Plant Archives Vol. 25, No. 1, 2025 pp. 1163-1172 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.no.1.175

FLOOD RESILIENCE IN CROPS: EMERGING INNOVATIONS AND EFFECTIVE MANAGEMENT FOR ENHANCED PRODUCTIVITY AND FOOD SECURITY

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(Date of Receiving-20-12-2024; Date of Acceptance-10-03-2025)

ABSTRACT

Climate change is leading to increasingly severe weather events, including flooding and soil waterlogging, which adversely impact crop production. It is crucial to comprehend the effects of flooding stress on crops and to develop enhanced production practices that bolster the resilience of cropping systems, enabling them to better withstand extreme weather conditions. Flooding also increases nitrogen losses from the soil through processes such as runoff, leaching, and denitrification. Flood-adaptive mechanisms in crops, such as ethylene biosynthesis and signalling under flooding stress, low oxygen sensing mechanisms, and various morphological modifications and traits, have been identified. These discoveries are crucial for breeding crops that are more tolerant to flooding. To alleviate soil waterlogging stress, potential management practices include employing flood-tolerant crop varieties, modifying management practices, enhancing drainage systems, cover crops, and implementing adaptive nutrient management strategies, supported by crop modeling techniques and many more. These practices may be specific to particular sites or crops and should be assessed for their economic feasibility before being incorporated into future management plans aimed at achieving sustainable crop yields under flooded conditions.

***Key words*:** Cover crops, crop modeling, drainage systems, ethylene biosynthesis, flood

Introduction

Climate change has enhanced global environmental risks, particularly concerning the effects of abiotic stresses on agricultural productivity. Among these stresses exacerbated by climate change, such as complete submergence, stagnant flooding, and soil waterlogging, flooding stands out as a critical challenge for plant growth and food production worldwide. Enhancing crop plants' ability to adapt to flooding conditions is crucial in addressing the rising frequency and severity of floods, which could potentially be achieved by manipulating adaptive physiological and molecular processes. Full submergence drastically reduces the diffusion rates of oxygen (O_2) and carbon dioxide (CO_2) by approximately 10,000 times, elevates ethylene production and accumulation within plant tissues, and limits access to light (Fukao and Bailey-Serres, 2008). When soil moisture levels rise, the soil's capacity to diffuse oxygen diminishes, leading to hypoxic or anoxic conditions that hinder the activity of nitrifying microorganisms. Consequently, this reduction in nitrogen availability negatively affects the productivity of nitrogen-dependent crops (Paul *et al.*, 2023). When molecular oxygen levels in the soil decrease, the physio-chemical properties of the soil undergo several changes. These changes also affect the soil's electrochemical composition by lowering redox potential and causing excess electron shifts, such as the reduction of Fe^{3+} and Mn^{4+} to Fe^{2+} and Mn^{2+}, respectively (Singh and Setter, 2017). This leads to an increase in the solubility of iron and manganese to potentially harmful levels, which can damage plant roots.

Indeed, submergence stress impacts virtually every stage of plant growth and development, spanning from seed germination to maturity. As a result, persistent stress from any form of flooding will ultimately produce similar effects, including reduced root permeability, decreased mineral absorption, lower photosynthesis rates, diminished stomatal conductance, changes in hormonal balance, development of aerenchyma, and increased levels of reactive oxygen species (ROS). These factors collectively contribute to early plant death (Wu and Yang, 2016). Additionally, the low-pH environment in the rhizosphere may elevate the concentration of secondary metabolites like phenolic and volatile fatty acids, which can become toxic to sensitive root tips (Coutinho *et al.*, 2018). The accumulation of volatile organic acids and increased CO_2 levels can further lower soil pH. Plants have the ability to adapt to challenging environments, either temporarily or permanently, by adjusting their physiological, biochemical, and molecular processes. Under flooding conditions, they employ various adaptive strategies to enhance survival. For instance, they may develop aerenchyma in their roots to improve gas exchange in anaerobic conditions (Armstrong, 1979). Additionally, when partially submerged, plants initiate further adaptive mechanisms such as hyponastic growth and rapid elongation of their aerial parts to ensure sufficient aeration (Cox *et al.*, 2003).

Climate change has resulted in extreme variations in water availability, leading to severe drought in some regions and flooding in others due to intense rainfall events (Bailey-Serres *et al.*, 2012). Without the development of new crop varieties that can tolerate these abiotic stresses, agricultural productivity will be significantly impacted. Until recently, there was limited knowledge about the genes responsible for submergence tolerance. However, in recent years, significant progress has been made in understanding the molecular mechanisms of oxygen sensing and signalling in plants (van Dongen & Licausi, 2015).

Flood Damage Classification

1. Direct instantaneous damage: Floods can affect various components of a farm, impacting both flows such as crops and stocks, and assets like perennial plant material, farm buildings, and machinery. Based on qualitative studies of flood impacts on agriculture, seven key types of direct and immediate damage have been identified: loss of crops and reduced yields; harm to or destruction of perennial plants such as vineyards and orchards; fatalities and injuries among livestock; loss of livestock products like milk and eggs; damage to soil through erosion, debris, and contamination; damage to farm buildings; damage to machinery and equipment; and damage to stored materials including inputs, feed, and fodder (Brémond *et al.*, 2013). A decrease in yield can lead to changes in production costs, such as savings from reduced time spent on certain tasks. These cost reductions typically take place after the flood and may persist throughout the remainder of the production cycle (Morris and Brewin, 2013).

