiltration losses, groundwater levels are rising in most of the canal command regions as a result of this carelessness. In large irrigated regions, the groundwater table quickly increased within about 1.5 m of the surface of the soil (WAPDA 2007).

4 Waterlogging Stress: Physiological and Metabolic Processes in Plants

Waterlogging has been related to the number of responses shown by plants that are frequently speculative (Parent et al. 2008; Shaw et al. 2013). Oxygen transport rate in root tissues is significantly slowed down (104 times) by waterlogging in mesophytes. Ethylene, which is produced from its precursor ACC transferred from roots, regulates apoptosis induction in specific tissues and cells, nodal adventitious root formation, the creation of air chambers, metabolic variations during anaerobesis, also several other tasks (Subbaiah and Sachs 2003).

4.1 Oxygen Deprivation

Lack of oxygen caused by excessive water negatively impacts root and shoot development, photosynthesis, hydraulic conductivity, and nutrient uptake. The flow of oxygen to the soil, roughly 3 lac 20 thousand folds lesser pore spaces filled with water when compared to one filled with gas, and in water the oxygen diffusion rate compared to air is about 1/10,000th (Armstrong and Drew 2002; Colmer and Flowers 2008). Compared to air, gas diffusion in water is 104 folds slower, and O_2 deprivation is a primary barrier to waterlogging stress (Bailey-Serres and Voesenek 2008). Reduced O_2 availability slows down plant respiration and ATP synthesis, which inhibits root development (Bailey-Serres and Voesenek 2010). Decreased respiration and Adenosine Tri Phosphate production loss in wet roots are the causes of plant wilting (Sairam et al. 2008). Glycolysis uses glucose as its main fuel to provide energy for plant reproduction and growth through downstream processes including respiration (Galant et al. 2015). During respiration, glucose enters the pathway of glycolysis to create two molecules of ATP and pyruvate. Then, as a component of the TCA cycle (tricarboxylic acid), pyruvate burns to produce CO_2 and H_2O and high energy (36 ATP) in the mitochondria. Figure 3 illustrates the formation of ethanol on cytoplasm from pyruvate under hypoxic conditions, generating two ATP molecules (Sauter 2013). Waterlogged maize, rice, wheat, and barley showed energy deficiency-related restriction of root development. A study on barley and wheat for 11 days (waterlogged treatment) indicated that the growth of roots and shoots considerably decreased (Steffens et al. 2005). In comparison to plants with good drainage, wet shoots, and roots had significantly lower dry weights and root/shoot ratios (Araki et al. 2012). Waterlogging in maize slowed root senescence, which significantly reduced the roots and shoots dry weight (Ren et al. 2016a, b, c). In addition, both lowland and highland rice types' dry weight and root elongation

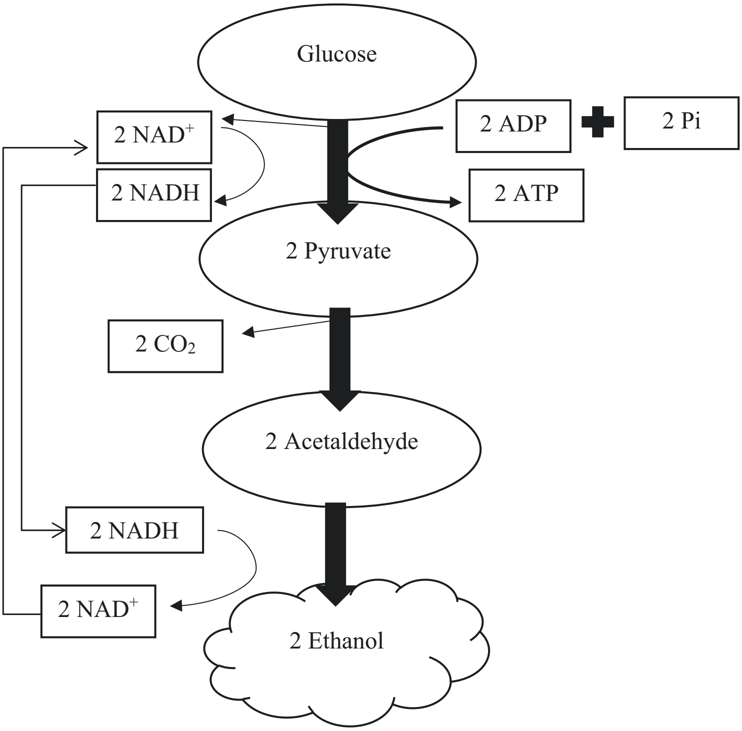

Fig. 3 Fermentation occurring in waterlogged plant roots. (Source: Poulisw 2011. Available at: http://biomhs.blogspot.com/2011/04/anaerobic-respiration-fermentation.html)

were reduced by hypoxia (Liu et al. 2020b). Waterlogged plants' poor root development also reduced their ability to absorb water and nutrients (Ren et al. 2016a, b, c).

4.2 Photosynthesis Rate

Waterlogging stress on crops reduces their photosynthetic rate because of closure of stomata, the conductance of mesophyll, degradation of chlorophyll, disruption to photosystem II, also decreased activity of photosynthetic enzymes (Ploschuk et al. 2018). Photosynthetic enzyme activity is further decreased with a prolonged waterlogging duration. Reduction in photosynthesis during flooding circumstances was shown to be caused by stomatal closure, which was found to be associated with the CO_2 exchange rate and transpiration (Irfan et al. 2010). Chlorophyll fluorescence metrics can be used to determine the various photosynthesis activities that took place in PS II including light absorption, photochemical reactions, and energy transfer (Ashraf et al. 2011). Normal leaf photosynthesis depends on the function of the chloroplast structure in mesophyll cells, which has been discovered to be damaged in waterlogged maize (Ren et al. 2016a, b, c). This damage persistently prevents photosynthetic electron transport (Yordanova and Popova 2007). After 6 h of waterlogging treatment, the photosynthesis rate of barley plants (waterlogged) initially fell by 40% (Ploschuk et al. 2018).Waterlogged treatment for 5 days, a substantial reduction of photosynthetic rate occurred and RuBisCo activity (ribulose-1.5-bisphosphate carboxylase) in barley (Yordanova and Popova 2001). Although rice is a crop that can withstand flooding, it also showed a 50% reduction in the rate of photosynthesis following an anoxic treatment of four days (Mustroph and Albrecht 2003). Flooding stress decreased soybean chlorophyll concentration by 18–34%. (Mutava et al. 2015). The maize leaf area index decreased as the period of waterlogging increased (Liu et al. 2013). Respiratory activity of wheat roots, photosynthetic rate, leaf greenness (SPAD reading), transpiration rate, grain production, number of grains per spike, stomatal conductance, and weight of 1000 grain significantly decreased due to flooding during the post-anthesis stage. Yet, the intercellular amount of CO_2 rose (Wu et al. 2012). In addition, flooded maize plants had lower chlorophyll (a + b) content and were around 20% smaller than control plants (Yordanova and Popova 2007). During the treatment for waterlogging, RuBisCo activity decreased in maize plants by 20–30% (Yordanova and Popova 2007).

4.3 Root Hydraulic Conductance

Wilting, which results from decreased root water intake and decreased root hydraulic conductance (Lp), is a frequent reaction against waterlogging stress (Herzog et al. 2016). Water absorption capacity is determined by Lp, which is connected with transpiration rate (Tan et al. 2018). Under prolonged waterlogged conditions, the death of root cells decreases Lp through erecting barriers (physical) to the flow of water (Bramley et al. 2010). Aquaporin gating and anaerobic respiration caused by a lack of oxygen are additional causes of a large shift in Lp (Tournaire-Roux et al. 2003). Energy production and cytosolic pH control aquaporin, an essential protein of membrane allowing uptake of water by the development of proteinaceous membrane pores (Aroca et al. 2012). Cellular acidosis, which is brought on by CO2 buildup through respiration and ATP depletion, and aquaporin phosphorylation, which results from these processes, control the reduction of aquaporin gating of wet plant roots (Aroca et al. 2012; Tan et al. 2018). Low-ambient oxygen and waterlogging diminish Lp in plants, but species-specific responses differ based on the water transport channel (Bramley et al. 2010).

There are three methods for transporting water:

1. Apoplastic method that is around the protoplasts.
2. Synthetic method that is by plasmodesmata.
3. Transmembrane/across the membranes.

