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Effects of combined waterlogging and salinity stress on plants: A review

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Abstract: The present scenario of the growing human population has led to the unsustainable expansion of agriculture and irrigated land, which is one of the main reasons for waterlogging and excessive salinity problems in semiarid, arid, and coastal regions. Waterlogging and salinity combination reduces the crop yields and ultimately leads to economic losses in different dimensions. The reduction of plant growth occur at a much higher rate when compared to the growth reducing ability of any individual stress. In the event of saline waterlogged stress, the functioning of intracellular K+/Na+ homeostasis gets disturbed; stomatal conductance, transpiration rate and net photosynthetic rate get decreased as well. The decreased chlorophyll content confirms the decreased photosynthetic rate in such conditions. Some plants develop adaptive features like low respiration rate, improving antioxidant capacity, increase in stele diameter, vascular number, aerenchyma and metaxylem development, increase in endodermis layer, salt ion channelization and their removal. The present review discusses in detail the changes, from phenotypic to molecular level, which the plant goes through to overcome the adverse effect of waterlogging and salinization stresses. We further suggest the integration of proper irrigation and drainage systems like management approaches to deal with the combined waterlogging and salinity problems.

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Introduction

Currently, the whole world is affected by countless and uncertain transformations in nature. On the other hand, the rapidly growing population is set to reach 9.6 billion by the end of 2050. This results in an increase in resource demand which will ultimately cause more urbanization and industrialization on the agricultural and forest lands. The progression of exclusion of natural vegetation has already picked the speed after the pre-industrial era (1750 – 1850) (Davidson 2019) but in recent decades an enormous turmoil in the natural balance has been caused (Borunda 2020). The rising global warming, greenhouse gases, global temperature, drought, flooding, salinity and increased cases of different diseases are the indicators of changing global climatic conditions. According to the Intergovernmental Panel on Climate Change (IPCC), 2001 and 2004 report, there is an evolution in the atmospheric CO_2 concentration from 280 ppm (pre-industrial period) to about 390 ppm (today's) accompanying the escalation in global earth surface temperature from 1.1 to 6.4°C range. Such alterations have bought a variety of environmental changes like increasing drought and flood levels, rising sea level, alteration in precipitation and wind pattern, etc. affecting almost every sector all over the world (IPCC 2001).

Water availability turns out to be at extremes, causing drought conditions on one and flooding on the other side (Kaur et al. 2020). The present precipitation fluctuations have especially affected the global food productions which need to be increased by 38% and 57% by 2025 and 2050, respectively to feed the ever-increasing world population (Wild 2003). On one hand, there is a prerequisite of irrigation expansion while on the contrary the expansion of irrigated agriculture has by now become the main cause of waterlogging and salinization problems in semiarid, arid and coastal regions (Singh 2015).

Waterlogging (excess of water than an optimum requirement) and salinization (presence of salt in excess than an optimum ionic requirement) have developed into the chief damaging abiotic stresses especially for plants, besides drought (Barrett-Lennard 2003; Jackson 2009; Shabala 2011). Around 17 million sq. km of the world's total land surface is influenced by waterlogging annually including 10-12% agricultural land (Shabala 2011). Similarly, salinity involves~1125 million hectares of the world's land, which is approximately 6% of the total global area including 20% of cultivated and 33% of the irrigated land (Hossain 2019). The 76.6 Mha global land are under the effect of secondary salinity (Ghassemi et al. 1995). About 1.5 million hectares of the area turns into unbefitting for agricultural production every year because of high salinity levels. The chances of 50% cultivable land become vanished will loom soon if the salinization of soils continues in such a way (Hasanuzzaman et al. 2014).

The additive outcomes of waterlogging and salinization problems laid down the foundation of lethality to plant growth and yield at much higher rates than individually (Barrett-Lennard 2003; Singh 2015). Around 30 million ha of world area is impinged on by waterlogging and salinization, furthermore, 80 million ha of land has been imposed with this condition to some level (Bakker et al. 2010). Ojo et al. (2011) estimated that globally, waterlogging and salinization together are responsible for the loss of at least 0.2 – 0.3 million ha irrigated land every year. More than three-fourths (75%) of the world's population living in semiarid and arid regions face food and other resource difficulties due to intensifying waterlogging and salinization problems (Singh 2015). Many countries are under the influence of this twin situation (Table 1), and some will approach shortly. According to Ahmad and Singh (1991) and Khan (2003), the increasing problem of the water table and salinization together have influenced the canal irrigation areas in countries like India, Pakistan, Argentina, Mexico, Mali, North Africa, western U.S.A., Afghanistan, Egypt, Iran, Sudan, Syria, and the USSR. In India, the canal command area of Indus River, Indira Gandhi canal and Indo-Gangetic plan along with several states such as Bihar, Maharashtra, Gujarat, Uttar Pradesh, Orissa, West Bengal, Punjab, Tamil Nadu, Andhra Pradesh, Haryana, Kerala, Rajasthan. Few other states are the several hot spots of waterlogging and salinity twin problem (Patra and Banik 2018). It is said that the left bank of the Indus River lakes will turn into waterlogging and salinity areas rapidly in the next 10 to 15 years. The reason behind this is the cultivation of the same crops like rice and sugarcane continuously for the last few decades, exploiting groundwater table to a dangerous level, thus, turning fertile land into barren land. Further, due to the non-cemented canal area, the irrigation water seeps through the ground which ultimately results in waterlogging. This stagnant water gradually converts the area into saline spot, destroying nearby arable lands (Saeed 2015).

Excessive water utilization in crops, the non-cemented canals along with poor drainage systems are accountable for rising waterlogging and salinity problems together (Saeed 2015). The higher irrigation levels than consumption in semiarid and arid zones, around canal command areas and seawater intrusion in coastal regions bring a higher level of salt with them. In addition, the evapotranspiration process leaves behind salts concentrated in a smaller volume of water. Thus, prevent leaching of the salts or infiltration of the salts imported by the irrigation water and salt remain persist in the soil along with water. Figure 1 shows the combined waterlogging and salinization causes, mechanism and further effects on plants and economy. In irrigated land salts are also received by weathering of parent material (Michael 2009). Waterlogging is often accompanied by soil salinity in many irrigated agricultural land. The saline soils, in fact, attract more water by the osmosis process from plants and as a result, the plant suffers from physiological drought conditions. The presence of excess salt ions also generates ionic toxicity inside plants. The addition of hypoxia condition of soil due to waterlogging state affects plant growth and yield at a very higher rate than affected by any of them individually. Worldwide, the vast crop yield and productivity thrashing under irrigated agriculture have been illustrated in Table 2. This reduction in crop yields is accountable for growing economic losses (Rhoades 1990; Abdel-Dayem 1997). The presence of salinity in water declines its quality makes plant unable to absorb water to its full extent due to the osmosis process and this restricts the urban or agricultural re-use of drainage water. The crisis had questioned the most significant long-term water quality concern for managing irrigated agriculture in arid and coastal areas (ICID 2016).

