EFFECTS OF TEMPORARY SOIL WATERLOGGING ON AGRICULTURAL CROP PERFORMANCE: A REVIEW

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Abstract: *Temporary soil waterlogging is an increasingly significant environmental stress factor affecting agricultural crop production worldwide. Climate change, with its intensified and irregular precipitation patterns, has amplified the frequency and extent of short-term flooding events, particularly in lowland and poorly drained agricultural regions. Such excess water not only influences the growth and productivity of cereals such as wheat (Triticum aestivum L.), but also impacts a wide range of other field crops, including oilseeds, legumes, and vegetables. Prolonged or repeated waterlogging disrupts the soil–plant–atmosphere continuum, leading to oxygen depletion, reduced nutrient availability, and impaired root functionality. This review summarizes current knowledge on the effects of periodic soil water excess on soil–plant interactions, emphasizing the physiological, morphological, and yield responses of major agricultural species. By integrating findings from diverse cropping systems, the paper aims to highlight both the common stress mechanisms and crop-specific adaptation strategies that determine plant performance under transient flooding conditions.*

Key words*: waterlogging, excess water stress, climate change, flooding tolerance, sustainable agriculture*

INTRODUCTION

Due to its natural geographical characteristics, Hungary is particularly vulnerable to inland water formation, especially in the lowland regions of the Great Hungarian Plain, where the combination of flat topography and soil physical properties favors the accumulation of surface water. Inland water refers to temporary, large-scale water coverage that develops when precipitation, snowmelt, or groundwater rise cannot infiltrate, drain, or evaporate, thus accumulating on the soil surface. The formation of inland water is influenced not only by natural conditions but also by land use and water management practices [1].

Among the natural factors, topography, the annual distribution of precipitation, soil structure and permeability, as well as the average depth of groundwater, play key roles. Decision-making relies on monitoring that is both rapid and scalable. Using Sentinel-2 imagery, a head-to-head comparison of index thresholds, traditional machine learning, and deep learning found a convolutional neural network to yield the most consistent inland excess water delineation with minimal user tuning and reduced sensitivity to cloud/shadow effects—features that suit operational surveillance [4]. In low-lying, poorly drained depressions, even moderate excess rainfall or rapid snowmelt can result in soil saturation, preventing air from entering the root zone and leading to oxygen deficiency. When soils remain water-filled for extended periods, gas movement within the pore system becomes severely restricted. As a consequence, root activity is among the first processes to be affected, followed by alterations in microbial functioning. Impaired root respiration limits nutrient acquisition and restricts root expansion, which in turn suppresses shoot development and reduces overall plant productivity.

However, inland water formation is also closely linked to human activities. Intensive agriculture, the decline of natural vegetation cover, the degraded condition of drainage channels, urban expansion, and industrial land development all contribute to the disruption of the natural water balance [2]. Historically, water management interventions were designed mainly for rapid drainage, but the extreme precipitation patterns emerging due to climate change—storms with high intensity and short duration—present new challenges. While inland water used to occur mainly in spring, in recent decades flooding events during autumn and winter have become more frequent, when soil moisture levels are already high.

Inland water has significant agricultural impacts: it deteriorates seedbed conditions, delays or prevents sowing, reduces germination, restricts vegetative growth, and limits the formation of sufficient assimilating leaf area required for yield formation. If water coverage persists, yield losses may range from 20–70%, particularly in cereals such as wheat and maize, which are sensitive to oxygen deficiency in the root zone [16].

Therefore, inland water is not only a water management issue but a complex ecological and agronomic challenge strongly connected to climate change, soil physical conditions, plant adaptability, and land use decisions. Reducing its impact requires an integrated approach that includes water retention strategies, regular maintenance of drainage channels, field-level drainage systems, and research on plant physiological adaptation [11].

Soil–plant interactions under waterlogging

Temporary waterlogging fundamentally alters the physical, chemical, and biological properties of the soil, which directly disturbs essential plant life processes. When the soil pore space becomes saturated with water, gas diffusion is significantly reduced, as oxygen diffuses approximately 10,000 times more slowly in water than in air [3]. This leads to hypoxia or complete anoxia in the root zone, inhibiting root respiration and energy production. Under oxygen-limited conditions, plant roots are forced to rely on alternative metabolic processes that generate significantly less usable energy. This metabolic adjustment is often accompanied by the build-up of fermentation by-products, which can disrupt cellular integrity and contribute to progressive root tissue deterioration [6, 15].

The reduction in oxygen concentration simultaneously affects nutrient cycling within the soil. Anaerobic conditions promote denitrification, during which nitrate is converted into gaseous nitrogen compounds, resulting in substantial nitrogen loss [5]. Moreover, changes in soil redox potential increase the solubility of iron, manganese, and other metal ions, which may reach phytotoxic levels [10]. In parallel, the composition of the soil microbial community also shifts: microorganisms that tolerate low oxygen conditions become dominant, which accelerates nutrient mineralization and mobilization processes.

Plant physiological responses to temporary waterlogging

Temporary soil waterlogging represents a complex stress condition for plants, that primarily begins with a drastic reduction in oxygen availability within the root zone [13]. As the soil pores become saturated with water, gas diffusion slows down by several orders of magnitude, resulting in hypoxia or, in more severe cases, anoxia in the rhizosphere. The lack of oxygen for respiration forces the metabolism of root cells to shift from aerobic respiration to anaerobic fermentation pathways, which provide only limited energy output. During this process, by-products such as ethanol, lactic acid, and aldehydes accumulate, causing cellular toxicity and contributing to the accumulation of reactive oxygen species (ROS), which lead to membrane damage and oxidative stress [7].