The transmembrane system is regulated by aquaporins, whereas the apoplastic pathway depends on the structure of the root and the characteristics of the cell wall (Maurel et al. 2015). Under hypoxic conditions, lower hydraulic conductance was discovered in Arabidopsis, maize, and wheat as cellular acidosis impairs the activity of aquaporin (Tan et al. 2018). However, the primary route in other species is apoplastic, thus root Lp is not significantly affected by the decrease in the activity of aquaporin in flooding stress (Tournaire-Roux et al. 2003; Bramley et al. 2010). In addition, morphological modifications in *Oryza sativa* (rice), like the creation of barriers that prevent O_2 transport through roots, may have a deleterious impact on roots' hydraulic systems (Aroca et al. 2012).

4.4 Nutrient Absorption

Leaf chlorosis is a frequent symptom of waterlogging stress, which encourages early senescence in the leaf to remobilize N (nitrogen) to new leaves. Reduced nitrogen uptake and transport from roots results in the lower nutritional content of waterlogged shoots (Herzog et al. 2016). It accomplishes this by reduced surface, compromised function, decreased PMF (proton motive force), decreased potential of the membrane also decreased loading of xylem (Steffens et al. 2005). Particularly, wheat and barley under waterlogging stress have significantly lower amounts of magnesium (Mg), copper (Cu), phosphorous (P), potassium (K), zinc (Zn), nitrogen (N), and manganese (Mn) (Steffens et al. 2005). When compared to aerated circumstances, wheat seminal roots took up fewer nutrients from stagnant solutions (Wiengweera and Greenway 2004). Within a few minutes, the hypoxia in the barley roots' mature zone reduced net K+ uptake (Shabala and Pottosin 2014). At various phases of maize growth, Nitrogen assimilation, as well as metabolism, is reduced due to flooding stress (Ren et al. 2017). A physical barrier is created in rice in response to flooding stress in order to prevent O_2 passage form the roots, which might reduce roots nutrition absorption capacity, in contrast to waterlogging vulnerable barley, wheat, and maize that exhibited a significant loss in nutrient content (Rubinigg et al. 2002). For roots to absorb nutrients, there are three possible routes (Reichardt and Timm 2012):

1. Interception of roots' haphazard expansion into new soil areas in search of nutrients.
2. Mass flow, which represents water movement caused by evaporation and transpiration together with ion transfer to the root surface.
3. Diffusion, which is the gradient in chemical potential that encourages the flow of nutrients.

By reducing nutrient interception, in waterlogging stress reduction of growth of roots drastically reduced the potential intake of nutrients (Mancuso and Shabala 2010). The majority of roots of maize (apart from adventitious roots) were not able to take nutrients from ambient soil under waterlogging treatment for 6 days (Qiu et al. 2007). The majority of nutritional absorption relies on diffusion and is fueled by proton motive force and membrane potential, both of which are suppressed during conditions of waterlogging stress. Limited ATP supply resulted in a depolarized plasma membrane, reduced proton motive force, and impaired activity of the plasma membrane proton-pumping ATPase, all of which lowered the cytoplasmic pH. (Mancuso and Shabala 2010). With the help of plasma membrane H + -ATPase, ions that the roots have taken up are transferred to the shoot through the xylem. Waterlogged situations, inhibit xylem transport due to a decrease in H + - ATPase in the parenchyma of the xylem, which constantly lowers the shoot's nutritional content in waterlogged plants (Colmer and Greenway 2011).

5 Anatomical Adaptation

5.1 Formation of Aerenchyma

An air tissue in some plants' adventitious roots creates gaps between cells and does gaseous transportation between roots and shoots, a typical adaptive characteristic linked to the ability to withstand waterlogging (Colmer 2003). Two distinct forms of aerenchyma, schizogenous, and lysigenous, are produced when cells are separated and then lysed, respectively. The cortex of roots of the majority of cereal crops, such as wheat, maize, barley, and rice develops lysigenous aerenchyma (Yamauchi et al. 2013). Lysigenous aerenchyma for wetland plant rice develops constitutively including well soil conditions and rises in wet situations. However, the aerenchyma production in barley, maize, wheat, and other terrestrial plants is only brought on due to moisture stress (Yamauchi et al. 2011). Following 7 days of flood treatment, aerenchyma was found in mature root zones of barley in the tolerant cultivars at a distance of around 6 cm from the root apex (Zhang et al. 2015). According to a study on maize, under conditions of waterlogging, cell death began at 10 mm from the tips and was fully developed at 30–40 mm from the tips (Evans 2004). Higher root porosity and the production of aerenchyma are significant adaptive features that contribute to the ability to withstand waterlogging (Setter and Waters 2003). By starting planned death in cells of particular cell types, ROS abbreviated as reactive oxygen species and the phytohormone ethylene in gaseous form are associated with lysigenous aerenchyma formation. Due to obstruction of gas transport to the rhizosphere and the increased ethylene production caused by waterlogging stress, ethylene builds up in roots (Yamauchi et al. 2018). In response to the stress of waterlogging, antioxidant defense systems are used to combat the harmful consequences of ROS build up (Ashraf et al. 2011).

5.2 Adventitious Root Growth

Seminal root growth is inhibited in wet plants, which results in a lower root/shoot ratio. There are two main plant root types: seminal roots and adventitious roots. Comparatively to seminal roots, which only have a fully developed main root axis, adventitious roots have much more core metaxylem and cortical cell layers (Knipfer and Fricke 2011). As seen in Fig. 4, waterlogged plants frequently respond by

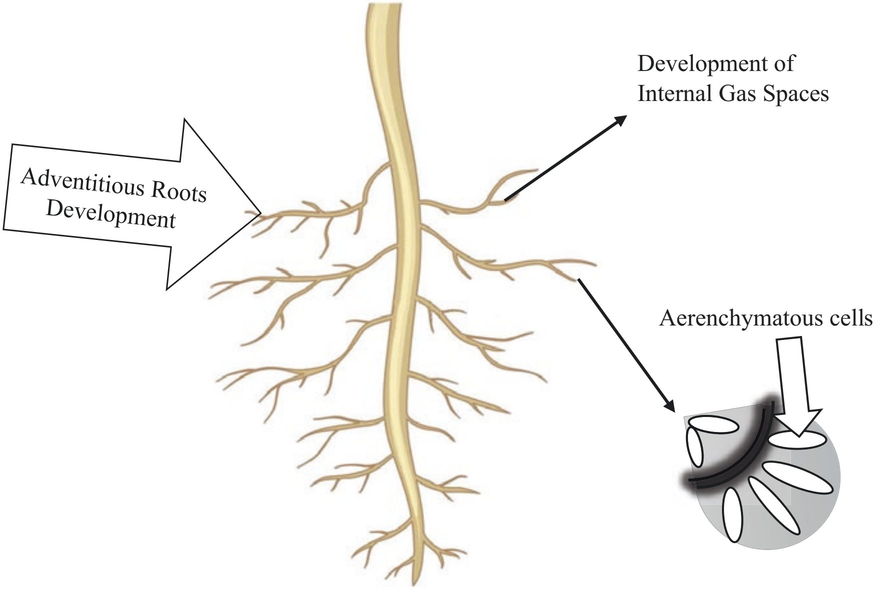

Fig. 4 Aerenchyma cells and adventitious root formation in waterlogged condition. [Kaur et al. 2020(source) (modified)]

forming adventitious roots, which can substitute the damaged seminal roots and produce more aerenchyma to increase the capacity for inner O2 delivery. In trials conducted in greenhouses, seedlings of Zea mays ssp. huehuetenangensis displayed higher adaptation toward submersion with adventitious root formation (Mano et al. 2005). The number of adventitious roots in barley genotypes (tolerant) after 21 days of waterlogging treatment was significantly higher than that in genotypes that were sensitive (Luan et al. 2018a, b). Aerenchyma was found to occupy 20–22% and 19%, respectively, of adventitious roots of wheat and barley (Ploschuk et al. 2018). A study on rice discovered that the hormone auxin gradient in root tips determines the adventitious root growth direction (Lin and Sauter 2019). Adventitious roots extend upward to get closer to the oxygen-rich water surface to help with water and nutrient absorption from the top layer of the moist soil (Jia et al. 2021; Steffens and Rasmussen 2016). Additionally, as it develops at the stem nodes, adventitious roots can shorten the distance that oxygen is transported between shoots and roots (Steffens and Sauter 2009). Epidermal cell death induced by ROS and ethylene promotes the formation of adventitious roots from the epidermis of the node (Nguyen et al. 2018a, b).