Although, the effects of individual waterlogging and salinity stress on several plants species are very well documented, the combined effects of both the stresses are still not fully understood (Haddadi et al. 2016). The present review reflects the overall changes from phenotypic to molecular level face by plants as an effect of combined waterlogging and salinization stresses along with the adaptive features to deal with the problem. The study also includes various management practices against combined waterlogging and salinization problems going in different parts of the world.

Occurrence of phenotypic modifications

Plant growth and its survival rate are greatly challenged under combined waterlogging and salinity conditions (El-Nashar 2013). Besides the toxic effects of ions and osmotic irregularities under saline conditions the plants also suffer from hypoxia beneath the waterlogging condition (Figure 2). This adds to the reduction of plant growth at much higher rates than in the case of any individual stresses (Lu et al. 2003; Barrett-Lennard and Shabala 2013). Saqib et al. (2005), Smethurst et al. (2005) and Sheng et al. (2008) also reached to similar conclusions regarding crop yield. Waterlogging, on one hand, may damage plants even at low levels of salt while on the other hand salinity state is more easily perceptible in waterlogged plants especially at early growth stages (El-Nashar 2013).

The growth of *Mentha aquatica* plant significantly declined under combination stresses. As the salinity increases from 50 to 150 mM NaCl (50, 100 and 150 mM NaCl) in the presence of waterlogging conditions for 30 days, the fresh and dry weight of leaf and root dropped drastically when compared to control. Both the stresses together also affected the stele diameter and endodermis layer by causing the reduction in them under waterlogging and 100 mM NaCl salinity. The observation in root cross-section depicted that the presence of salinity causes suberization of the endodermis and hypodermis in roots, together with the development of Casparian strips near to root apex. In contrast, no such alterations were observed in non-salinity roots. These changes result in a decrease in xylem size which might be a reason for the restriction of ions movement through the vasculature to xylem elements. Thus, further making an addition in growth reduction (Kozlowski 1997; Haddadi et al. 2016). Xie et al. (2020) also found the lowest shoot and root biomass in native *Phragmites australis* and exotic *Spartina alterniflora* plants under the combined treatments of waterlogging and 30 ppt salinity. However, *S. alterniflora* showed more tolerance to prolonged tidal waterlogging and increased salinity than the native *P. australis* (Bradley & Morris 1991; Ge et al. 2014; Li et al. 2018). The effects of combined waterlogging and salinity problems, no doubt differ from species to species.

Forest tree species faces harsh impacts as well under the combination of waterlogging and salinity stress. Moezel et al. (1988) reported a reduction in height of *Eucalyptus camaldulensis* and *Eucalyptus lesouefill* by 25% and almost 0, respectively under seven-week of waterlogging and Na/Mg/Ca ratio (10:2:1) salinity as compared to control. After 11 weeks, 25% of *E. camaldulensis* seedlings and 69% of *E. lesouefii* seedlings died while all control and non-saline waterlogged seedlings survived. The observations on total biomass and leaf area of *Pongamia pinnata* showed reduction at a very higher rate when compared to waterlogged conditions alone and control. Although, individual saline conditions acted very harshly as biomass was a little lesser than combined results along with the occurrence of complete leaf senescence. This indicated the species sensitivity more towards salinity than waterlogging which supported its growth under a combined situation (Sachan et al. 2020).

Waterlogging and salinity (200 mM NaCl) when applied together on two barley (*Hordeum vulgare* L.) varieties *viz;* Naso Nijo and CM72, showed a significant reduction in average shoot fresh-dry weight by 81 and 76% whereas the corresponding reduced average root values were 85 and 77% respectively as compared with the control under sandy loam soil. On the contrary, vermiculite soil showed less reduction than observed under sandy loam soil, *viz*: average shoot fresh-dry weight reduced by 71 & 32% and root by 78 & 73% respectively. This assures the fact that more the soil pore space lesser is the space to gather up water molecules. The inversely proportional relationship makes obvious the presence of compact pore space in sandy loam soil than vermiculite one. Thus, the study also tried to make us understand the importance of soil type (regarding pore space) in relation to water retention and salt ions accumulation capacity which directly impact the plant water-ion status and then growth ability. The above study also revealed that the twin problem effects differ from variety to variety of same species as Naso Nijo (12% survival) observed to be more sensitive than CM72 (25% survival) after 14 days of waterlogging with the same level of salinity (Zeng et al. 2013).

The experiment conducted on combined waterlogging and salt stress in wheat consequences in a significant reduction in yield, grain weight, and spike length (Singh 2015c) including the number of spikelets (Saqib et al. 2004). In fact, the reduction caused was more than the reduction occur under individual stresses. In the previous studies conducted on wheat under saline (30 mol m^{-3} NaCl) hypoxia conditions, Barrett-Lennard et al. (1999a) also concluded that after 5 weeks of combined treatment shoot weight and yield ceased to grow. About 10-40 and 50% yield reduction was observed under combined stresses in rice, wheat, cotton (Singh and Singh 1995) and sugarcane (Chandio and Mirbahar 1991) crops, respectively.

Physiological changes are the cause of phenotypic modifications

The plants suffer through enormous physiological changes as a result of two stresses acting on them together, thus, battling for survivability. Waterlogging diminishes the root respiration ability due to soil anaerobic conditions, which induces root oxygen deficiency and low soil water potential (Figure 3). Oxygen is a key factor for energy production inside any living cell (Singh 2017). This declines the production of ATP by 2-3 fold (from 30 to 36 mol ATP via mitochondrial oxidative phosphorylation to 2–4 mol ATP via glycolysis per hexose, Bailey- Serres and Voesenek 2008) disturbing membrane selectivity and further can become a reason for the root death under prolonged waterlogging duration (Zeng et al. 2013; Singh 2017; Xie et al. 2020). The nutrients uptake from soil gets majorly affected as the procedure requires energy. Furthermore, the company of substantial salt ions in the soil initially increases the salt ions (electrolytes) uptake and ionic concentration in the roots. Thus, supporting waterlogging action in limiting the nutrients uptake. Later on, there is an increase in ionic concentration in shoots which results in ionic toxicity. Moreover, the high salt ionic concentration and low water potential in the soil increases the osmotic potential, creating water deficiency inside the plants (Xie et al. 2020).