2. Direct induced damage: The extent of direct induced damage to agriculture depends on the scope of the agricultural analysis. When examining agriculture solely through land use, such as individual parcels and farm buildings, the extent of direct damage may appear minimal. However, as noted by Bauduceau (2001), destruction of perennial plant material can result in future yield losses that persist for several years after a flood. Regarding livestock, Posthumus *et al.*, (2009) highlight direct damage such as decreased milk production due to reduced grass yield and feed value, as well as increased veterinary costs from animal stress. Bauduceau (2001) also points out potential rises in production costs due to additional inputs needed to mitigate losses. Furthermore, if some direct damage, like soil erosion or contamination, is not fully addressed, it can lead to restrictions in land use, such as prohibiting certain crops. Pivot *et al.*, (2002) also emphasize that, in addition to direct damage to fundamental components, the extent of damage at the farm level can vary based on factors such as the farm's internal organization, the availability of production resources, and the decisions made by the farm operators.

3. Indirect damage: To capture indirect damage, a broader scale beyond the individual farm is necessary, such as a regional or national scale. Some qualitative studies indicate that flooding can affect agricultural activities outside the floodplain area (Brémond *et al.*, 2008). For example, farmers who are not directly affected may experience disruptions in their input supplies, including stored fodder, if these supplies are impacted. Additionally, closely related economic sectors can also face disruptions. For instance, if harvests are destroyed, the food industry might experience shortages and struggle to find market substitutes. If many farms go bankrupt, the food industry may need to reorganize to address the new market conditions.

Flood Adaptive Mechanisms in Crops

1. Biosynthesis of ethylene and signaling under flooding stress: The process of ethylene biosynthesis varies significantly between stress conditions and normal conditions. Under abiotic stresses such as chilling, salt, drought, heat, flooding, heavy metals, and photo-oxidative stress, there is a notable increase in ethylene production, leading to higher concentrations of the gas. In particular, complete submergence speeds up ethylene production and accumulation in many plant species. Unlike other stresses, where gas diffusion remains relatively unaffected, flooding severely restricts the exchange of gases between the plant and its environment. Submergence stimulates ethylene production, causing the gas to accumulate in plant tissues and quickly reach response-saturating levels within 1 to 2 hours (Voesenek and Sasidharan, 2013). This triggers flood-adaptive responses, enabling various species to thrive in temporarily flooded environments. Gaining insights into ethylene dynamics—such as its biosynthesis, signalling, and perception in flood-tolerant plants—could be valuable for improving the flood tolerance of essential food crops (Khan *et al.*, 2020). Among submergence-tolerant species, rice (*Oryza sativa*) stands out as the most extensively researched food crop due to its agricultural and economic significance. During submergence stress, changes in cell and organ structures enhance gas exchange (Bailey-Serres and Voesenek, 2008). Elevated ethylene levels in submerged tissues initiate various acclimation responses, including the development of adventitious roots, shoot elongation, carbohydrate consumption, aerenchyma formation, and ethanolic fermentation (Bailey-Serres and Voesenek, 2008). During submergence, *ACS*1 mRNA levels rise primarily in the internodes, which are involved in cell elongation, whereas other parts of the stem, such as the cell differentiation zone, intercalary meristem, and nodes, exhibit lower *ACS*1 mRNA levels compared to those in air (Zarembinski and Theologis, 1997). A similar increase in *ACS*5 mRNA expression is noted in the vascular bundles of young stems and leaf sheaths, where cell division and elongation are active during stress (Zhou *et al.*, 2002). The findings suggest that both *ACS*5 and *ACS*1 contribute to ethylene production under prolonged submergence, promoting internode elongation and cell growth in the vascular bundles of young stems.

2. Low Oxygen Sensing Mechanism: Gibbs *et al.*, (2011) observed that genotypes defective in the N-end rule pathway of targeted proteolysis (NERP)—such as those lacking Arg-tRNA protein transferases (ATE) or the E3 ubiquitin ligase known as *proteolysis6* (*prt6*)—exhibited constitutive overexpression of many hypoxia-responsive gene transcripts. These mutants showed enhanced seed germination and improved seedling survival under hypoxic conditions compared to wild-type plants. Licausi *et al.*, (2011) also reported that *RAP2.12*, which is constantly synthesized and translated, is initially confined to the plasma membrane by an Acyl-CoA binding protein (ACBP1/2) under normal oxygen conditions. When oxygen levels drop, *RAP2.12* rapidly relocates to the nucleus, leading to the activation of genes responsive to hypoxia. The constitutively expressed ERFs, such as *RAP2.2*, *RAP2.3*, and *RAP2.12*, likely function as primary sensors of low oxygen. In contrast, ERFs that are strongly induced by low oxygen, such as HRE1/2, need to be transcriptionally activated before they can influence downstream targets, positioning them as secondary players in the low oxygen signaling pathway. This indicates that different ERFs have specialized roles: first, constitutively expressed ERFs like *RAP2.12* likely serve as an initial line of defense, rapidly initiating an adaptive transcriptional response under hypoxic or anoxic conditions by stabilizing proteins (*e.g.*, quickly up-regulating hypoxia-responsive genes). Second, ethylene-induced ERFs are involved in regulating flood-adaptive processes under normal oxygen conditions (*e.g.*, promoting rapid underwater elongation of photosynthetic shoots), which requires these ERFs to be insensitive to NERP. Third, under normal oxygen levels, ethylene-induced ERFs that are NERP substrates might be regulated and sequestered, allowing them to activate key hypoxia-responsive genes when oxygen levels eventually fall.