5.3 Radial Oxygen Loss (ROL) Barrier

Radial Oxygen Loss barrier, yet some other crucial response characteristic in order to deal with stresses like waterlogging in addition to aerenchyma formation. An apoplastic barrier called the ROL barrier, which is found in the outer root cell layer stops oxygen from escaping into the anaerobic environment (Yamauchi et al. 2018). In general, rice generates ROL barriers in waterlogged or stagnant conditions, whereas flooding-sensitive cereals like barley, wheat, and maize don't (Ejiri et al. 2021). Under hypoxic soil, the ROL barrier enables a plant to maintain high quantities of oxygen at the tips of its roots (Abiko et al. 2012). The development of lignified sclerenchyma and suberized hypodermis in roots regulates ROL (Watanabe et al. 2013). Light ROL barrier development was stimulated for flooding-resistant *Zea nicaraguensis* (wild maize), and lignin and suberin, found in inner and outer layers, orderly (Watanabe et al. 2017). Rice roots' basal region can be shown to have both suberized and lignified cells after two to three weeks of waterlogging (Soukup et al. 2007). Figure Microarray analysis on rice adventitious roots showed during the construction of the ROL barrier, numerous putative genes connected to suberin biosynthesis were highly elevated, while only a small number of genes related to lignin production were induced (Shiono et al. 2011). Malic acid and long-chain fatty acids are connected to the production of suberin, according to metabolite analyses

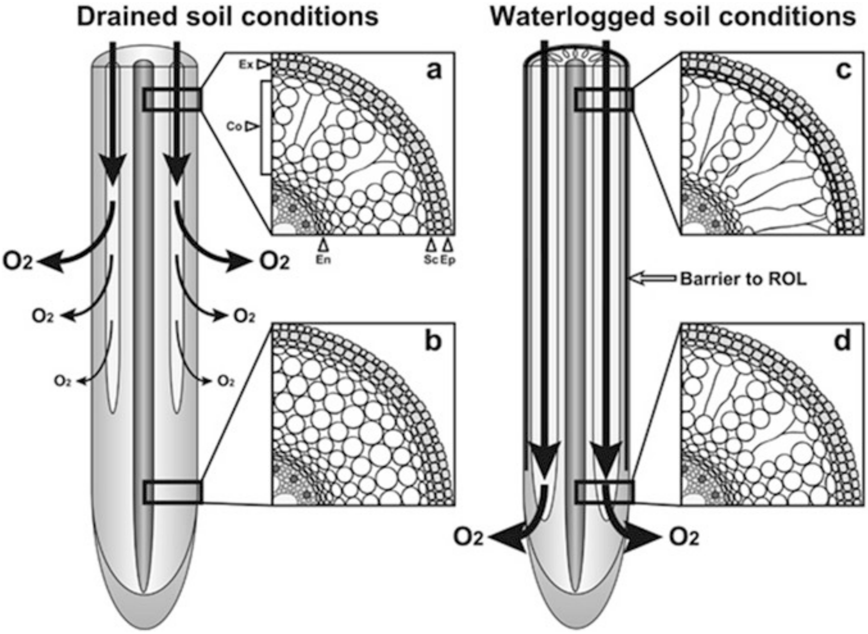

Fig. 5 Rice roots grown in both wet and drained soil exhibit different trends of radial O_2 loss (ROL) and lysigenous aerenchyma development. "Ex" stands for exodermis; "Sc" for sclerenchyma; "Co" for cortex; and "En" for endodermis. (Nishiuchi et al. 2012)

of rice adventitious roots. Malic acid and long-chain fatty acids accumulated during ROL growth (Kulichikhin et al. 2014). Lysigenous aerenchyma is continuously produced under drained soil conditions, but barriers to ROL are not established, which lowers O_2 diffusion towards the apical portion. On the other hand, lysigenous aerenchyma development is accelerated, and the construction of the barrier to ROL is stimulated in wet soil conditions, which promotes longitudinal O_2 diffusion to the root apex. Figure 5 shows how the basal region of the roots constitutively produces lysigenous aerenchyma (a) under drained circumstances of soil, typically not produced at the apical root part (b). At the basal region, lysigenous aerenchyma is formed (c) and the apical part (d) of roots in wet soil conditions. The roots' basal (a, c) compared to its apical portion, the lysigenous aerenchyma is much more developed (b, d). The O_2 availability is shown by the thickness of the arrow. In barley waterlogging tolerant cultivars, lignin deposition under waterlogging stressors greatly increased the activity of the enzyme caffeic acid o-methyltransferase (COMT), which is associated with the formation of lignin (Luan et al. 2018a).

6 Signaling and Response to the Stress of Waterlogging

6.1 Phytohormone Signaling

Under conditions of waterlogging, ethylene, an essential phytohormone that controls plant development and senescence, was shown to accumulate (Iqbal et al. 2017). The development of a plant root barrier that restricts ethylene diffusion leads to ethylene buildup (Voesenek and Sasidharan 2013). In addition, it has been discovered that the activity of two enzymes, ACC oxidase, and synthase (1-aminocyclopropane-1-carboxylic acid), increases due to waterlogging stress (Dat et al. 2004; Broekaert et al. 2006;). Ethephon, an agrochemical that releases ethylene, increased aerenchyma development at the tips of roots and prevented wilting due to waterlogging in barley after pretreatment (Shiono et al. 2019). In order to facilitate plants' movement of O_2 from shoots to roots when there is a lack of oxygen, ethylene controls the creation of gas spaces (aerenchyma) in roots (Steffens and Sauter 2009). In waterlogged maize and barley roots, a transcription level of XET expression was shown to be increased (Luan et al. 2018b). Thus, XET expression and cellulase are induced by ethylene and aid in the production of aerenchyma in roots by dissolving cell walls. Gibberellin (GA), ethylene, and abscisic acid (ABA), significantly play a role in the survival of waterlogged plants by inducing elongation of the shoot. Gibberellic acid encourages elongation between nodes through the breakdown of proteins that are growth inhibitory (Hedden and Sponsel 2015), also through the breaking of starch, releasing cell walls in order to mobilize dietary resources thus enhancing the growth of plants (Else et al. 2009). GA significantly boosts the growth of shoots whereas elongation of roots is inhibited by ABA, acting as antagonists in plants' reactions to growth stimuli (Dat et al. 2004). After 3 h of the flooded plants receiving the ethylene treatment, GA1 increased four-fold and ABA decreased by 75% in deep-water rice (Vaahtera et al. 2014). The stem node

ABA content and gene expression level in ABA production were both decreased in the adventitious roots of flooded wheat. After 3 weeks of waterlogging treatment, ABA content was observed to be reduced in the roots and leaves of varieties of barley (tolerant & sensitive), with a greater decrease in tolerant species (Luan et al. 2018a, b).

6.2 Reactive Oxygen Species Accumulation (ROS)

For crop stress conditions like droughts, salinity, freezing, and mechanical stress, ROS plays a crucial supplementary messenger role, even though they can be harmful to plants because they unrestrictedly oxidize cell components (Mittler 2002; Mhamdi and Van Breusegem 2018). Figure 6 illustrates the primary metabolic adaptations of flooding tolerance of plants as well as stress responses to

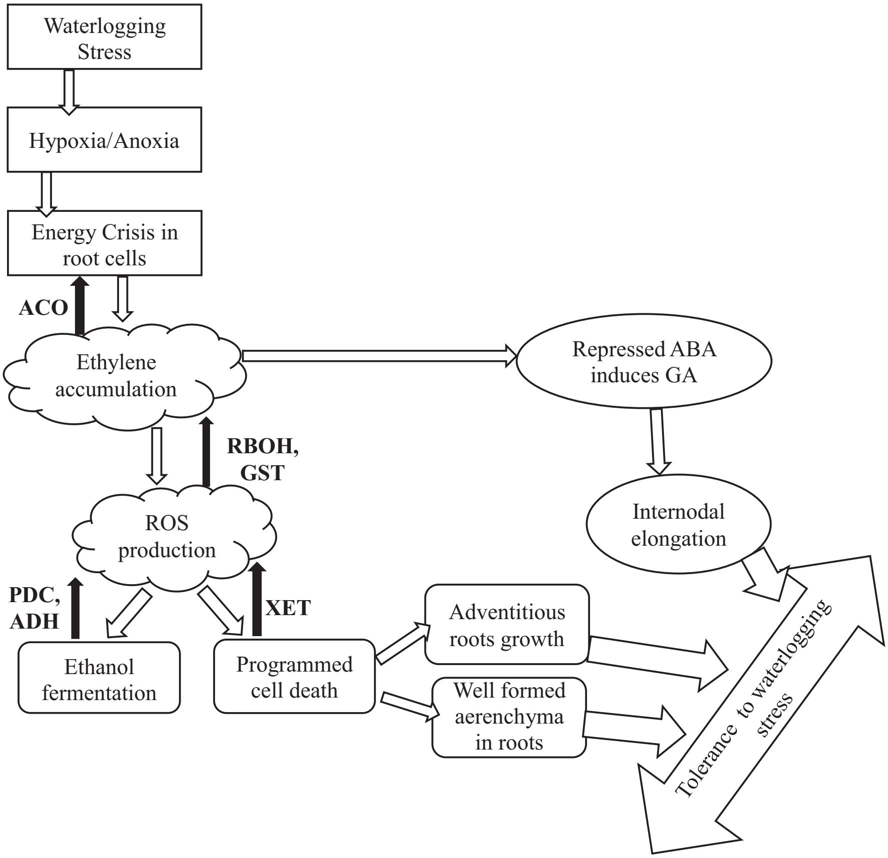

Fig. 6 Schematic diagram of the main waterlogging stress responses and metabolic adaptive traits for waterlogging tolerance in plants. PDC: pyruvate decarboxylase, ADH: alcohol dehydrogenase, RBOH: respiratory burst oxidase homolog, GST: glutathione S transferase, XET: xyloglucan endo-transglycosylase, ACO: 1-amino-cyclopropane-1-carboxylic acid oxidase (Tong et al. 2021)