Marcar et al. (2002) concluded that under waterlogging and saline environment the hypoxia condition around the root zone leads to increase sodium and chloride ion concentrations in the shoot. According to John et al. (1977) observations recorded on 14 days waterlogged barley and rice plant under saline conditions at 70 & 125 mol m^{-3} and 40 & 80 mol m^{-3} NaCl respectively, illustrates higher concentrations of Na^+ and Cl^- ion in the root-shoot. Both the crops showed an increasing trend of ionic concentration with the rising salt concentration as compared to plants grown at similar salinity levels under normal drained conditions. Similarly, *Eucalyptus camaldulensis* salinized with NaCl, $MgSO_4$ and $CaCl_2$ in 10:2:1 ratio (EC 42 dS m^{-1}) and waterlogged for seventy-seven days showed 850 and 590% increment in Na^+ and Cl^- ionic concentration in the top half of the shoot. The higher ionic concentration in shoots, leaves or other vegetative parts, was also observed in plant species *viz*: *Hordeum vulgare, Lycopersicon esculentum, Nicotiana tobaccum, Phaseolus vulgaris, Triticum aestivum, Acacia ampliceps, Acacia eremaea, Acacia ixiophylla, Casuarina glauca, Casuarina obes, Eucalyptus globulus*, *Eucalyptus robusta*, *Eucalyptus tereticornis* and *Vitis vinifera* under various salinity and waterlogging levels (Barrett-Lennard 2003).

The combined waterlogging and salinity conditions, no doubt, are the reason for a higher uptake of electrolytes and low water potentials exposure, which builds impairment in the root system and enhances the damaging effects more at higher salinities (Barrett-Lennard 2003). Dropping off the air-filled porosities of soil below 8% is the point from where plant damage starts taking place (Wesseling 1974). Intracellular K^+/Na^+ homeostasis, a key determinant of plant salinity tolerance play a very important role in regulating Na^+ and Cl^-. The plasma membrane SOS1Na^+/H^+ antiporters normally expel Na^+ from the cytosol and this depolarization activates outward rectifying channels, responsible for K^+ retention in the cytosol. The oxygen availability is critically necessitated for operation of both of these transporters. The oxygen reduction compromises the plant's ability to fuel H^+-ATPases, affecting both Na^+ exclusion and K^+ retention. On the contrary, there is mass flow travelling of excessive Na^+ and Cl^- ions to the xylem which accumulates in the shoot tissues with the greatest rate as an effect of twin stresses, compared to individual one (Zeng et al. 2013). The raised electrolyte concentrations than an optimum requirement in the shoot and failure of ionic exclusion transporters tend risky for plant growth and survival (Hatton et al. 2003; Smedema and Shiati 2002).

Stomatal conductance, transpiration rate and net photosynthetic rate were also found decreased in saline waterlogged seedlings after 3 weeks of the experiment than control, waterlogged and salinity alone in *Eucalyptus camaldulensis* and *E. lesouefii* (Moezel et al. 1988). A significant decline in relative water content (RWC) was observed in *Mentha aquatica* L. with the increase of salinity level (50, 100, 150 mM NaCl) under waterlogging conditions (Haddadi et al. 2016). Reduce photosynthetic rate and stomatal conductance results observed in *Pongamia pinnata* under combined stresses when compared to control and waterlogging alone (Sachan et al. 2020). The reduction in stomatal density and gas exchange attribute takes place due to stomatal closure under combined stresses which inhibits the photosynthetic process further (Tounekti et al. 2018). Similar results reported in *Populus euphratica* under a high concentration of flooding and salinity (Azizi et al. 2017). The increased concentrations of sodium and chloride ions in the xylem under waterlogging may cause stomatal closure under both saline (Huang et al. 1995; Moezel et al. 1989) and non-saline conditions. The unfavourable Na^+/K^+ ratios make ionic accumulation in the shoot and other vegetative parts of the plant which channelize from roots through the xylem, consequent to a significant increase in leaf sap osmolality and decrease in photochemical efficiency of PSII. There is the development of physiological deficiency of water in plants as an outcome of low osmotic potential in plants accompanying the low water potential in soil. Therefore, this unnatural water deficiency is also one of the reasons behind the net decrease in transpiration and photosynthetic rate along with disturbed ionic homeostasis. The plant growth is associated with the proper balance among water, ionic and nutrient channelization with the support of suitable transporters. Thus, any interference with this natural balance influences the growth and yield of plants in turn.

The combined waterlogging and salinity (200 mM NaCl) treatment effect on two barley varieties (CM72 and Naso Nijo) showed a severe reduction in the photochemical efficiency of PSII (Fv/Fm) by 25-55% and leaf water content by 2.5-11%, as compared to waterlogging and salinity individual treatment respectively (Zeng et al. 2013). Further observations suggest that the plant physiology was also strongly influenced by the growth conditions (sandy-loam vs. vermiculite) in both the varieties (CM72 and Naso Nijo). A much stronger decline of PSII (Fv/Fm) was observed in sandy-loam grown plants (approx. 0.4-0.7 abs. units reduction) as the compact pore space remain to occupy the water molecules. Leaf osmolality observed higher under combined stress with a 2-fold difference in both the varieties. Both varieties on average showed Na^+ content in leaf sap increased about 1.7–2-fold while K^+ content showed decreased by 27-44% under combine stresses when compared to salinity alone. However, the ionic changes didn't show any significant difference in roots. The disturbed leaf physiology made 20% CM72 and 28.5% Naso Nijo affected by leaf chlorosis whereas 25% CM72 and 45% Naso Nijo by necrosis disease respectively. Thus, maintained the higher rate under combined stress in both varieties. The less water availability and higher ionic concentration in the leaf causes a decline in stomatal conductance and transpiration rate which boosts the leaf senescence, chlorosis and necrotic diseases (Zeng et al. 2013). Furthermore, supporting the cause of reduction in plant growth efficiency and productivity.