3. Morphological Modifications: A significant adaptation in submerged plants is the development of intercellular gas spaces, known as aerenchyma, which facilitates better gas transport and distribution within the submerged plant tissues. Aerenchyma can form in various plant parts, including the root cortex, stems, and leaves. This adaptation can be triggered by flooding in some non-wetland species like wheat and maize (Colmer and Voesenek, 2009), or it can be a permanent feature in many wetland species such as rice and *Zea nicaraguensis* (Yamauchi *et al.*, 2018). Additionally, some submerged plants, like rice and *Solanum dulcamara* (Dawood *et al.*, 2016), produce shoot-born adventitious roots, which also contain extensive aerenchyma. To minimize gas loss from the root surface, many wetland plants develop a radial oxygen loss (ROL) barrier around the aerenchyma-containing tissues.

When fully submerged, some plants have evolved mechanisms to elevate their leaves to the water's surface to re-establish contact with the air. This is accomplished through hyponastic growth, where the angle of the leaf changes to a more upright position. This adaptation is observed in both wetland and non-wetland species, such as *Arabidopsis thaliana* and *Rumex palustris* (Cox, 2003). Additionally, some species adopt an "escape strategy" by increasing growth under water to lift their leaves above the surface. This can involve rapid growth of petioles, as seen in *Rumex palustris* and *Ranunculus* *sceleratus*, or accelerated stem elongation, as demonstrated by rice (Hattori *et al*., 2009).

4. Flood/Waterlogging Tolerance in *Hordeum* Species: Barley is notably more sensitive to flooding compared to other cereal crops (Setter and Waters, 2003). However, it shares this sensitivity with maize, although it has related species like *Hordeum marinum* and *Hordeum spontaneum* that are more tolerant to flooding. These relatives have been valuable in researching the mechanisms behind flood tolerance.

Several evaluations of waterlogging tolerance have been conducted, including tests on extensive collections of barley cultivars at the germination stage (Qui and Ke, 1991). The waterlogging tolerance observed in *H. marinum* is attributed to its anatomical features, such as high porosity in adventitious roots and the presence of a barrier that reduces radial oxygen loss (ROL) (Kotula *et al*., 2017). A study of 35 Hordeum species and genotypes showed significant variation in their anatomical responses to waterlogging, particularly in their ability to form aerenchyma or develop ROL barriers (Garthwaite *et al*., 2003). Fine mapping efforts identified a region containing 58 candidate genes associated with waterlogging tolerance (Zhang *et al*., 2017). More recently, proteomic analyses of different barley cultivars under waterlogging conditions revealed that tolerant varieties exhibit greater protection against reactive oxygen species (ROS) and enhanced fermentation capacity compared to sensitive varieties (Luan *et al*., 2016).

5. Flood Tolerance in Wheat: Ginkel et al. (1991) evaluated 1,344 lines of spring wheat from the CIMMYT (Centro Internacional de Mejoramiento de Maíz y Trigo) germplasm collection. Further analysis of six selected lines, along with additional samples, confirmed that the cultivar Ducula exhibited notable waterlogging tolerance (Sayre *et al*., 1994). One potential mechanism for this tolerance is the increased root porosity observed in waterlogged roots of the tolerant lines (Boru and Kronstad, 2003). A screening of 34 winter wheat cultivars assessed both flooding tolerance and winter hardiness (McKersie and Hunt, 1987). More recent evaluations of Norwegian wheat genotypes identified tolerant varieties that exhibited distinctive root traits, such as increased stele and aerenchyma area, compared to sensitive cultivars (Sundgren *et al*., 2018). An additional study found that the tolerant cultivar Jackson outperformed Coker 9835 in terms of flooding tolerance, likely due to its lower respiration rate (Huang and Johnson, 1995). There are also potentially more flood-tolerant relatives of wheat, such as *Triticum macha* L., T. *dicoccum* cv. Pontus (Davies, and Hillman,1998), and *T. spelta* (Burgos *et al*., 2001a), which could be leveraged to enhance flooding tolerance in wheat. Notably, *T. spelta* was included in a quantitative trait locus (QTL) analysis that identified several loci associated with flooding tolerance during germination, including five loci linked to improved coleoptile growth (Burgos *et al*., 2001b).

6. Soybean and *Brassica Spp.* Tolerance under Flooded Condition: In a screening of soybean cultivars, researchers observed that the cultivar Manokin exhibited spongy white roots indicative of an aerenchyma-like structure, whereas this feature was absent in the highly tolerant cultivar Delsoy 4710 (Rhine *et al*., 2010). Secondary aerenchyma, which develops around roots, stems, and nodules from phellem in waterlogged soybeans, has been noted previously and may enhance the aeration of flooded tissues (Shimamura *et al*., 2010).

Recently, Genome-Wide Association Studies (GWAS) have been employed to pinpoint genomic loci linked to waterlogging tolerance in various legumes, including *Phaseolus vulgaris* L. (Soltani *et al*., 2018). These studies revealed significant overlaps between flooding tolerance loci in *Phaseolus vulgaris* and soybean QTLs, specifically with markers Sat_064 (VanToai *et al*., 2001) and Satt187 (Sayama *et al*.,2009). Additionally, *Glycine soja*, a close relative of soybean, demonstrates higher waterlogging tolerance and could be a valuable resource for breeding programs aiming to improve tolerance (Valliyodan *et al*., 2017).