waterlogging. Different organelles in plants, such as chloroplasts for photosynthesis, mitochondria for respiration, and peroxisomes for photorespiration, all participate in the metabolism of ROS (Foyer and Shigeoka 2011). The breakdown in mitochondria of the electron transport chain during oxygen deprivation results in the production of hydrogen peroxide (H_2O_2), It acts as a stimulus for epidermal cell death to generate aerenchyma, protecting plants from anaerobic environment stress (Fukao and Bailey-Serres 2004; Steffens et al. 2011; Rajhi et al. 2011). H_2O_2 treatment increased lysigenous aerenchyma production by processes of cell death in flooded *Oryza sativa* (rice) (Blokhina et al. 2001). Similarly, under wet conditions, H_2O_2 accumulation was discovered in the roots of wheat and barley (Yamauchi et al. 2014). ROS accumulation, a trigger for wheat seedlings to respond to waterlogging by controlling gene expression, is associated with fermentation of ethanol (ADH and PDC) and aerenchyma formation (Sumimoto 2008). Respiratory Burst Oxidase Homolog (RBOH), which genes for an NADPH oxidase found in the plasma membrane for the production of H_2O_2, controls the accumulation of ROS (Steffens 2014).

7 Agronomic Practices to Grow the Crop in Waterlogged Soil

Given how weather-sensitive agronomic crop production is, global climate change has an impact on the agricultural industry (Aderonmu 2015). The amount of seasonal precipitation as a whole, as well as the differences between and within seasonal precipitation events, have changed due to climatic fluctuations. Extremes in water availability, particularly waterlogging, have increased during the past 50 years in agricultural districts all over the globe (Aderonmu 2015; Bailey-Serres et al. 2012). Whenever all or a portion of a plant is submerged in water, the condition is referred to as “flooding” (Bailey-Serres et al. 2012). Figure 7 illustrates suggested procedures for various wet environments. The measures listed below can help you deal with the effects of waterlogging:

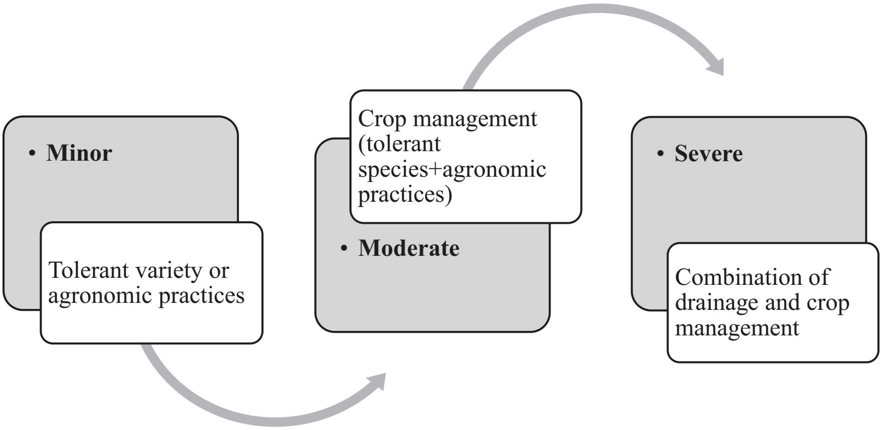

Fig. 7 Recommendations for managing soil and crops dependent on the severity of waterlogging (Manik et al. 2019)

8 Modeling of Crops and Decision-Making Systems

Numerous models, such as DRAINMOD, can simulate how crops respond to waterlogging in the soil in terms of growth and yield (Skaggs 2008). These models can be used to determine which places or circumstances will result in a decrease in yield and to evaluate the effect of management practice modifications on the reduction of flooding stress on crop plants. For instance, the Agricultural Production Systems Simulator (APSIM-Wheat) was used in order to predict impacts on wheat due to waterlogging at various dates of the plantation. It was discovered, only in places with a minimal to medium risk of waterlogging will an earlier planting date boost crop output, yet had no effect in areas that frequently experienced waterlogging (Bassu et al. 2009). However, the effectiveness of these simulation models for use in evaluating waterlogging stress depends on how well the processes are represented in them (Shaw et al. 2013). Additionally, remote sensing and GIS are utilized to locate fields' sensitive areas to soil flooding or dry conditions and can assist in the precise positioning of crops or strategies of management of nutrients thus lessening waterlogging stress. Selectively regions with the greatest nutrient losses, employment of cover crops may lower the cost of planting cover crops and result in financial savings for farmers. For producers to make decisions on the precise placement of various crop management measures to reduce the stress caused by soil waterlogging, they need decision support tools. The Right, Practice, Right, Place (RPRP) Toolbox, which consists of collection preservation strategizing tools online that connect at the local, watersheds, and field level, applying the "right practice of conservation " to the "right spot" can help increase the efficacy as well as efficiency of efforts to improve quality of the water. (McLellan et al. 2018). Using several BMPs (Best Management Practices), individually /collectively, to reduce the loss of nutrients in crop fields is evaluated using the SWAT (Water Assessment Tool) model (Merriman et al. 2019). Although these decision-support systems have been tested for identifying BMPs for improving the quality of water, yet not been examined in determining how well BMPs mitigate stresses like flooding in various situations. Crop producers can use these models as tools to help them make well-informed choices about the use of techniques of crop management for locations where the chances of waterlogging stress are high. Still no information regarding how to apply these systems for deploying methods for management at individual sites are available (Kaur et al. 2020).

9 Crop Management Practices

9.1 Application of Nutrients

Nutrient deficiency is among the main impacts of waterlogging upon plants, which reduces net carbon fixation and photosynthesis and, eventually, growth and production (Bange et al. 2004). Increased productivity will result from the application of vital nutrients, which will help to lessen the effects of abiotic pressures such as waterlogging (Noreen et al. 2018). N fertilizer applications may increase and speed up a plant's ability to adapt to waterlogging stress, including root regrowth and adventitious root growth following a flooding event. This may raise a plant's tolerance to waterlog stress. Due to low O_2 during flooding, which may prevent plants from absorbing N, its loss through leaching and denitrification may result in N deficits, decrease nitrogen availability, and restrict root function (Nielsen 2015), as seen in Fig. 8. The application of enhanced-efficiency N fertilizers, such as slow-release or controlled-release (SR/CR) fertilizers, under wet conditions, is crucial for enhancing plant growth and development (Shaviv 2001; Varadachari and Goertz 2010). By coordinating nitrogen release with crop needs, throughout growing crops, slow-release fertilizers can emit nitrogen across a long duration of time, maximizing (NUE) nitrogen use efficiency (Trenkel 2021). Externally applied fertilizers may be effective if the nutrient ions infiltrate the root architecture, enabling plants to heal from waterlogging-related damage, claims many research studies (Ashraf et al. 2011; Habibzadeh et al. 2012; Najeeb et al. 2015). Wheat (Pereira et al. 2017; Zheng et al. 2017), barley (Pang et al. 2007), corn (Kaur et al. 2018), canola (Kaur et al. 2017), and cotton (Wu et al. 2012; Li et al. 2013) are among the crops that are (Habibzadeh et al. 2012). Application of fertilizer also extends the time that the canopy is open and speeds up the development of photo-assimilates that are transferred to grain rather than straw, raising HI (harvest index) (Kisaakye et al. 2015, 2017). Additionally noted that potassium fertilizer can mitigate the negative impacts of waterlogging in a variety of crops, including rapeseed and cotton (Cong et al. 2009; Ashraf et al. 2011). In phosphorous deficiency, during a rainy growing