Status of biochemical changes

The occurrence of any phenotypic variation in the plants is the result of physiological and biochemical alterations which occur as per the surrounding environment. The biochemical constituents inside plants experience a number of modifications under waterlogging and salinity mixed effect (Figure 2). Zeng et al. (2013) recorded a massive decline in total chlorophyll content by 37.5% in CM72 and 70% in Naso Nijo variety of barley respectively under combined stresses as compared to salinity alone under which both the varieties were found hardly inclined to any change. The chlorophyll content is associated with the photosynthetic rate. Gratani et al. (1998) also observed a positive correlation between chlorophyll content and photosynthetic rate in *Quercus ilex* L, where both of them followed decreasing trend under combined effects. The salinity and waterlogging combination also reduced the total chlorophyll content in Euhalophyte *Suaeda glauca* (Duan et al. 2018), *Salvadora persica* (Tounekti et al. 2018) and 12 varieties of *Hordeum vulgare* (Falakboland 2016; Falakboland et al. 2017). Similarly, the total chlorophyll and protein content analysis in *Pongamia pinnata* leaves showed a significant decrease under combined stresses as compared to control and waterlogging treatment alone. On the contrary, the twin conditions induced the proline content tremendously high (Sachan et al. 2020).

The increase of salinity (50, 100 and 150 mM NaCl) under waterlogged conditions induces a significant increase in leaf proline, leaf-root hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) contents of *Mentha aquatica*. The excess production of proline and MDA is always associated with the highly active defence mechanism (Haddadi et al. 2016). The production of the number of enzymatic and non-enzymatic antioxidant species activated against the elevated reactive oxygen species (ROS) as a protective system response under any type of environmental stresses (Dat et al. 2000; Matysik et al. 2002). However, the rise of proline, H_2O_2 and MDA contents in waterlogging plants were lower than the well-drained ones at the same salinity level which implies that waterlogging supports salt stress alleviation (Haddadi et al., 2016). The higher proline and lipid peroxidation content under combined waterlogging and salinity is also supported by Carter et al. (2005) in *Melaleuca cuticularis* and *Casuarina obese* and by Tounekti et al. (2018) in *Salvadora persica* species respectively. Gill et al. (2019) identified identical qualitative trait loci (QTL) for both superoxide anion ($O2^{\cdot -}$ - QSO.TxNn.2H) and hydrogen peroxide (H_2O_2 - QHP.TxNn.2H) contents on chromosome 2H of barley (TX9425 x Naso Nijo). Also, the QTL location was found at the same position as the QTL for overall waterlogging and salt tolerance, with 23% and 24% of the phenotypic variation for $O2^{\cdot -}$ and H_2O_2 contents, respectively. The study gives information about the fundamental association between ROS production and both waterlogging and salt stress tolerance.

According to Haddadi et al. (2016) studies on *Mentha aquatica* showed that under severe salt stress and waterlogging conditions leaf protein content increases by 24.2 % as compared to well-drained. The combined effect of waterlogging and salinity (100 and 150 mM NaCl) caused strong induction of enzymes like peroxidase (POD), polyphenol oxidase (PPO), ascorbate peroxidase (APX), catalase (CAT), DPPH and superoxide dismutase (SOD) activities significantly. The mixed effect of waterlogging and salinity strongly induced total protein content and enzymatic activities, especially in severe salinity conditions. Also, the supportive attribute of waterlogging condition is perhaps associated with the increasing proteins and enzymes synthesis, involved in the several physiological changes and generation of anaerobic proteins (stress response proteins) (Gibbs and Greenway 2003). For instance, 20 anaerobic protein set was detected under low oxygen treatment by two-dimensional electrophoresis, out of which many of the proteins belonged to the glycolytic and fermentation pathways (Haddadi et al. 2016). Salinity and hypoxia together encourage the excessive production of ROS and antioxidative mechanisms (Blokhina et al. 2003). Higher activities of ROS scavenging enzymes under waterlogging could effectively alleviate the oxidative damage under salinity conditions. Elevation of antioxidant enzyme activity under waterlogging can decrease the negative effect of salt stress in *Mentha aquatica*. Even, the high membrane stability under combined stresses is due to the support of waterlogging condition.

Luo et al. (2008) observations on protein contents in the Bt cotton leaves under 7 to 21 days after combined salinity and waterlogging stress recorded the significant decrease in total protein content by 40–46% and 45-65% while in Bt protein content by 38-50% and 45-72% for SCRC17 and 33B cultivars respectively, when compared with their controls. The results indicated that a combination of salinity and waterlogging was more potent in reducing total soluble and Bt protein content than salinity or waterlogging alone. Such reduction might be due to the inhibited N uptake or protein synthesis, down regulation, switch off of certain proteins, enhanced protein decomposition and damage in cellular components under either or combination of the stress (Gouia et al. 1994; Zhu 2016). This resulted in a significant decline in the bollworm control efficacy (Luo et al. 2008). The protein profiling performed on *Pongamia pinnata* fresh leaves after one year of the experiment showed two new protein bands (47.26 and 32.84 kDa) along with control ones under salt and waterlogging combined (8 dS/m + severe waterlogging) treatment. These new proteins are found related to photosynthesis (46.30 kDa), carbohydrate (47.20 kDa) and lipid (32.10 kDa) related proteins. The appearance of new protein bands under twin treatment contrast to individual stresses indicates the synthesis of new proteins might have taken place as a defensive response (Sachan et al. 2020).

The soil organic carbon, total nitrogen, carbon/nitrogen ratio, available nitrogen, available phosphorous, extracellular enzyme activity and microbial biomass were observed lowest under the combined treatments of waterlogging and high salinity (15 and 30 ppt) in *Phragmites. australis* and *Spartina alterniflora*. However, relative to *P. australis*, the microbial biomass and extracellular enzyme activities in the *S. alterniflora* soil decreased to a lesser degree (Xie et al. 2020). Probably, the C4-type of photosynthesis and specialized salt-secretion glands of *S. alterniflora* can keep up the ionic balance in plants and contribute to tolerance against salt and inundation stresses to some extent compared with *P. australis* (C3 plant) (Bradley & Morris 1991; Li et al. 2018).

Possible adaptations against combined waterlogging and salinity conditions

According to Barrett-Lennard (2003), some adaptive features developed by plants under combined waterlogging and salinity conditions are grouped into three categories (Figure 2):

1. **Aerenchyma development** in adventitious roots takes place in the tissues in response to tolerate hypoxia conditions. This provides support in maintaining the regulation of ion uptake and transport through the formation of an endodermis.
2. Occurrence of **stomatal conductance** reduction.
3. **Salt removal strategies** are adapted by certain plants. Higher plants utilize three mechanisms to avoid salts accumulation in the mesophyll cells of the leaves: (a) salt absorption sites in the xylem stream, (b) bladder cells and succulence, and (c) salt secreting glands.