Diploid Brassica species have also been investigated for flooding tolerance, uncovering cultivar-specific differences. An analysis of two *Brassica rapa* populations with varying waterlogging tolerance highlighted the role of carbohydrate supply to roots as a key factor in tolerance (Daugherty *et al*., 1994). Similarly, *Brassica oleracea* was studied at the seed stage, where oxygen availability significantly affects germination. A QTL analysis comparing a sensitive Chinese cultivar (A12DHd) with a more tolerant calabrese cultivar (GDDH33) identified three QTLs related to germination under low-oxygen conditions (Finch-Savage *et al*., 2005). Another study involving six cultivars with different waterlogging tolerances revealed both additive and non-additive genetic effects, with Zhongshuang 9 identified as the most effective cultivar (Cheng *et al*., 2001). Furthermore, a different group used a double haploid population from two distinct lines with high and low waterlogging and drought tolerance to identify at least 11 QTLs associated with waterlogging tolerance, indicating a complex regulatory network in this species (Li *et al*., 2014).

Table 1: Some Important flood tolerant varieties/hybrids of different crops.

Crop	Varieties
Rice	Swarna Sub-1, Sambha Mahsuri Sub-1, Varshadhan, Gayatri, Sarla, Pooja, Prateeksha, Durga, JalaMani, CR Dhan 505, CR Dhan 502, Jalnidhi, Neerja, Jaladhi 1, Jaladhi 2, Hemavathi
Maize	HM-5, Seed Tech-2324, HM-10, PMH-2
Sugarcane	Co 98014 (Karan-1), Co 0239, Co 0118, Co 0238, Co 0233, Co 05009
Jute	JRO 7835, JRO 878, JRC 321, JRC 7447, JRC 532, JRC-517, Bidhan Pat-1
Soybean	Misuzudaizu, Peking, Benning, Danbaekkong, I27, Pangsakong, Geumkangkong and 'Sohokong (Yijun *et al.*, 2022)
[**Source:** Ministry of Agriculture & Farmers Welfare, GOI].	

The rice varieties Swarna-sub1, MTU-1010, MTU-1001, and MTU-1140 stand out for their high yield, excellent grain quality, and tolerance to submergence, making them particularly effective in flood-prone areas. Among these, Swarna-sub1, developed by IRRI and CRRI, Cuttack and introduced in 2009, is notable for its ability to withstand submergence for up to two weeks, outperforming other improved and local varieties in such conditions. MTU-1010, characterized by its short duration and dwarf stature, is resistant to lodging and can handle moderate wind speeds, thereby protecting both grain and straw yield—an important source of dry fodder. MTU-1140 is another promising variety, known for its non-lodging nature and grain quality comparable to BPT-5204.

Agronomic Intervention for Flood Resilience in Crops

1. Mixed Seedling Cropping System: This method helps mitigate the negative effects of low oxygen stress in the rhizosphere on upland crop growth. Research conducted in glasshouse and laboratory settings examined the flood tolerance of upland staple crops, such as pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*), when intercropped with rice (*Oryza spp.*). The study observed that growing one wetland and one drought-tolerant species together using this technique enhances the flood tolerance of upland crops (Iijima *et al.*, 2016). The intertangled root systems resulting from mixed cropping improved the photosynthetic and transpiration rates of upland crops exposed to flood stress (low oxygen conditions in nutrient culture). Shoot growth rates during a 24-day flooding period were generally higher with mixed cropping compared to single cropping. The radial oxygen loss from the wetland crop's roots may have contributed to this effect. The mixed cropping of wet and dryland crops represents a novel approach with potential to alleviate flood stress in varying environmental conditions.

2. Growing flood tolerant varieties: Plants that tolerate flooding often possess several key mechanisms to cope with waterlogged conditions. These include the ability to transport oxygen to roots deprived of oxygen, high rates of anaerobic respiration, maintenance of glycolytic metabolism, the capacity to keep stomata open for photosynthesis, and mechanisms to prevent oxidative damage (Caudle & Maricle, 2012). Traits of flood-tolerant plants typically involve adaptive features such as the formation of aerenchyma, development of adventitious roots, and stem swelling. For instance, Mano and Omori (2007) explored the use of 'teosinte' as a genetic resource for breeding flood-tolerant corn due to its ability to produce adventitious roots at the soil surface during prolonged saturation and its capacity to develop aerenchyma both constitutively under non-flooded conditions and inducibly during flooding. Additionally, breeding programs may benefit from focusing on traits that enhance nitrogen uptake, nitrogen use efficiency, and improvements in seed or grain quality for developing flood-tolerant crop varieties. Some of the flood tolerant varieties of different crops are mentioned in Table 1.

3. Planting dates adjustments: Adjusting planting dates can significantly mitigate flood risks by aligning crop growth with anticipated weather patterns and flood peaks. By planting early or late in the season, farmers can avoid critical growth stages coinciding with peak flood periods, thereby reducing the likelihood of submersion during vulnerable times. This strategy allows crops to establish stronger root systems in less waterlogged conditions, potentially improving resilience and overall yield. Planting crops early extends the growing season, which can lead to higher yields by providing more time for solar radiation absorption and biomass development (Kucharik, 2006). Additionally, leveraging weather forecasts to time planting can help farmers better manage soil conditions and avoid the worst impacts of flooding, ultimately enhancing crop survival and productivity.