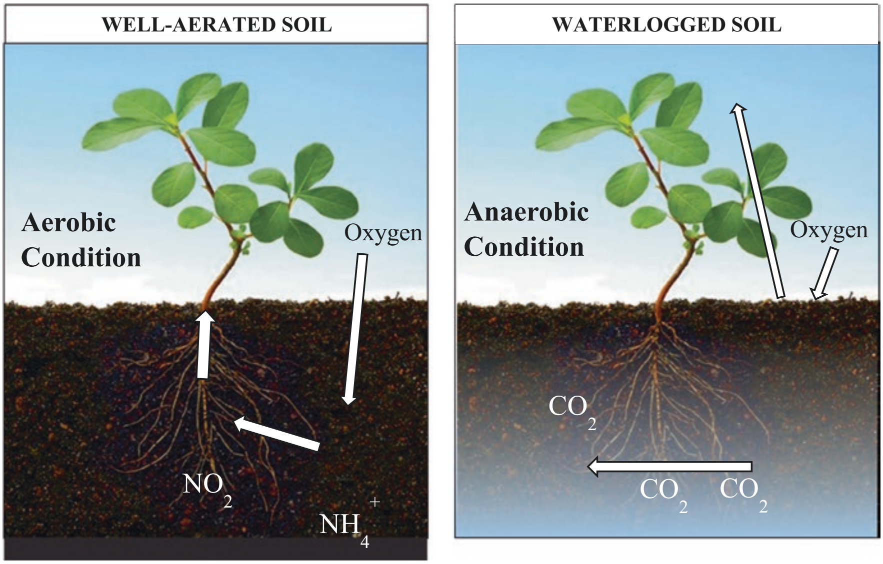

Fig. 8 Different soil conditions, both aerated and anaerobic, are used to demonstrate the nitrification and denitrification processes. Available at: https://civiljungle.com/waterlogging/

season, external application of different phosphorus (P) sources, such as Meat & Bone Meal (MBM) and Dairy Cow Manure (DCM), is beneficial for providing the highest yields (Ylivainio et al. 2008, 2018). Under flooded conditions, the administration of FYM (Farm Yard Manure), greatly enhanced iron, zinc and copper concentrations in grain (Masunaga and Fong 2018).

Even with high-value crops, the application of fertilizer to prevent waterlogging loss in extensive farming is limited due to the lack of research on their potential benefits for improving crop performance in waterlogged circumstances (Trenkel 2021). To prevent tissue toxicities (such as manganese) and nutrient imbalance from harming soil ecology, it is important to examine the application techniques, nutrient types, timing, and rate that are acceptable (Rochester et al. 2001; Jackson and Ricard 2003).

9.2 Plant Growth Regulator

Applying PGRs at the proper growth stage can reduce the damage that waterlogging causes to plants (Wu et al. 2018; Ren et al. 2018). Plant growth under wet conditions is improved by plant growth regulator administration (Pang et al. 2007; Ren et al. 2016a, b, c). In waterlogged barley, auxin (synthetic) 1-NAA (1-naphthalene acetic acid) encourages adventitious roots formation (Pang et al. 2007), while the external administration of cytokinin 6-BA (6-benzyl adenine) can reduce the effects of waterlogging and boost maize output (Ren et al. 2016a, b, c, 2018). By enhancing leaf photosynthesis, pre-waterlogging ABA foliar treatment enhanced the resistance of cotton plants to subsequent waterlogging-related damage (Pandey et al. 2002; Kim et al. 2018). Triazole is recognized to be a fungus-toxicants, and they also affect how plants respond to stress and regulate their growth (Rademacher 2015). For instance, paclobutrazol reduces the harm caused by waterlogging in sweet potato plants and canola (Lin et al. 2008). 5-methyl-1,2,4-triazole (3,4-b) benzothiazole (Tricyclazole) treatment reduces plant damage when there is waterlogging (Habibzadeh et al. 2013). However, there hasn't been much usage of plant growth regulators to lessen waterlogging damage due to inconsistent results at the commercial level (Manik et al. 2019).

9.3 Pretreatment with Hydrogen Peroxide

Pre-treating plants with an agent could be a successful method to boost their tolerance to various stresses as shown in Fig. 9. For instance, pretreating crops with H_2O_2 can shield them from oxidative harm brought on by waterlogging, intense light, chilly weather, salt stress, drought, and heavy metal exposure (Gechev et al. 2002; Rajaeian and Ehsanpour 2015; Andrade et al. 2018). Increases in the diameter of the stem, high accumulation of biomass, the volume of the root, and photosynthetic pigments were also brought about by H_2O_2 pretreatment (Andrade et al. 2018). H_2O_2 pretreatment resistant against waterlogging, despite substantial research being done

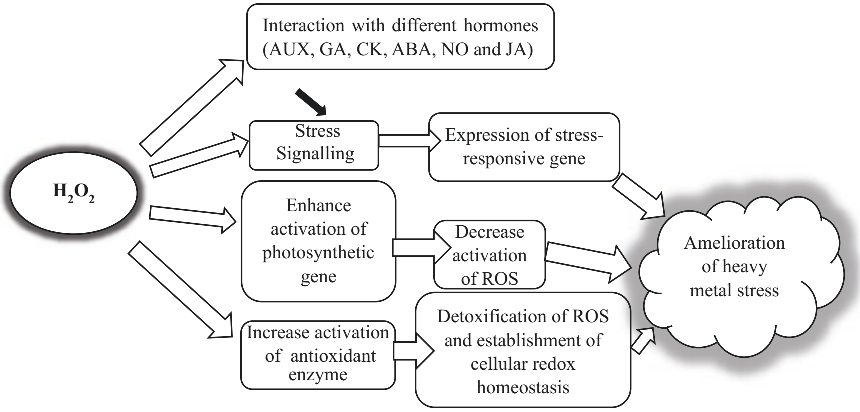

Fig. 9 Reactive oxygen species are shown to be produced by heavy metals in a schematic representation, and hydrogen peroxide is used since it is a signaling substance to activate the antioxidant system, that lowers the concentration of reactive oxygen species and safeguards plants from harm caused by heavy metal stress (Htet et al. 2019)

on treatments against both biotic and abiotic stresses, is still in its infancy (Mustafa et al. 2017; Lal et al. 2018; Ashraf et al. 2018).

9.4 Utilization of Tolerant Varieties and Species

Waterlogging tolerance is one of the most effective ways to reduce the loss brought on by flooding in available plant species (Zhou 2010; Wani et al. 2018). There are genetic variations in waterlogging resistance among several crops, including wheat and barley (Zhang et al. 2015; Huang et al. 2015; Herzog et al. 2016; Wu et al. 2018; Nguyen et al. 2018a, b). Waterlogging tolerance, however, is a dynamic condition that is regulated by a diverse range of mechanisms, including the maintenance of membrane potential (Gill et al. 2018), the control of ROS production under stress conditions, resilience to metabolites (Pang et al. 2006), toxicity of ion (Huang et al. 2018), aerenchyma formation in roots under waterlogging stress, and many quantitative trait loci (QTL) (Gill et al. 2018). The identification of genes that are associated with different tolerance mechanisms is crucial for the success of breeding programs because it enables producers to elevate tolerance genes. Depending on the region and the weather, flooding can happen at any stage of the crop's growth. Waterlogging brought on by heavy rains in the fall can delay crop harvesting, so it's critical to breeding crop varieties with traits like strong stems, superior seed quality, and reduced sensitivity to diseases and pests. It is important to create variety with tolerance both to cold and floods stress since flooding in the early part of the growing season often subjects crops to cold soil temperatures. In conclusion, it's critical to create and test novel varieties of crops that are resistant to a variety of biotic or abiotic stresses, such as heat, drought, and waterlogging stress, along with disease vectors (Kaur et al. 2020).

9.5 Adjusting Dates of Planting

In order to encourage favorable crop emergence and development during the initial spring season, planting dates might be modified to minimize waterlogging circumstances. The emergence of crop and plant development vigor can be delayed by cool, damp soils. A short growth period and exposure to dryness subsequently in the planting season may result in decreased crop yields, while later sowing dates may prevent potential initial extreme rainfall events and saturated soil conditions. Droughts that occur over the summer have pushed the dates of the plantation, sooner into the spring (Kucharik 2006). The creation of cultivars resistant to unfavorable weather conditions and diseases, treatment of seed, enhanced plantation tools, crop protection products, and the use of time-saving crop management techniques like conservation tillage are further variables that contribute to early planting dates (Kucharik 2006). By extending the time for solar radiation absorption and biomass accumulation, early planting dates enable a longer growing period and larger yields (Kucharik 2006). Crop varieties chosen for early planting ought to be resistant to a low temperature of soil that develops after or during planting because there is a danger of plant injuries due to inadequate soil temperature at these early planting dates. Changing planting dates to reduce soil waterlogging depends on when and how long the waterlogging lasts (Kaur et al. 2020).