Haddadi et al. (2016) observed adaptive features like low respiration rate, improving antioxidant capacity, increase in stele diameter, vascular number, aerenchyma and metaxylem development and increase in endodermis layer in *Mentha aquatica* plant in the presence of waterlogging together with salinity condition. The studies further showed higher aerenchyma development, increased under combined waterlogging and salinity as compared to waterlogging conditions alone. The adaptive features developed due to waterlogging stress helps in the alleviation of the excess salinity. Perhaps, cortex degeneration and cell death are the supportive reasons for rising aerenchyma. The ethylene hormone and nitric oxide (NO) production as a waterlogging effect also lead to the death and disintegration of cells in the root cortex. Song et al. (2011) observed the adventitious root growth in *Suaeda salsa* under waterlogging and salinity twin problem. The increase in fermentation enzyme activity, net transport of Na^+ to the shoots and antioxidant activity increased in *Suaeda maritime* under the same condition (Wetson and flowers, 2010; Alhdad et al., 2013). The enhanced aerenchyma in the adventitious roots of *Melaleuca cuticularis* contributed to higher tolerance of combined salinity and waterlogging (Carter et al. 2005).

Rising RWC was observed in *M. aquatic* leaves under waterlogged condition as compared to well drained and moderately drained plants in all salinity levels. The metaxylem development, an increase of stele diameter and vascular number maintained the better water flow and higher RWC in *M. aquatica*. Also, the voids created due to the degenerated cells facilitate the movement of oxygen. (Haddadi et al. 2016). Sarvade et al. (2017) noticed the evergreen broad leaved tree species with extensive vertical and horizontal root spreading considered the most important character for capturing and transpiration of excess water from the waterlogged area and have the potential in reclamation of waterlogged saline soils efficiently and sustainably by improving soil health quality. The grapevine plants with a closed canopy, where upper foliage can shade and reduce the transpiration of the lower foliage, Na^+ and Cl^- may accumulate to higher concentrations in the upper and middle than in the lower-canopy (West and Taylor 1984). The stomatal closure prevents sudden major increase in the concentrations of Na^+ and Cl^- in the xylem due to waterlogging under saline environment (Barrett-Lennard 2003). Under saline-waterlogged conditions, the regulation of foliar sodium (Na^+), chloride (Cl^-) and potassium (K^+) concentrations were maintained in *M. cuticularis* (Carter et al. 2005).

Absorption of Na^+ and/or Cl^- occur as a protective mechanism by glycophytes from the xylem stream into the cells of stems, petioles or leaf sheaths. The halophyte *Atriplex amnicola* when grown at 400 mol m^{-3} NaCl and under 7 days of hypoxia, increased the Na^+ and Cl^- ion concentrations in the leaves by only 10% while under 14 days of hypoxia Na^+ and Cl^- concentrations increased by 60 and 110%, respectively. However, the plant considers two mechanisms for sequestering salt away from the sites of metabolism, specialised trichomes (bladder cells) on the leaf surface and an ability to sequester salt into vacuoles. Certain species like *Diplachne fusca*, *Distichlis spicata*, *Avicennia marina*, *Aegiceras corniculatum* and *Aegialitis annulata* secretes salt at the leaf surface through secretary glands (Barrett-Lennard 2003). There were few genotypes like *Casuarina obesa*, *C. glauca*, *Eucalyptus striaticalyx*, *Melaleuca halmaturorum* and *Acacia lineolata* where adverse interactions of salinity and waterlogging on survival did not occur (Patra and Banik 2018). Some plant species with tolerant attributes against combined waterlogging and salinization are represented in table 3.

Some management approaches

Many countries of the Near-Eastern region have already initiated to undertake the appropriate soil and water management strategies for the utilization of vast areas of desert soil (Elgabaly, 1977). The declination in waterlogging conditions helps in the management of salinity too (Agriculture and Food, 2021). The saline water can be managed by utilizing for surface irrigation in the fields using sprinklers and drip irrigation like techniques. The use of other irrigation techniques like pitcher irrigation one found successful for crop productivity at CSSRI, Karnal which applied the same saline water. Using this technique, the crops were found normal to grow without any hindrances (Gupta et al., 1992). The irrigation through saline water for plantations can also be achieved by proper irrigation scheduling (Marcar, 2016). Drip irrigation is the most efficient method of using saline waters in widely-spaced fruit trees (Zeinadini et al., 2009; Kamiab et al., 2012). According to Mass (1986) date palm (*Phoenix dactilifera*) appeared as tolerant while fig (*Ficuscarica*), jujube (*Ziziphus mauritiana*), olive (*Olea europaea*), papaya (*Carica papaya*), pineapple (*Ananas comosus*), and pomegranate (*Punica granatum*) appeared as moderately tolerant when cultivated under saline water using drip irrigation technique.

The improvement in drainage systems has been suggested as a remedial measure for the amelioration of the combined problems of waterlogging and soil salinity (Report Working Group, 1991). Under Salinity Control and Reclamation Projects (SCARPs) - a vertical drainage project to control the rising combination problem in the Indus basin of Pakistan, installed 14,000 tubewells (covering about 2.6 million ha of irrigated land) with an average capacity of 80 l s^{-1} in fresh groundwater areas (Badruddin et al., 1999). The efforts lowered down the groundwater level below 1.5 – 3 m in 2 – 4 million ha area and also minimized the salt-affected area from 7 to 4.5 million ha resulting in 80 to 120% increment in crop intensities and productivity too (IWASRI, 1998). Furthermore, Left Bank Outfall Drain (LBOD) project launched in the same region, also showed remarkable results in lowering groundwater tables, increasing cropping intensities and crop yields (Qureshi et al., 2008). In the Ukai-Kakrapar command area, drainage management obtained yield improvement to varying degrees (Gupta and Khandelwal, 1996). The RAJAD project of the Chambal command area, Rajasthan, presented an improved leaching pattern substantially by drainage organization, that is, made 20-22% of surface salts leached out (Tyagi et al. 1996).

