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Waterlogging Stress in Late Kharif Onion: Soil–Plant Processes and Integrated Field Management Strategies

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Onion (*Allium cepa* L.) is a high-value bulb crop and a key component of vegetable-based farming systems in India. Late kharif plantings are particularly important because they bridge the supply gap between rabi and early kharif harvests and thus contribute to price stabilization and market continuity. However, late kharif coincides with the tail end of the monsoon, when high-intensity and poorly distributed rainfall frequently cause waterlogging in onion fields, especially on heavy textured Vertisols and low-lying topographic positions. Under these conditions, even short-term inundation severely impairs crop performance, as onion is inherently sensitive to excess soil moisture and hypoxic stress. A scientific understanding of soil–plant processes under waterlogging and the management options available is therefore essential for designing resilient late kharif onion systems.

Diagnosis of the waterlogging problem

Waterlogging is characterized by soil saturation to the extent that the diffusion of oxygen from the atmosphere to the root zone is restricted, resulting in hypoxia (low oxygen) or anoxia (no oxygen). In late kharif onion fields, this typically arises from intense rainfall events, inadequate surface drainage, uneven land leveling, and cultivation on flat beds without raised structures or furrows. Because onion roots are confined mainly to the upper 15–20 cm of soil, they are directly exposed to the oxygen-depleted layer. Critical growth stages such as early vegetative establishment and bulb initiation often overlap with waterlogging episodes, making the crop highly vulnerable to stress-induced yield losses.

Effects on soil physical, chemical and biological properties

Saturation of the soil profile leads to rapid depletion of oxygen in pore spaces and a sharp decline in redox potential. Under these conditions, aggregate stability deteriorates, bulk density may increase, and infiltration rates decline, particularly in heavy soils. Surface sealing and crusting are common after repeated wetting–drying cycles, which further predispose the field to recurrent ponding.

Chemically, waterlogging modifies nutrient transformations and their plant availability. Nitrate nitrogen is reduced to gaseous forms via denitrification, leading to substantial N losses from the system. Ammonium may accumulate temporarily but is poorly utilized due to impaired root activity. Reductive dissolution of iron and manganese oxides releases Fe^{2+} and Mn^{2+} into soil solution, which can reach phytotoxic concentrations. Phosphorus availability may initially increase due to the dissolution of Fe–P complexes but often becomes restricted again when conditions alternate between reduced and oxidized states. Potassium and several micronutrients display altered mobility and uptake patterns, contributing to nutrient imbalances in the crop.

Biologically, populations and activities of aerobic microorganisms decline, while facultative and obligate anaerobes become dominant. Enzyme activities such as dehydrogenase, phosphatases and urease generally decrease, indicating suppressed microbialmediated nutrient cycling. Overall, the soil environment becomes less favourable for root growth and nutrient acquisition by onion.

Plant-level responses to waterlogging

Onion exhibits distinct morphological and physiological symptoms when exposed to waterlogging. At the seedling stage, poor emergence, stand gaps and damping-off are common due to seed and root decay. In established crops, leaf turgor declines despite high soil moisture, and plants show wilting, chlorosis and stunted growth. Examination of the root system reveals darkened, necrotic, and brittle roots with reduced root length density and poor branching. This loss of functional root biomass restricts uptake of water and nutrients.

Physiologically, hypoxic conditions in the rhizosphere limit aerobic respiration, forcing root tissues to rely on less efficient anaerobic pathways and generating toxic metabolites such as ethanol and lactate. Hormonal imbalances involving ethylene, abscisic acid and cytokinins occur, triggering stomatal closure, reduced leaf expansion, and accelerated senescence. Gas-exchange measurements show a decline in photosynthetic rate and stomatal conductance, while chlorophyll and carotenoid contents decrease, reflecting impairment of the photosynthetic apparatus.

Waterlogging and subsequent re-oxygenation phases also induce oxidative stress. Excessive production of reactive oxygen species (ROS) such as superoxide radicals and hydrogen peroxide damages cellular membranes, proteins and nucleic acids. Tolerant genotypes typically exhibit higher activities of antioxidant enzymes like superoxide dismutase, catalase and peroxidases, along with accumulation of compatible solutes (proline, soluble sugars) that help maintain membrane stability and osmotic balance. Sensitive genotypes, by contrast, show higher electrolyte leakage, lower relative water content and faster leaf senescence under the same stress.

Consequences for bulb development, yield and quality

Bulb initiation and maturity are the most critical phenophases with respect to waterlogging. When stress coincides with bulb initiation, differentiation of bulb scales is delayed or partially inhibited, causing uneven or malformed bulbs. During bulb enlargement, sustained reductions in photosynthesis and assimilate supply restrict dry matter accumulation in bulbs. Quantitatively, this is expressed as decreases in bulb diameter, mean bulb weight, and total and marketable yield per unit area.

Quality parameters also deteriorate. Bulbs produced under waterlogged conditions generally have lower dry matter and total soluble solids, thicker necks, poor skin development and higher incidence of internal rots. These attributes adversely affect curing behaviour, storability and processing suitability. Post-harvest losses during storage rise sharply due to increased susceptibility to fungal and bacterial decay. Economically, farmers may lose a large proportion of potential income, and in extreme situations, entire plantings are rendered unmarketable.