Oxygen deficiency in the roots also significantly alters nutrient uptake and transport processes. The inhibition of nitrate uptake, combined with enhanced denitrification in the soil, results in poorer nitrogen supply to the plant. Meanwhile, the reducing soil environment increases the solubility of Fe^{2+} and Mn^{2+} ions, which may reach phytotoxic concentrations. These physiological disturbances directly affect processes occurring at the leaf surface: the regulation of stomatal closure becomes impaired, water balance deteriorates, and chlorophyll degradation begins, leading to a rapid decline in photosynthetic performance [8, 12]

However, plant stress responses do not only involve damage but also include the activation of adaptive mechanisms. Plants exposed to short-term soil saturation may partially compensate for oxygen deficiency through structural modifications in their root systems. One such response involves the development of internal air spaces that facilitate limited gas exchange between aboveground tissues and submerged roots. In parallel, some species initiate the growth of new root structures closer to the soil surface, where oxygen availability is comparatively higher. These responses have been observed mainly in crop genotypes showing improved tolerance to excess soil moisture [14].

The signaling of water pressure and oxygen deficiency in plants is closely linked to hormonal regulation. Under waterlogging conditions, ethylene concentration increases within the cells, playing a key role in stress-induced leaf yellowing, cell wall loosening, and aerenchyma development. Meanwhile, modifications in ethylene–auxin–cytokinin interactions lead to a pronounced reduction in shoot growth and tillering, which ultimately results in decreased biomass accumulation and lower yield capacity. Overall, plant responses to waterlogging arise from multi-step physiological processes that are closely interconnected. Oxygen deficiency in the root zone initiates metabolic shifts at the cellular level, which, through altered nutrient uptake, photosynthesis, and hormonal signaling, ultimately lead to long-term reductions in plant growth dynamics and productivity. The plant's ability to develop functional adaptations depends largely on its genotype, the duration of the stress, and the phenological stage at which waterlogging occurs.

The response of winter wheat (Triticum aestivum L.) to waterlogging stress

The responses of different agricultural crop species to waterlogging vary considerably, which is primarily related to the structural characteristics of their root systems, their capacity for internal oxygen transport, as well as their hormonal and genetic stress response mechanisms. Although the general effects of waterlogging (such as hypoxia, reduced nutrient uptake, and inhibition of photosynthesis) occur in all plant species, the degree of sensitivity and the potential for recovery differ markedly among species.

Temporary soil water accumulation has a substantial impact on the development, physiological processes, and yield formation of winter wheat (Triticum aestivum L.). In water-saturated soils, the air present in the pore spaces is displaced by water, leading to oxygen deficiency (hypoxia) in the root zone. This condition restricts root respiration and nutrient uptake, which subsequently affects the plant's overall metabolism and growth.

Research indicates that wheat is the most sensitive to waterlogging during the flowering period. When waterlogging occurs during this stage, spike formation and grain set are disrupted, resulting in significant yield reductions [9].

Yield loss may arise from several contributing factors:

- The number of grains per spike is reduced, as waterlogging interferes with fertilization and the early development of grains.
- Thousand-kernel weight may also decrease, since limited oxygen availability and impaired photosynthesis reduce the amount of assimilates transported to the grains.
- Waterlogging during the tillering stage reduces the number of secondary shoots, resulting in fewer spikes developing per plant.

Wheat is particularly vulnerable when waterlogging persists for more than 7–14 days [8]. Under such conditions, cell death may occur within the root system, leaves begin to yellow, and the plant initiates premature senescence processes. A decline in photosynthetic activity under waterlogged conditions has been confirmed in several studies using chlorophyll fluorescence measurements.

Overall, the impact of waterlogging on winter wheat is substantial and multifaceted. Yield losses may reach up to 50%, especially in years characterized by intensive rainfall or in fields with poor drainage capacity [16]. Effective mitigation strategies include appropriate soil cultivation practices, improvement of soil structure, and the selection of varieties with enhanced tolerance to waterlogging stress.

CONCLUSIONS

Temporary soil waterlogging represents a significant agronomic and ecological challenge in regions prone to excess surface water, such as the lowland areas of Hungary. The combined influence of climatic variability, soil physical properties, and human-induced landscape modifications contributes to the increasing frequency and severity of inland water events. Waterlogging disrupts soil structure, nutrient cycling, and root respiration, leading to reduced photosynthetic efficiency, inhibited growth, and substantial yield losses, particularly in sensitive crops such as winter wheat.

Although plants possess adaptive mechanisms—such as aerenchyma formation and the development of adventitious roots—the effectiveness of these responses is strongly dependent on the genotype, stress duration, and the phenological stage at which waterlogging occurs. Therefore, improving crop tolerance to waterlogging requires an integrated approach that includes the enhancement of soil structure, maintenance and modernization of drainage infrastructure, the application of precise water management strategies, and the targeted selection or breeding of tolerant cultivars.

Continued research into plant physiological responses, coupled with advances in remote sensing and field-level monitoring, will play a crucial role in mitigating the agricultural impacts of waterlogging under future climate conditions..

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