Apart from the surface and sub-surface drainage engineered system the drainage through natural means came out to be a successful approach. The drainage arrangement by tree plantations called bio drainage has been advocated as an alternative for water fluxes management, their successful recharge and for dryland salinity control (Marcar 2009). The bio darainage concept has been emerged out to be very effective to tackle the problem economically and eco-friendly. Several tree species which may tolerate high salinity and waterlogging state and can be used for rehabilitation purposes in such areas are *Tamarix articulata*, *Prosopisjulifl ora*, *Acacia nilotica*, *Salvadora oleoides* and *Eucalyptus sp.* Certain shrubs also support this feature like Saji (*Haloxylon recurvum*) and Lana (*Haloxylon salicornicum*) (Roy et al., 2016).

However, the particular methodology to combat and mitigate the problem cannot make the successful urge. The integration approaches towards proper irrigation and drainage systems necessitate it being considered (Figure 3). Also, institutional interferences are required for the development of superior irrigation and drainage systems by eliminating any constraints at the farm, system, provincial and basin levels.

Conclusion

Waterlogging and salinity problems are escalating rapidly and are strongly impacted by changing climatic conditions. The unmanaged irrigation systems, drainage systems, imbalance of water level and other related anthropogenic activities are the fundamental sources of this problem. The combined effect is more detrimental to plant growth, yield and productivity. Proper water and irrigation management strategies are required to deal with these rising combined situations, especially in the coastal, arid and semi-arid lands. Moreover, plants with the ability to combat both salinity and waterlogging effects are of prime importance as they help in sustainable agricultural practices. Therefore, we believe that there should be an increase in programmes and projects associated with the crop screening for tolerance, optimum yield and nutritive factors under the combined effects of salinity and waterlogging. Extensive studies related to biochemical, physiological and molecular markers are required which could potentially be used in future breeding programs to improve waterlogging and salinity tolerance. Along with traditional methods to assess, monitor, and quantify water and salinity problems; employing soil surveys, questionnaires, and laboratory analyses, modern techniques such as aerial photography, GIS and remote sensing (RS) are being used these days to overcome most of the fore mentioned limitations and to find out the calibration between the laboratory data and real field situations.

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Table 1: Area affected by combined waterlogging and salinization in different countries.

Country	Affected Area (mha)	Area Considered	Sources
South Africa	0.054	total cultivated land	Ojo et al., 2011
Pakistan	4.5	total irrigated land	Qureshi, 2016
India	13	total country	Datta and Joshi, 1992
Iraq	More than 50%*	Lower Rafadain Plain	Elgabaly, 2014
Syria	50%*	total irrigated land of Euphrates valley	Elgabaly, 2014
Egypt	0.8	total country	Elgabaly, 2014
Iran	24.72	total country	Elgabaly, 2014
World	30	total country	Bakker et al., 2010

* , value is in percentage instead of common unit mha

Table 2: Some crop species production affected under combined waterlogging and salinization problem.

Crop species	Yield reduction (%)	Sources
Gossypium spp. (Cotton)	60	Kahlown and Azam, 2002
Cicer arietinum (Chickpea)	50	Roy et al., 2016
Triticum aestivum (Wheat)	20-50	Hossain and Uddin, 2011
Saccharum officinarum (Sugarcane)	33	Kahlown and Azam, 2002
Oryza sativa (Rice)	10-40	Singh, 2017

Table 3: List of plant species tolerant to combined waterlogging and salinization.

Plant species	Adaptive Feature	Sources
Mentha aquatica (Water Mint)	Formation of aerenchyma, endodermis layer, increased RWC and non-enzymatic protective compounds	Haddadi et al., 2016
Helianthus annuus (Sunflower)	Formation of aerenchyma and endodermis layer	Kriedemann and Sands, 1984
Atriplex amnicola (River Saltbush)	Reduce stomatal conductance	Galloway and Davidson, 1993
Diplachne fusca (Salt Meadow Grass)	Salt removal through secretary gland	Qureshi et al., 1982
Distichlis spicata (Saltgrass)	Salt removal through secretary gland	Yensen et al., 1988
Avicennia marina (Grey mangrove)	Salt removal through secretary gland	Ball, 1988; Ball and Farquhar, 1984
Aegiceras corniculatum (Black Mangrove)	Salt removal through secretary gland	Ball, 1988; Ball and Farquhar, 1984
Zea mays cultivars LG11 Pioneer 3906	Salt avoidance Salt absorption in shoots	Drew and Dikumwin, 1985 Drew and Läuchli, 1985
Eucalyptus tereticornis (Forest Red Gum)	Water removal through large leaf surface area	Patra and Banik, 2018

Causes of Waterlogging and Salinization Twin Problem

Primary/Natural causes

- Weathering of parent rock material
- Salts accumulation through surface runoff from salt range mountains
- Heavy rainfall and runoff accumulation
- Poor land drainage conditions
- Shallow water table/deep percolation
- Physically poor soil/Clayey soil
- Dry climate/Evapotranspiration
- Unleveled land

Secondary/Anthropogenic causes

- Faulty irrigation water management practices whether over or under irrigation
- Improper drainage architect/disturbances of natural drainage system
- Unlined irrigation systems
- Poor knowledge of farmers in treating their lands
- Uncontrolled seepage of water
- Intensive agriculture of same type of crop