Genotypic variability and mechanisms of tolerance

Considerable variation in waterlogging response exists among onion cultivars and breeding lines. Tolerant genotypes maintain relatively higher leaf area index, chlorophyll content, and photosynthetic rate under stress, and experience smaller reductions in yield compared with non-stressed conditions. They often possess more extensive shallow root systems, greater root porosity or aerenchyma formation, and superior antioxidant defence capacity. Maintenance of membrane stability, efficient ROS detoxification and better nutrient uptake under hypoxia appear to be key physiological mechanisms contributing to tolerance.

For late kharif production, deployment of such tolerant genotypes offers an important adaptation strategy. Screening nurseries under controlled waterlogging at defined growth stages, combined with physiological and biochemical characterization, can facilitate the identification of promising material. Integration of tolerance traits into high-yielding backgrounds through conventional breeding and, where available, marker-assisted approaches can accelerate genetic improvement.

Disease complexes under waterlogged conditions

Waterlogging frequently coincides with a higher incidence of onion diseases. Prolonged leaf wetness and humid microclimate favour foliar pathogens causing purple blotch, downy mildew and leaf blight. Saturated soils promote infections by soil-borne fungi such as *Fusarium*, *Pythium* and *Sclerotium* spp., resulting in basal rot, damping-off and root rot. These pathogens exploit weakened plants whose root systems and defence mechanisms are already compromised by hypoxia. Neck rot and bacterial soft rot become particularly problematic during curing and storage of bulbs produced in waterlogged fields. Consequently, any waterlogging management strategy must be integrated with disease management to be effective.

Agronomic and engineering interventions

Mitigation of waterlogging in late kharif onion is best achieved through a combination of land shaping, surface drainage and appropriate crop management. Raised-bed and ridge–furrow systems are the most practical interventions at farmer level. Planting onion on beds 15–30 cm above the furrow bottom reduces the duration and intensity of root-zone saturation, as excess rainfall drains into the furrows. Bed width and row spacing can be optimized based on local machinery and manual operations, but typically two or three rows per bed provide adequate plant population while maintaining good drainage and aeration.

Well-designed surface drainage channels along field boundaries and across long slopes are essential to evacuate excess water from the field. These channels should have adequate gradient and should be connected to main drains or natural waterways. Regular desilting and removal of obstructions maintain their effectiveness. Land leveling—preferably laser-assisted but also achievable through conventional methods—minimizes micro-depressions where water tends to accumulate. In chronically waterlogged areas with high water tables, more capital-intensive options such as subsurface drains may be required, though their feasibility for smallholders must be carefully evaluated.

Nutrient and soil management strategies

Under waterlogging-prone conditions, nutrient management should be adjusted to minimize losses and support plant recovery. Nitrogen should be applied in multiple small splits, with a conservative basal dose and subsequent topdressings timed to periods with lower rainfall probability. This reduces the fraction of N exposed to denitrification and leaching during heavy rains. Phosphorus and potassium should be applied on the basis of soil tests to ensure adequate root development and stress tolerance. Where micronutrient disorders are suspected—especially zinc and boron—foliar applications offer a rapid and efficient correction route.

Incorporation of well-decomposed organic manures or compost improves soil structure, enhances infiltration and water-holding capacity, and supports microbial activity during non-saturated periods. However, very high rates of fresh organic matter in heavy soils should be avoided, as they may aggravate anaerobic conditions. Soil amendments such as gypsum can be beneficial in sodic soils by improving physical condition and promoting better drainage.

Cultural and remedial practices

Choice of planting date should aim to minimize overlap between the most sensitive stages (bulb initiation and enlargement) and the peak of intense rainfall. In many locations, this implies slightly shifting transplanting so that early vegetative growth occurs under higher rainfall, while bulbing coincides with a relatively drier window. Staggering plantings within a 10–15 day window can distribute risk. Adequate spacing ensures better aeration within the canopy, quicker drying of foliage after rain, and reduced disease pressure.

Following a waterlogging episode, remedial actions can help salvage the crop. Once water recedes, shallow intercultivation or hoeing between rows, without damaging roots, helps re-aerate the soil. A light nitrogen topdressing or foliar spray of N and K can stimulate new leaf emergence and support recovery. Removal of severely affected plants reduces inoculum load for soil-borne diseases. Where damage is localized and the season allows, gap filling with reserve seedlings may partially restore plant population.

Outlook under climate variability

Projected increases in the frequency and intensity of extreme rainfall events under climate change scenarios imply that waterlogging risk in late kharif onion is likely to intensify in many regions. This underscores the need for integrating structural measures (raised beds, drainage networks) with biological options (tolerant genotypes) and climate information services (short- and medium-range rainfall forecasts). Economic analyses that quantify the long-term benefits of drainage investments and risk-reduction practices can support decision-making by farmers and policymakers.

Conclusion

Waterlogging during late kharif represents a major abiotic constraint to onion productivity in monsoon-affected regions. Stress alters soil physical, chemical and biological properties, disrupts root function, and induces profound morphological and physiological disturbances in plants, culminating in yield and quality losses and heightened disease susceptibility. Nevertheless, a combination of improved field engineering, tailored nutrient and cultural management, and deployment of waterlogging-tolerant genotypes can substantially mitigate these impacts. Adoption of such integrated, scientifically informed strategies will be critical for safeguarding late kharif onion production and ensuring stable returns to farmers under increasingly variable rainfall regimes.

Figure 1. Late kharif onion crop planted on raised beds with well-drained furrows after heavy rain, illustrating proper field layout to minimize waterlogging stress