9.6 Use of Cover Crops

By enhancing soil structure, lowering compaction, and boosting the rate of water infiltration, the use of cover crops may not just improve soil health but also reduce waterlogging (Blanco-Canqui et al. 2015). Cover crop roots can create more macropores, which will result in more water moving through the soil. Increased cover crop transpiration during the spring may potentially dry the soil in time for earlier crop planting. Through larger evapotranspiration (ET) losses, cover crops with higher water requirements and warmer springtime temperatures can assist in eliminating extra moisture from the waterlogged soils. Numerous studies have documented how cover crops can reduce soil moisture content (Monteiro and Lopes 2007; Zhang and Schilling 2006). Reed canary grass (Phalaris arundinacea) had a reduced water table and soil moisture content due to increased ET losses, which decreased groundwater recharge, according to research on the impact of land cover on these variables (Zhang and Schilling 2006). Utilizing cover crops during the winter fallow season is another possible strategy for preventing soil waterlogging. However, depending on the soil type, climate, and cover crop species employed, the impact of cover crops on the water distribution in the soil profile can be beneficial, negative, or neutral (Blanco-Canqui et al. 2015). Therefore, further research should be done on the utilization of different types of cover crops for fields that are prone to flooding or drought. Topography, which can affect nutrient and water dynamics within a field and provide variability biomass synthesis of cover crop and cash crop yields, is not always present in agricultural fields. Therefore, it is crucial to better assess how topography and cover crops interact to lessen the stress caused by waterlogging in big agricultural areas. Using spatial modeling and remote sensing techniques from the geographic information system (GIS), it may be possible to spot parts of an agricultural field that are prone to flooding (Kaur et al. 2020).

9.7 Using Conservation Tillage Techniques

Conservation tillage techniques include mulch tillage, minimal (reduced) tillage, ridge tillage, and contour tillage. The term “minimum tillage” (MT) refers to soil manipulation with only a minimal amount of plowing utilizing primary tillage tools. No-tillage (NT) refers to field cultivation with little to no soil surface disturbance. Mulch tillage involves preparing or tilling the soil in a way that allows plant wastes or other materials that cover the surface to the greatest possible amount. In ridge tillage, crops are planted in rows either on top of or along the ridges that are formed at the start of a cropping season. Variations in conservation tillage’s effects on soil characteristics rely on the specific system selected. The soil qualities, particularly in the top few centimeters, have changed significantly as a result of no-till (NT) methods, that achieve high top soil coverage (Anikwe and Ubochi 2007). NT technologies are particularly successful at minimizing erosion losses, decreasing the amount of residue disturbance, and moderating soil evaporation (Lal et al. 2007). No-till soils have been linked to much more stable aggregates mostly in the soil’s upper surface than tilled soils, which leads to high permeability under NT plots. Over 37–40 years of tillage operations in Gottingen, Germany, minimum tillage (MT) enhanced both levels of SOC and nitrogen inside the aggregate in the upper 5–8 cm soil depth as well as aggregate stability (Jacobs et al. 2009). In tropical and subhumid tropics, no-till has been proven to be more beneficial in terms of water saving. Contrary to tilled plots, untilled plots hold more water (Kargas et al. 2012).

Compared to normal plowing, minimum tillage increased the soil pores (0.5–50 mm), also many elongated transmission pores (50–500 mm), which improved the soil’s pore system (Pagliai et al. 2004). The upper layer of soil (0–10 cm) under NT has been observed to have a greater holding capacity for water (McVay et al. 2006). Therefore, to improve soil water storage and increase water use efficiency (WUE), the majority of research has recommended shifting to conservation tillage rather than just traditional tillage (Fabrizzi et al. 2005; Silburn et al. 2007). Table 2 lists many benefits and drawbacks of crop management techniques.

10 Adaptive Water Management

Numerous initiatives have been launched to address the issue of waterlogging since the early 1960s. Farmers made no investments in the majority of these initiatives because they were subsidized by the government. Despite significant investment, progress in resolving land degradation issues has been slow. Waterlogging issues were not as easily handled as originally thought. A high groundwater level is a

Table 2 Merits and demerits of management techniques for crops

The practice of managing the soil and crops	Merits	Demerits	Reference
Application of nutrition (particularly N)	Promoting the development and growth of plants	The right methods, nutrients, duration, and quantities should be considered for large-scale administration	Rao et al. (2002), Pang et al. (2007), Wu et al. (2012), Najeeb et al. (2015), Pereira et al. (2017), Li et al. (2013), Kaur et al. (2017, 2018), Zheng et al. (2017)
Plant growth regulators	Encourage water-logged plants' and photosynthetic ability	When applying on a wide scale, the right timing, rate, and procedures should be taken into account	Ren et al. (2016a, b, c, 2018), Habibzadeh et al. (2013)
Hydrogen peroxide pre-treatment	Defend plants from oxidative harm brought on by waterlogging	Unproven in commercial agriculture	Gechev et al. (2002), Ishibashi et al. (2011), Savvides et al. (2016)
Tolerant species and varieties	Economical for farmers	It takes time and effort to introduce waterlogging tolerance into current plant varieties	Zhou et al. (2007), Gill et al. (2018)
Modifying plant dates	Utilizing the soil's current water acts as a buffer and prevents catastrophic waterlogging incidents	Small benefit in cases of extreme waterlogging	Bassu et al. (2009), Sundgren et al. (2018), Wollmer et al. (2018)

problem for 20–30% of the population as a result of excessive surface water use (Smedema 2000).

10.1 Drainage Systems

One of the key strategies for increasing yields per available agricultural area is land drainage (Malano and Van Hofwegen 2018; Singh 2018b). The two major goals of agricultural drainage are to decrease soil submergence and open up a new areas for agriculture (Singh 2018b). When compared to irrigation, drainage is a more effective agriculture engineering solution to fight to waterlog; nevertheless, neither individual farmers nor governmental organizations have given it the same priority as irrigation. Around the world, drainage is utilized to reduce waterlogging (Milroy et al. 2009). Numerous research from North America, Europe, and England show that draining can successfully lower the water table and boost crop production (Gramlich et al. 2018). Many techniques to lessen the waterlogging problems have been proposed (Kazmi et al. 2012; Singh 2012, 2016). These techniques are explained below:

10.1.1 Surface Drainage

Surface drainage is the method of employing manufactured channels to safely remove surplus water from the surface of the ground (Ritzema et al. 2008; Ayars and Evans 2015). Surface drainage systems have been proven to be cost-effective, with cost-benefit ratios ranging from 1.2–3.2, average return rates from 20 to 58%, and payoff times of 3 to 9 years (Ritzema et al. 2008). The simplest and most affordable option is to keep the surface drains that already exist and build additional ones across edges or via depressions while considering their proper size and placement. Using cut-off drains to stop water from flowing from higher to lower paddocks is also a smart option (Palla et al. 2018). However, inadequate lateral water flow or internal soil drainage qualities frequently limit the effectiveness of surface drainage, resulting in poor drainage near the drains (Saadat et al. 2018). This means that the solutions to these issues may involve both subsurface and surface drainage.

Raised Beds

In semi-arid and arid areas, these are re-utilized to address hurdles like irrigation requirements and also waterlogging (Govaerts et al. 2007). By preserving a suitable moisture level in soil via enhanced seepage and acting as a channel to distribute irrigation water, raised seedbeds can improve crop yields (Velmurugan et al. 2016). It increases drainage, and aggregate stability and reduces bulk density (Hassan et al. 2005). To prevent compaction of soil, which promotes penetration of soil, development of roots, and surface and subsurface infiltration, traffic in the furrows should be kept to a minimum. In comparison to flat seedbed planting, raised bed planting has been shown in several studies to increase crop yields in soil that is saturated with water (Blessitt 2007). Soil structure enhancement as seen by infiltration rate and lower bulk densities in clay soil (duplex), which decreased the likelihood of waterlogging and promotes rates of runoff seen in raised beds due to the availability of furrows (Bakker et al. 2005a). As the top 15 centimeters are kept dry during planting in raised beds, as shown in Fig. 10, raised bed planting minimized waterlogging stress. Raised beds have helped to lessen the consequences caused by flooding, but it also has some demerits. These include the price of modifying and adapting machinery, the difficulty of managing drainage water, the use is restricted where the water table is too high, handling stubble and preserving fodder, firefighting and mobilizing livestock, the possibility of pesticide contamination of waterways and leaching into the water table, ineffectiveness of machinery, and weed management in furrows (Bakker et al. 2005b; Gibson 2014).