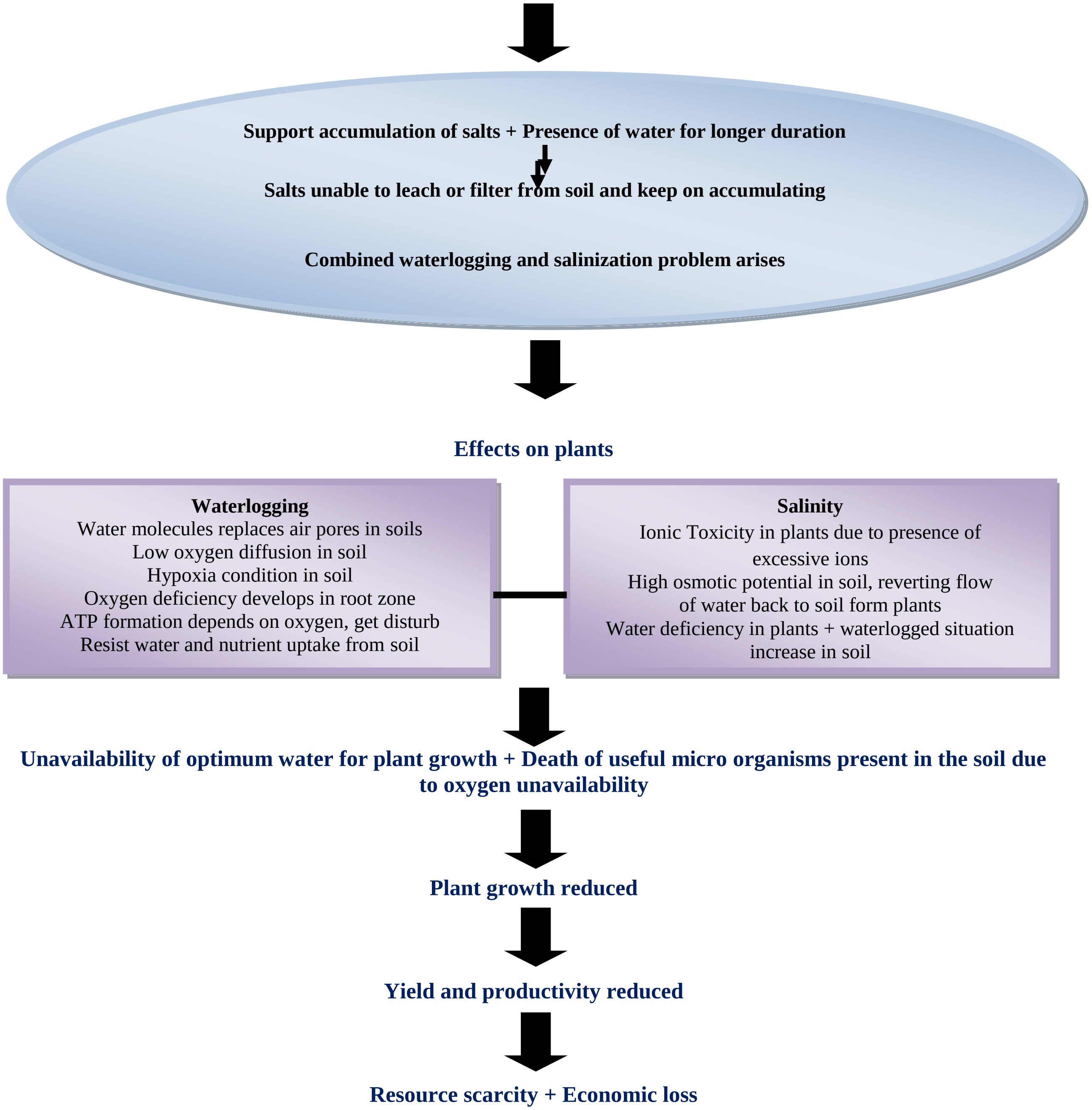
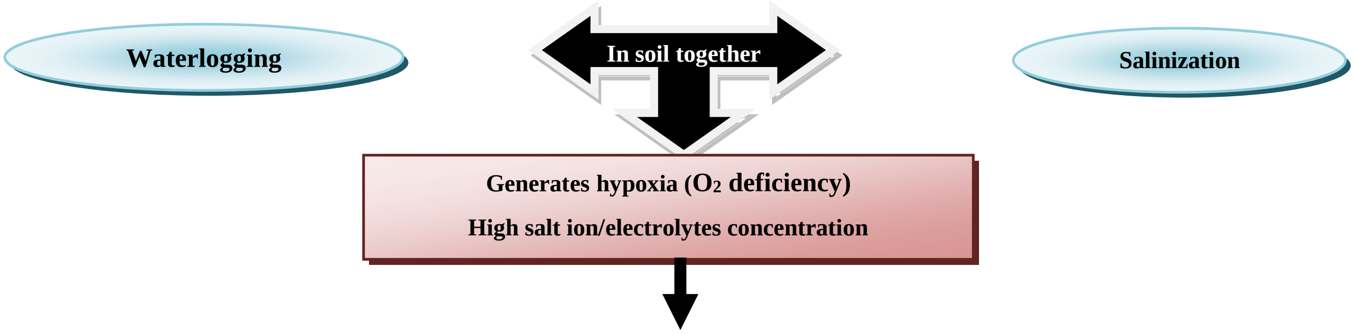


Fig. 1: Combined waterlogging and salinization problem – causes, mechanism, and effect on plants & economy.