4. Cover crops: Using cover crops over the long term can enhance soil health and reduce waterlogging by improving soil structure, lessening compaction, and boosting water infiltration rates (Blanco-Canqui *et al.*, 2015). The root systems of cover crops create channels that increase macropores, facilitating better water movement through the soil. For instance, a mix of bromegrass (*Bromus inermis* Leyss.) and strawberry clover (*Trifolium fragiferum* L.) was shown to lower surface soil strength by 38-41% and enhance both steady infiltration rate and cumulative water intake by 37–41% and 20–101%, respectively, compared to areas without cover crops (Folorunso *et al*., 1992). Winter cover crops can also influence water availability for summer crops by reducing evaporation and utilizing stored soil moisture for transpiration. The higher transpiration rates of cover crops in spring can help dry the soil, making it more suitable for early planting. Additionally, the increased water demand of cover crops, combined with higher spring temperatures, can aid in removing excess moisture from waterlogged soils through enhanced evapotranspiration.

5. Adaptive Drainage System: Drainage systems help eliminate excess water from soil, enhancing plant root development, emergence, and overall plant stands, leading to increased crop yields. Research has shown that drainage systems, particularly when combined with effective nitrogen management, boost crop yields, nitrogen uptake, and nitrogen use efficiency (Nelson *et al*., 2009). Both free drainage and managed tile drainage systems, which incorporate water table control structures, have been found to improve yields and reduce fertilizer losses through runoff. For example, subsurface tile-drained systems installed at 6.1- and 12.2-meter intervals on poorly drained claypan soils increased yields by 11–22% compared to untreated plots (Nelson, 2017a). Additionally, tile drainage has been shown to improve soil moisture, allowing for earlier soybean planting by up to 17 days and increasing yields by 9–22% over non-drained plots (Nelson *et al*., 2011b). Connecting subsurface tile drainage systems to on-farm irrigation reservoirs could address water quality concerns while enhancing both waterlogging and drought resilience in crop production, though this approach requires further investigation.

6. Adoption of Raised Beds Technique: Raised beds are an effective solution for managing waterlogging in areas where tillage is employed for land preparation, though they may not be suitable for no-till systems. They address water management issues, including waterlogging and irrigation challenges, particularly in semi-arid and arid regions. By enhancing drainage, raised seedbeds help maintain optimal soil moisture levels and facilitate better irrigation water application, which can lead to increased crop yields (Velmurugan *et al*., 2016). Raised beds improve soil physical characteristics such as macroporosity, infiltration, bulk density, and aggregate stability, resulting in better soil structure. Research has shown that raised bed planting can enhance crop yields in waterlogged conditions compared to flat seedbed planting (Blessitt, 2007). They mitigate waterlogging by increasing runoff through furrows and improving soil structure, evidenced by reduced bulk densities and enhanced infiltration rates in poorly drained clay soils (Bakker *et al*., 2005). Raised beds help alleviate waterlogging stress by keeping the top 15 cm of soil unsaturated. According to Blessitt (2007), raised seedbeds are a viable option for minimizing waterlogging damage to early-planted soybeans in the Mississippi River Delta region.

7. Flexible Nutrient Management: Adaptive nutrient management enhances crop flood tolerance by precisely tailoring nutrient application to fluctuating soil and water conditions. This approach involves adjusting nutrient rates, timing, and methods based on real-time assessments, ensuring that crops receive essential nutrients when needed despite variable water levels. By improving soil structure and health, adaptive management helps soils better handle excess water, reducing waterlogging and promoting better root function. It also addresses changes in nutrient availability caused by flooding, such as shifts in soil pH and nutrient leaching, by optimizing fertilizer types and application methods. Strong, well-nourished plants developed through adaptive nutrient management are more resilient to flooding stresses and can recover more swiftly. Additionally, this approach minimizes nutrient losses from runoff and leaching during floods, enhancing nutrient use efficiency and overall crop performance in flood-prone areas. Applying nitrogen in a single dose can lead to losses if soil waterlogging occurs due to extreme precipitation early in the season. In such cases, additional nitrogen applications, known as rescue N, may be necessary if pre-plant nitrogen is lost or if wet conditions prevent timely pre-plant or side-dress applications (Nelson *et al*., 2011b).

8. Application of Controlled release fertilizers: Enhanced efficiency fertilizers are designed to improve plant nutrient uptake and minimize environmental nutrient losses, such as through gas emissions, leaching, or runoff, compared to traditional fertilizers (Motavalli *et al*., 2008). These fertilizers include slow-release and controlled-release types, nitrification inhibitors (NI), and urease inhibitors (UI). Slow-release or controlled-release fertilizers manage the timing of nutrient availability by either delaying the initial release or extending the nutrient's presence in the soil throughout the plant's growth. They achieve this by controlling nitrogen release, limiting ammonium access to nitrifying bacteria, and reducing nitrate loss through leaching or gaseous emissions. This is often accomplished through semi-permeable coatings, occlusion, or chemically modified forms that release nutrients more slowly. Examples include urea-formaldehyde based fertilizers, sulfur-coated urea, and polymer-coated urea (PCU). "Controlled-release" refers to fertilizers with precisely regulated release rates due to their coating or encapsulation, while "slow-release" generally describes fertilizers that decompose more gradually, like urea-formaldehyde products. Nitrification inhibitors reduce the rate at which ammonium is converted to nitrate, cutting down on nitrate leaching and denitrification losses. Urease inhibitors, on the other hand, delay the conversion of urea, giving more time for it to move into the soil where it is less prone to loss through volatilization.