10.1.2 Subsurface Drainage

Due to the thick soil composition, compact layers, and naturally occurring or artificial hard pan as well as water flowing downhill from springs or from higher slopes, which raises the water table, poor subsurface water mobility occurs (Ward et al. 2018). Subsurface drainage reduces the water table or perched water and creates an

Fig. 10 Tackle waterlogging problematic soil, via Raised Beds (Source: Glenn McDonald 2022)

environment that is conducive to waterlogging in the root region (Christen and Skehan 2001; Xian et al. 2017). Open and pipe drains with varying drain depths and spacing constitute subsurface drainage systems (Ritzema et al. 2008). The sort of drain that should be installed often relies on the topography, the soil, and the needed drainage rate.

Horizontal Subsurface Drainage

The crop root zone is drained of excess water via horizontal subsurface drainage (Teixeira et al. 2018). The drainage system is made up of pathways of perforated pipes below the surface of the earth. Higher agricultural yields can be achieved by draining surplus soil moisture, to enhance root emergence and growth (Nelson et al. 2009, 2011). Flooded soil drainage can be improved globally through subsurface drainage technology (Nelson et al. 2012; Sharma et al. 2016). Using tiny pipes constructed of concrete that is placed at a predetermined depth, tile drainage is a form of horizontal subsurface drainage. In agricultural fields where subsurface excess water is a regular issue, tile drainage is widely used (Williams et al. 2015). In places with shallow groundwater and dense soil conditions, to strengthen the system typically gravel is utilized as a backfill material just above tile seepage (Filipović et al. 2014). This method might not be acceptable for agricultural locations where the top soils are prone to seasonal waterlogging due to inadequate hydraulic conductivity and the need to find a suitable outfall for drained water (Christen and Skehan 2001; Singh 2018a).

Tile Drainage

Agricultural fields with tile drainage may lose nitrate due to factors such as precipitation volume and time, initial soil moisture, season, tile depth, and tile distance (Drury et al. 2009). Figure 11 illustrates a study finding that this method enhanced

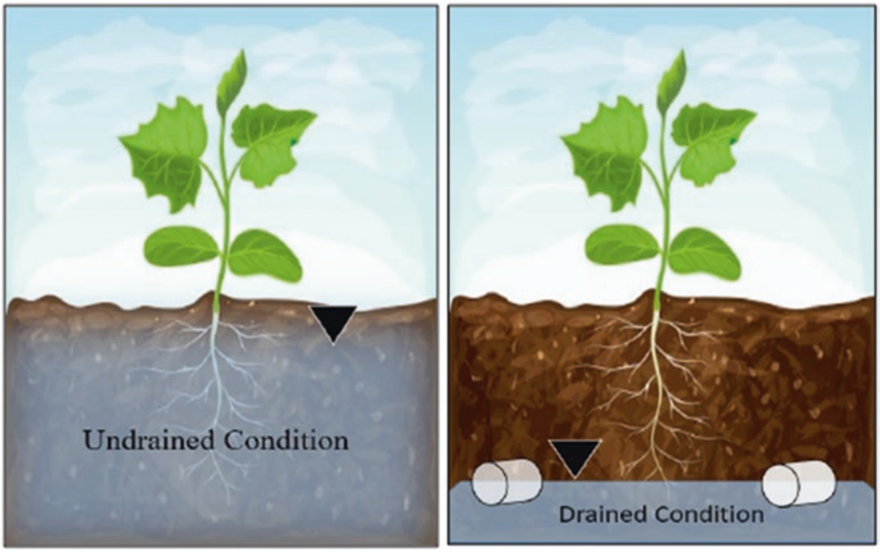

Fig. 11 Tile drainage advantages. Available at: https://pami.ca/beneficial-management-practices-for-agricultural-tile-drainage-in-manitoba/

moisture in the soil. In contrast to nondrained plots, it enabled soybean planting earlier at least 17 days and enhanced its output from 9% to 22%. Reducing nitrate that enters surface or groundwater systems, crop output can be increased using subsurface drainage systems that include controlled drainage and sub-irrigation (CDSI), increase the effectiveness with which nitrogen is used, and lessen the likelihood of adverse impacts on the quality of water (Drury et al. 2009; Frankenberger et al. 2004). Another possible strategy for addressing the water quality challenges while also offering crop production systems with flood and drought resilience is to connect subsurface tile-drainage to the irrigation reservoirs. However, this requires more analysis.

Vertical Subsurface Drainage

Sand compaction piles prefabricated vertical drains (PVDs), gravel piles, stone columns, and sand drains are a few examples of vertical subsurface drainage (Indraratna et al. 2005; Indraratna 2017). Compared to other subsurface drainage systems, the VD system has a few advantages. For instance, VDs are frequently chosen over other types of drainage because of their comparatively inexpensive cost of construction, also the surface drains shorter length that they provide (Christen and Skehan 2001). However, because operating a network of tube wells requires a lot of energy, the operating and maintenance expense compared to horizontal drainage is more (Food and Agriculture Organization [FAO] 2002; Prathapar et al. 2018). Vertical drainage is more effective for areas with a high water table.

Mole Drains

Subsurface drainage also includes mole drainage. In terms of design and functionality, mole drains are comparable to tile drainage as a semi-permanent solution (Dhakad et al. 2018; Tuohy et al. 2018). It is typically put in place to address issues with soil salinization and rising groundwater levels (Kolekar et al. 2014). Mole drainage depends on densely packed channels and subsoil fissures (Tuohy et al. 2015). The optimum applications for mole drains, which are put next to tile drains, are heavy soils with low permeability, such as clay (Monaghan et al. 2002; Monaghan and Smith 2004). We must put it, to the height of no more than 600 mm above the ground, forming a circle of drainage that is 40 to 50 mm in diameter (Gibson 2014). By dragging a metal object through the ground, such as a mole plow or a bullet with a blade-like foot, a mole drain can be created, as shown in Fig. 12. This method creates an open channel. The expense of installing mole drainage is less, but to maintain the integrity of the channel and improve system efficiency, the moles must be reformed every 2–5 years (Tuohy et al. 2018). To assist with drainage management in a flooded landscape and to successfully duplicate water balance and a drainage network system over a watershed, integrated drainage systems (tile and mole drainage) may be employed (Tuohy et al. 2018).

11 Strategies Adopted in Pakistan

In Pakistan, waterlogged soils have been repaired using reclamation, engineering, and bioremediation techniques. In addition to using subsurface drainage systems and industrial waste water conveyance lines, municipal surface drainage systems have been employed to remove extra water from agricultural areas. In fresh groundwater areas, Pakistan decided to construct tube wells in irrigated areas up to 14,000 in number that cover 2.6 Mha area, to lower the groundwater level to handle

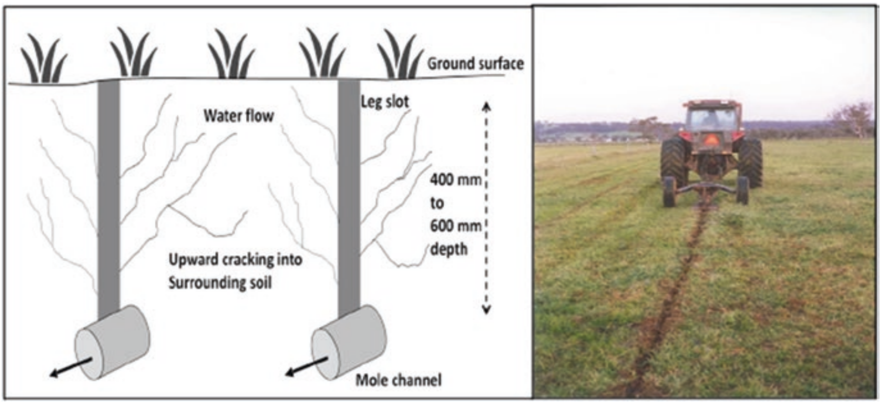

Fig. 12 Sketch of mole drainage. (Source: Don Bennett 2022). Available at: https://agriculture.vic.gov.au/livestock-and-animals/dairy/managing-wet-soils/mole-drainage-systems