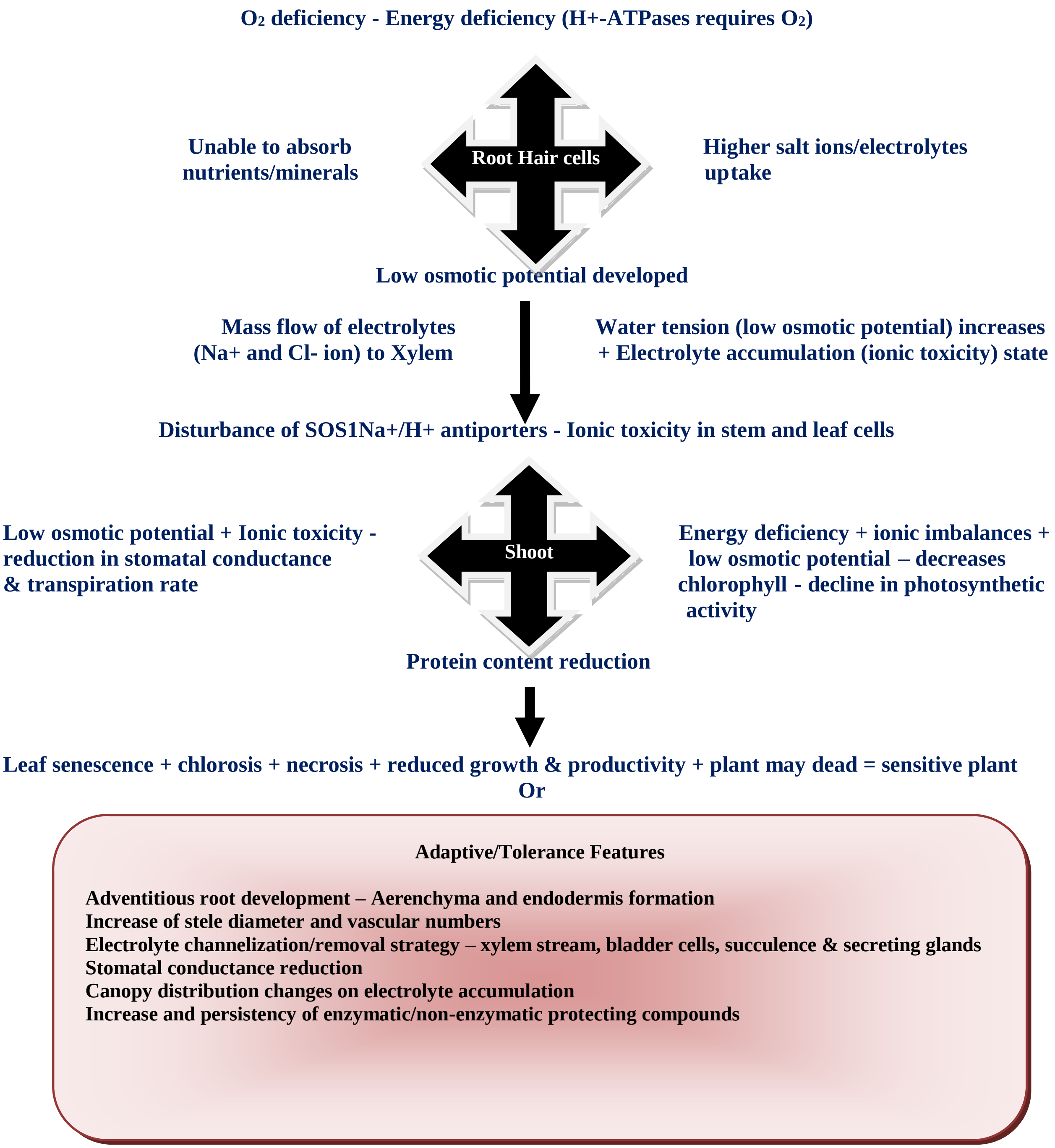
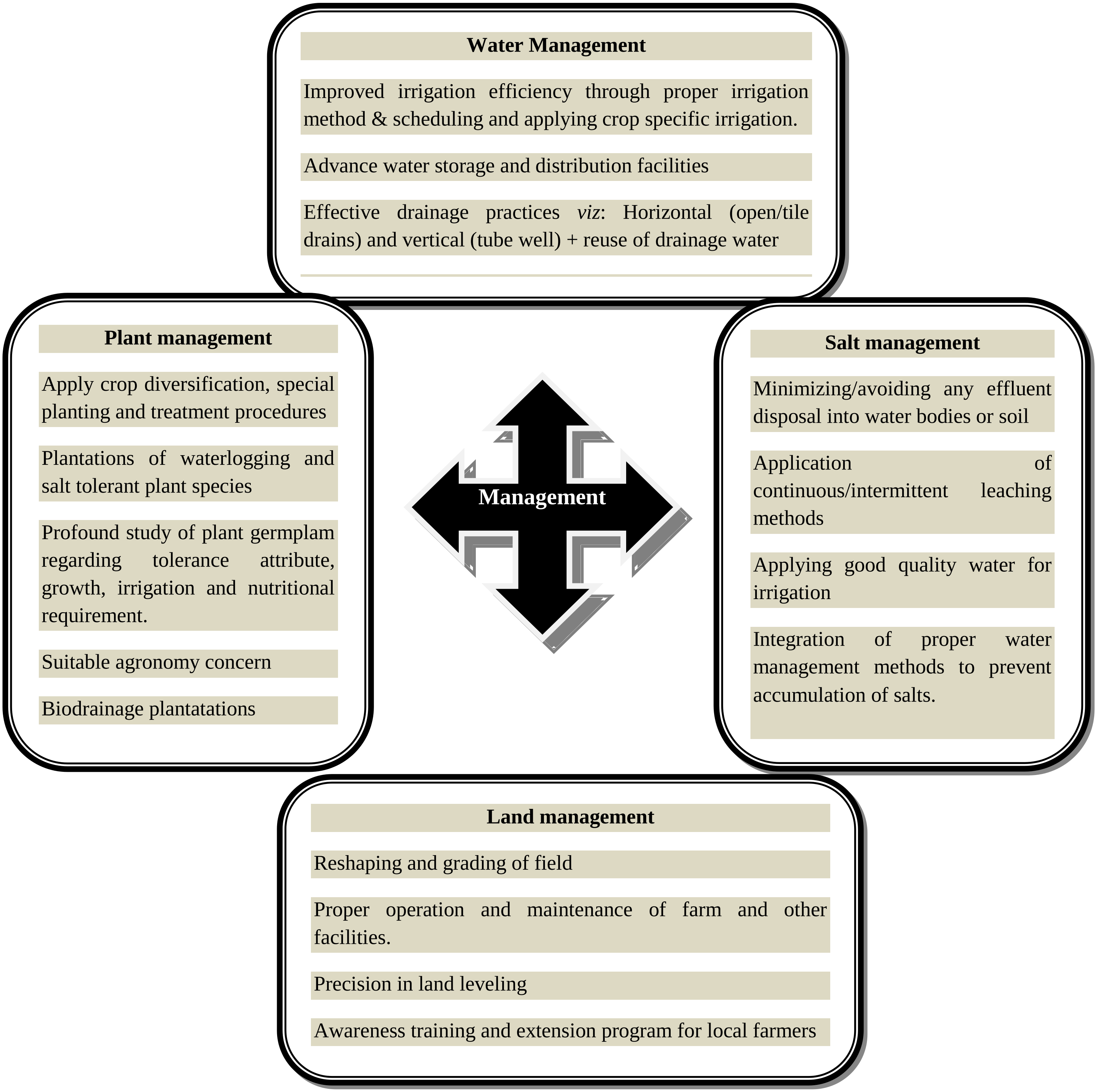


Fig. 2: Phenotypic, physiological and biochemical changes induced by combined waterlogging and salinization condition.



Water Management

- Improved irrigation efficiency through proper irrigation method & scheduling and applying crop specific irrigation.
- Advance water storage and distribution facilities
- Effective drainage practices *viz*: Horizontal (open/tile drains) and vertical (tube well) + reuse of drainage water

Plant management

- Apply crop diversification, special planting and treatment procedures
- Plantations of waterlogging and salt tolerant plant species
- Profound study of plant germplam regarding tolerance attribute, growth, irrigation and nutritional requirement.
- Suitable agronomy concern
- Biodrainage plantatations

Salt management

- Minimizing/avoiding any effluent disposal into water bodies or soil
- Application of continuous/intermittent leaching methods
- Applying good quality water for irrigation
- Integration of proper water management methods to prevent accumulation of salts.

Land management

- Reshaping and grading of field
- Proper operation and maintenance of farm and other facilities.
- Precision in land leveling
- Awareness training and extension program for local farmers

Fig. 3: Management of combined waterlogging and salinization problem

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