9. Precision Agriculture Strategy: Combining flood-tolerant crop varieties with optimal nitrogen (N) fertilizer rates and sources in areas of a field prone to occasional waterlogging could be an effective strategy for minimizing yield and N losses in low productivity zones. This approach requires further investigation to fully understand its potential. Additionally, managing waterlogging in these less productive areas can be improved by implementing tile drainage systems, complemented by control structures to regulate water table levels, which can help reduce N losses and boost crop yields. Precision agriculture technologies, such as yield maps, soil productivity maps, high-resolution digital elevation models from LIDAR (Light Detection and Ranging), flow accumulation, and soil electrical conductivity maps, can be used to identify specific management zones and tailor practices to enhance crop productivity (King *et al*., 2005). Technologies such as yield maps, soil moisture sensors, and high-resolution topographical data allow farmers to identify and manage areas prone to waterlogging with targeted interventions like optimized drainage systems and tailored fertilizer applications. By applying nutrients where they are most needed and adjusting irrigation schedules based on real-time soil conditions, farmers can reduce nutrient losses and prevent soil saturation. Additionally, precision agriculture helps in designing effective drainage systems and choosing flood-tolerant crop varieties, leading to better crop resilience and productivity even in flood-prone areas.

10. Role of Weather Forecasting: Weather forecasting plays a crucial role in agriculture by predicting atmospheric conditions that impact crop management, particularly in mitigating flood risks. Advanced techniques such as Numerical Weather Prediction (NWP), satellite, and radar data provide short-term to long-term forecasts, allowing farmers to anticipate heavy rainfall and severe weather. This information enables pre-emptive actions like adjusting irrigation, enhancing soil drainage, and applying protective measures. Integration with Decision Support Systems (DSS) and precision agriculture tools further refines field management strategies by tailoring practices to forecasted conditions. The timing of fertilizer application is influenced by weather conditions. Heavy rainfall might lead to nutrient leaching, necessitating reapplication, while dry periods could require more frequent applications to ensure soil fertility. Additionally, weather data helps farmers predict and manage pest outbreaks, as certain pests flourish under specific temperature and moisture conditions, following seasonal patterns that impact their breeding and growth (Sarma and Kakoti, 2024). Overall, accurate weather forecasts help farmers assess flood risks, plan strategically, and respond effectively to minimize crop damage and optimize yields.

11. Crop Modeling and Decision Support Systems (DSS): Crop modeling and decision support systems (DSS) play a crucial role in enhancing crop tolerance to flooding by providing valuable insights and predictions that guide management practices. These systems use simulations and historical data to model crop responses to various flooding scenarios, helping farmers anticipate potential impacts and make informed decisions. By integrating weather forecasts, soil moisture levels, and crop growth stages, crop models can predict when and where flooding might occur, allowing for timely adjustments in practices such as irrigation, fertilization, and planting. For instance, Bassu *et al.*, (2009) utilized the APSIM-Wheat model to assess how different planting dates affect wheat yields under varying levels of waterlogging. Their findings revealed that early planting could boost yields in areas with low to moderate waterlogging risk but did not have the same benefit in regions frequently experiencing waterlogging. The effectiveness of such simulation models in estimating waterlogging stress depends on the accuracy of their process representations. Furthermore, GIS and remote sensing technologies can be employed to pinpoint areas within a field that are susceptible to soil waterlogging or drought. These tools facilitate the precise application of crop and nutrient management practices, helping to alleviate waterlogging stress and optimize field management. Additionally, McLellan *et al.*, (2018) introduced the Right Practice, Right Place (RPRP) Toolbox, a suite of online conservation planning tools designed to match appropriate conservation practices with suitable locations at regional, watershed, and field scales. This approach aims to enhance the efficiency and impact of water quality improvement efforts. Decision support systems provide actionable recommendations, such as the optimal timing for planting flood-tolerant varieties or implementing drainage solutions. Additionally, these tools can help assess the effectiveness of different flood management strategies and identify best practices for minimizing damage and improving crop resilience.

Conclusion

Flood significantly impacts plant growth and global crop yields, with anticipated increases in crop losses due to climate change-induced alterations in temperature and precipitation. While some plants can adapt to waterlogging through traits like aerenchyma tissue or adventitious roots, not all commercial cultivars possess these traits, leading to potential yield reductions. It also exacerbates nitrogen losses and decreases nutrient uptake and use efficiency. Focus on new breeding approaches for flood tolerance traits in crops is a major concern. Effective management strategies, including the use of mixed seedling cropping system, cover crops, planting dates adjustments, raised beds, subsurface drainage, and precision nitrogen applications, are crucial for mitigating waterlogging stress, but their adoption depends on specific field conditions and existing management practices. Precision agriculture tools, such as crop modelling and decision support systems, can enhance the targeted implementation of these practices by considering local soil and environmental factors. Further research is needed to evaluate the cost-effectiveness of these strategies, ensuring their economic viability and fostering sustainable crop production under flooded conditions. Integrating adaptive management practices tailored to the severity and duration of flooding can significantly improve resilience and productivity in affected agricultural systems.

References

Armstrong, W. (1979). Aeration in higher plants. In H. W. Woolhouse (Ed.), *Advances in botanical research* (225-332). Academic Press.

Bailey-Serres, J., Fukao T., Gibbs D.J., Holdsworth M.J., Lee S.C., Licausi F., Perata P., Voesenek L.A.C.J. and van Dongen J.T. (2012). Making sense of low oxygen sensing. *Trends in Plant Science*, **17(3)**, 129-138.

Bailey-Serres, J. and Voesenek L.A.C.J. (2008). Flooding stress: Acclimations and genetic diversity. *Annual Review of Plant Biology*, **59**, 313-339.