waterlogging and to boost irrigation resources at the gate of the farm via blending canal and pumped ground water. The above decision was made after a thorough survey of the depth and salinity of the groundwater table in the 1950s. 63 projects costing 2 billion US$ covering an area of a total of 8 Mha were completed underneath this Salinity Control and Reclamation Projects (SCARPs) over the past 40 years (Qureshi 2011). With the help of the SCARPs initiative, the waterlogging issues were successfully managed, if not reversed, and more water was made available for irrigation. Cropping intensities increased, as a result, rising from 84 to 115% in the majority of SCARP locations. However, as time went on, rising maintenance and operational costs as well as an increase in the salinity of the groundwater being pumped diminished the effectiveness of SCARPs, causing water tables to rise and crop yield to decline. With the belief that with the passage of time drainage water quality would improve, increasing the likelihood of using drainage water for irrigation, thinking switched to horizontal (pipe) drainage systems in the middle of the 1970s. There will also be less of an issue with the disposal. In Pakistan since then, around ten significant horizontal drainage projects collectively drainage pipes of 12,600 km been constructed (Qureshi et al. 2008). In order to address this issue, Pakistan constructed a 2000 km surface drainage on the left bank of the Indus River to transport drainage water from over 500,000 acres of soil to the sea (Qureshi et al. 2008). Although the drain's initial results were highly positive, seepage quickly caused the neighboring communities to become flooded. This heightened interprovincial conflict between the Sindh and Punjab provinces led to a blockage of Punjab's drainage water's path through Sindh and ultimately into the sea. This makes Punjab's waterlogging issues worse. The advantages and disadvantages of the aforementioned adaptive management techniques for waterlogged conditions are shown in Table 3.

11.1 Bioremediation Strategies/Bio-Drainage

Scientists and engineers began considering alternate solutions that are more sustainable and cost-effective as a result of the limited effectiveness in addressing waterlogging issues despite significant investments. Using biological methods to reduce the water table is one of the possible solutions. The idea of improved evapotranspiration serves as the foundation for the utilization of bioremediation in wet environments (Ram et al. 2011). Figure 13 illustrates the fundamental idea of transpiration, absorption, and movement involved in bio-drainage. Waterlogging may be decreased by using herbaceous perennial legumes that are suited to flooding and waterlogging, like Messina (*Melilotus siculus*), lucerne (*Medicago sativa*), and Clovers (Genus: Trifolium), in cropping systems (Cocks 2001; Nichols 2018). Typically, compared to other annual crops, these deeply rooted pasture species can drain water and cause the soil to dry to greater depths (McCaskill and Kearney 2016). The suitability of different pasture species for seed production technologies, also to merge them thus providing the greatest merits have been thought of as information gaps that call for further research (Cocks 2001) because different pasture species' tolerance levels

Table 3 Merits and demerits of adaptive management practices of waterlogging condition

Crop and soil management techniques	Benefits	Drawbacks	Reference
Surface drainage	Both installations along with care are the least expensive	Less agricultural space due to open drainage; requires routine upkeep	Ritzema et al. (2008), Ayars and Evans (2015)
Raised bed system	The structure of the soil is modified	Crop acreage affects its efficacy, control of weeds in the furrows, equipment modification expense	Zhang (2005), Acuña et al. (2011), Bakker et al. (2005b, 2007)
Pipe drains	Dependable technique in extreme flooding	Expensive to install	Filipović et al. (2014), Teixeira et al. (2018)
Vertical drainage	Dependable technique for extreme waterlogging	Compared to horizontal pipe drainage systems, maintenance and operational expenses are higher	Christen and Skehan (2001), Kijne (2006), Prathapar et al. (2018)
Mole drains	Effective technique; less expensive than alternative subterranean drainage	Periodic care is required; dispersive soils will cause the integrity to be lost	Dhakad et al. (2018), Tuohy et al. (2018)
Bio-drainage	Successfully tried and tested in numerous places	Requires specialized plantation methods, thinning, pruning, and harvesting	Kapoor (2000), Lerch et al. (2017), Dash et al. (2005), Lin et al. (2011), Sarkar et al. (2018), Munoz-Carpena et al. (2018)

differ significantly from waterlogging. In order to deal with drainage congestion and environmental dangers, bio-drainage, or vertical drainage in soil water utilizing specialized forms of rapidly developing trees with a high evapotranspiration need (Kapoor 2000; Heuperman and Kapoor 2003; Sarkar et al. 2018). Trees in particular are often referred to as “biological pumps” and are crucial to the whole water cycle in a particular area. There is no need for us to:

- Stimulate soil water movement toward a pipe drain or tube well.
- Construct main and collector drains to remove water from the drainage area in bioremediation systems, which are advantageous compared to typical subsurface drainage systems.
- Run pumps to remove drained water, then transfer it to disposal facilities.
- Build disposal facilities (for example: through evaporation ponds).

Bioremediation’s durable viability has been heavily debated. As an alternative to conventional field drainage techniques, it has been suggested that bioremediation

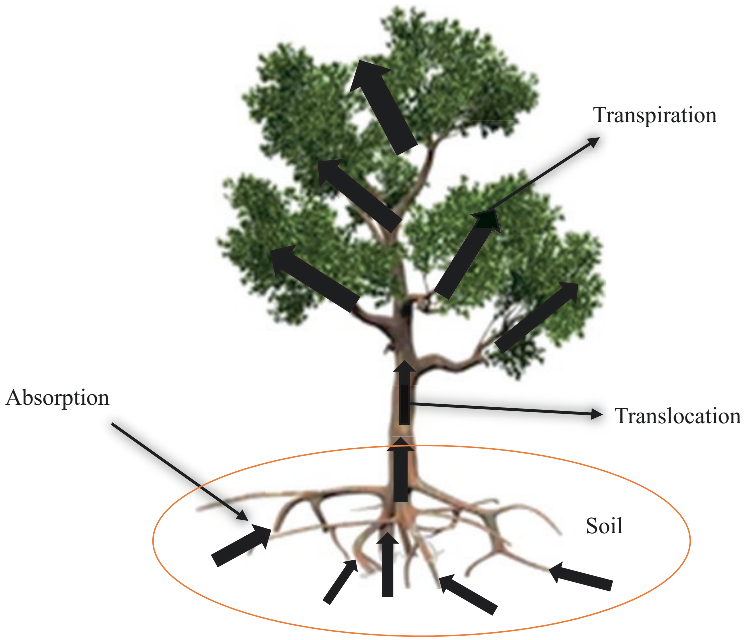

Fig. 13 Concept of biodrainage

may be employed in "parallel field drainage" designs for canal leakage interception and flooded landscape depressions (Smedema 2000). The bottom line is that this is a "pro-poor" technique that increases the revenue of struggling producers who might otherwise leave their properties fallow.

In Pakistan, waterlogged soils have been restored via bioremediation. Poplar (*Populus deltoides*), Eucalyptus, Tamarix, Gum arabic tree (*Acacia nilotica*), and mesquite (*Prosopis juliflora*), are among the trees that belong to this category. Non-woody plants, like shrubs, sedges, grasses, and herbs, can have deeply rooted systems that come into contact with groundwater like that of woody plants (Choudhry and Bhutta 2000). A recent study found that 2.5% of the 200 million irrigated agricultural trees in Punjab province are eucalyptus trees (Shah et al. 2011). The water table wouldn't be expected to be significantly affected by such a plantation until the plants occupy a sizable enough portion of the catchments so that their combined water demand equals the catchments' whole recharge. In Pakistan, the capacity of productive tree plantations to drain shallow groundwater is seen as a vital tool for controlling rising water levels.

12 Conclusion

Waterlogging of the soil significantly reduces crop yields around the world and has a negative impact on plant growth. The fluctuating precipitation patterns and temperature brought on by climate change are expected to increase crop losses owing to soil waterlogging in many regions. Waterlogging is a major problem for Pakistan's irrigated agriculture sector, depriving farmers of their productive resources and endangering their livelihoods. In general, plants can acquire some adaptive features, such as the expansion of adventitious roots or aerenchyma tissue to endure soil waterlogging stress. Commercial cultivars that are not resistant to waterlogging stress might anticipate experiencing yield losses. This article provides a summary of potential management techniques that land managers and farmers can use to increase production. However, the implementation of any management strategies will be region-specific depending on how simple it is to apply in the producers' current management plans. There are still large gaps in our knowledge of the advantages and disadvantages of appropriate management techniques for various types of soil or crop types, the governance of additional micro as well as macronutrients, and the genetic basis of plant responses to hypoxia and elemental toxicity in flooded soils. Cost-benefit analyses of these management strategies should be the main focus of future research in order to confirm their commercial feasibility and to create management plans that will encourage sustainable crop production from intermittent and variable duration waterlogged soils.

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