Bakker, D., Hamilton G., Houlbrooke D. and Spann C. (2005). The effect of raised beds on soil structure, waterlogging, and productivity on duplex soils in Western Australia. *Soil Research*, **43(6)**, 575-585. https://doi.org/10.1071/SR03118

Bassu, S., Asseng S., Motzo R. and Giunta F. (2009). Optimising sowing dates of durum wheat in a variable Mediterranean environment. *Field Crops Research*, **111(1-2)**, 109-118. https://doi.org/10.1016/j.fcr.2008.11.002

Bauduceau, N. (2001). *Éléments d'analyse des répercussions des inondations de novembre 1999 sur les activités agricoles des départements de l'Aude, des Pyrénées Orientales et du Tarn*. Technical report, Équipe pluridisciplinaire Plan Loire Grandeur Nature. (in French).

Blanco-Canqui, H., Shaver T.M., Lindquist J.L., Shapiro C.A., Elmore R.W., Francis C.A. and Hergert G.W. (2015). Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal*, **107(6)**, 2449-2474. https://doi.org/10.2134/agronj15.0086

Blessitt, J.B. (2007). *Productivity of raised seedbeds for soybean (Glycine max (L.) Merr.) production on clayey soils of the Mississippi delta* (Doctoral dissertation). Mississippi State University.

Boru, G. and Kronstad W.E. (2003). Oxygen use from solution by wheat genotypes differing in tolerance to waterlogging. *Euphytica*, **132(2)**, 151-158.

Brémond, P., Bauduceau N. and Grelot F. (2008). Characterizing agriculture vulnerability for economic appraisal of flood management policies. In *Proceedings of the 4th International Symposium on Flood Defence: Managing Flood Risk, Reliability and Vulnerability* (263-274). Institute for Catastrophic Loss Reduction, Toronto, Ontario, Canada.

Brémond, P., Grelot F. and Agenais A.L. (2013). Economic evaluation of flood damage to agriculture—Review and analysis of existing methods. *Natural Hazards and Earth System Sciences*, **13(10)**, 2493-2512.

Burgos, M.S., Messmer M.M., Stamp P. and Schmid J.E. (2001a). Flooding tolerance of spelt (*Triticum spelta* L.) compared to wheat (*Triticum aestivum* L.)-A physiological and genetic approach. *Euphytica*, **122(2)**, 287-295.

Burgos, S., Stamp P. and Schmid J.E. (2001b). Agronomic and physiological study of cold and flooding tolerance of spelt (*Triticum spelta* L.) and wheat (*Triticum aestivum* L.). *J. of Agronomy and Crop Science*, **187(3)**, 195-202.

Caudle, K.L. and Maricle B.R. (2012). Effects of flooding on photosynthesis, chlorophyll fluorescence, and oxygen stress in plants of varying flooding tolerance. *Transactions of the Kansas Academy of Science*, **115(1)**, 5-18.

Cheng, Y., Gu M., Cong Y., Zou C.S., Zhang X.K. and Wang H.Z. (2010). Combining ability and genetic effects of germination traits of *Brassica napus* L. under waterlogging stress condition. *Agricultural Sciences in China*, **9(7)**, 951-957.

Colmer, T.D. and Voesenek L.A.C.J. (2009). Flooding tolerance: Suites of plant traits in variable environments. *Functional Plant Biology*, **36(8)**, 665-681.

Coutinho, I.D., Henning L.M.M., Döpp S.A., Nepomuceno A., Moraes L.A.C. and Marcolino-Gomes J. *et al*., (2018). Flooded soybean metabolomic analysis reveals important primary and secondary metabolites involved in the hypoxia stress response and tolerance. *Environmental and Experimental Botany*, **153**, 176-187.

Cox, M.C.H. (2003). Plant movement. Submergence-induced petiole elongation in *Rumex palustris* depends on hyponastic growth. *Plant Physiology*, **132(1)**, 282-291.

Cox, M.C.H., Millenaar F.F., Van Berkel Y.E.M., Peeters A.J.M. and Voesenek L.A.C.J. (2003). Plant movement. Submergence-induced petiole elongation in *Rumex palustris* depends on hyponastic growth. *Plant Physiology,* **132(1)**, 282-291.

Daugherty, C.J. and Musgrave M.E. (1994). Characterization of populations of rapid-cycling *Brassica rapa* L. selected for differential waterlogging tolerance. *Journal of Experimental Botany,* **45(5)**, 385-392.

Davies, M.S. and Hillman G. (1988). Effects of soil flooding on growth and grain yield of populations of tetraploid and hexaploid species of wheat. *Annals of Botany,* **62(6)**, 597-604.

Dawood, T., Rieu I., Wolters-Arts M., Derksen E.B., Mariani C. and Visser E.J.W. (2014). Rapid flooding-induced adventitious root development from preformed primordia in *Solanum dulcamara*. *AoB Plants,* **6**.

Folorunso, O., Rolston D., Prichard T. and Loui D. (1992). Soil surface strength and infiltration rate as affected by winter cover crops. *Soil Technology,* **5(3)**, 189-197. https://doi.org/10.1016/0933-3630(92)90021-R

Fukao, T. and Bailey-Serres J. (2008). Ethylene-a key regulator of submergence responses in rice. *Plant Sci.,* **175(1)**, 43-51.

Gibbs, D.J., Lee S.C., Isa N.M., Gramuglia S., Fukao T., Bassel G.W., Correia C.S., Corbineau F., Theodoulou F.L. and Bailey-Serres J. (2011). Homeostatic response to hypoxia is regulated by the N-end rule pathway in plants. *Nature,* **479(7373)**, 415-418.

Hattori, Y., Nagai K., Furukawa S., Song X.J., Kawano R., Sakakibara H., Wu J., Matsumoto T., Yoshimura A. and Kitano H. *et al*., (2009). The ethylene response factors SNORKEL1 and SNORKEL2 allow rice to adapt to deep water. *Nature,* **460(7258)**, 1026-1030.

Press Information Bureau. (n.d.). Retrieved from https://pib.gov.in/newsite/PrintRelease.aspx?relid=123999

Huang, B. and Johnson J. (1995). Root respiration and carbohydrate status of two wheat genotypes in response to hypoxia. *Annals of Botany,* **75(5)**, 427-432.

Iijima, M., Awala S.K., Watanabe Y., Kawato Y., Fujioka Y., Yamane K. and Wada K.C. (2016). Mixed cropping has the potential to enhance flood tolerance of drought-adapted grain crops. *Journal of Plant Physiology,* **192**, 21-25.

Khan, M.I.R., Trivellini A., Chhillar H., Chopra P., Ferrante A., Khan N.A. and Ismail A.M. (2020). The significance and functions of ethylene in flooding stress tolerance in plants. *Environmental and Experimental Botany,* **179**, 104188.

King, J.A., Dampney P.M.R., Lark R.M., Wheeler H.C., Bradley R.I. and Mayr T.R. (2005). Mapping potential crop management zones within fields: Use of yield-map series and patterns of soil physical properties identified by electromagnetic induction sensing. *Precision Agriculture,* **6(4)**, 167-181. https://doi.org/10.1007/s11119-005-1033-4.

Kotula, L., Schreiber, L., Colmer, T. D., & Nakazono, M. (2017). Anatomical and biochemical characterisation of a barrier to radial O, loss in adventitious roots of two contrasting *Hordeum marinum* accessions. *Functional Plant Biology,* **44(8)**, 845-857.

Kucharik, C.J. (2006). A multidecadal trend of earlier corn planting in the central USA. *Agronomy Journal,* **98(6)**, 1544-1550.

Li, Z., Mei S., Mei Z., Liu X., Fu T., Zhou G. and Tu J. (2014). Mapping of QTL associated with waterlogging tolerance and drought resistance during the seedling stage in oilseed rape (*Brassica napus*). *Euphytica,* **197(3)**, 341-353.

Licausi, F., Kosmacz M., Weits D.A., Giuntoli B., Giorgi F.M., Voesenek L.A.C.J., Perata P. and van Dongen J.T. (2011). Oxygen sensing in plants is mediated by an N-end rule pathway for protein destabilisation. *Nature,* **479(7373)**, 419-422.

Luan, H., Shen H., Pan Y., Guo B., Lv C. and Xu R. (2018). Elucidating the hypoxic stress response in barley (*Hordeum vulgare* L.) during waterlogging: A proteomics approach. *Scientific Reports,* **8**, 9655.

Mano, Y. and Omori F. (2007). Breeding for flooding tolerant maize using "teosinte" as a germplasm resource. *Plant Root,* **1**, 17-21.

McLellan, E.L., Schilling K.E., Wolter C.F., Tomer M.D., Porter S.A., Magner J.A. and Prokopy L.S. (2018). Right practice, right place: A conservation planning toolbox for meeting water quality goals in the Corn Belt. *Journal of Soil and Water Conservation,* **73(2)**, 29A-34A. https://doi.org/10.2489/jswc.73.2.29A

Morris, J. and Brewin P. (2013). The impact of seasonal flooding on agriculture: The spring 2012 floods in Somerset, England. *Journal of Flood Risk Management*. Advance online publication.

Motavalli, P.P., Goyne K.W. and Udawatta R.P. (2008). Environmental impacts of enhanced-efficiency nitrogen fertilizers. *Crop Management*. https://doi.org/10.1094/CM-2008-0730-02-RV

Mustroph, A. (2018). Improving flooding tolerance of crop plants. *Agronomy,* **8(9)**, 160.

Nelson, K.A. (2017). Soybean yield variability of drainage and subirrigation systems in a claypan soil. *Applied Engineering in Agriculture,* **33(6)**, 801-809.

Nelson, K.A., Paniagua S.M. and Motavalli P.P. (2009). Effect of polymer coated urea, irrigation, and drainage on nitrogen utilization and yield of corn in a claypan soil. *Agronomy Journal,* **101(3)**, 681-687.

Nelson, K.A., Scharf P.C., Stevens W.E. and Burdick B.A. (2011a). Rescue nitrogen applications for corn. *Soil Science Society of America Journal,* **75(1)**, 143-151. https://doi.org/10.2136/sssaj2009.0456

Nelson, K., Smoot R. and Meinhardt C. (2011b). Soybean response to drainage and subirrigation on a claypan soil in northeast Missouri. *Agronomy Journal,* **103(5)**, 1216-1222. https://doi.org/10.2134/ agronj2011.006

Paul, A., Sarma H.H., Kakoti M. and Talukdar N. (2023). Waterlogging concerns and its impact on agricultural sustainability. In *Frontiers in Agriculture Sustainability*. **1**, 93-100. Integrated Publications TM.

Pivot, J.M., Josien E. and Martin P. (2002). Farms adaptation to changes in flood risk: A management approach. *Journal of Hydrology*, **267(1-2)**, 12-25.

Posthumus, H., Morris J., Hess T.M., Neville D., Philips E. and Baylis A. (2009). Impacts of the summer 2007 floods on agriculture in England. *Journal of Flood Risk Management*, **2(3)**, 182-189.

Qui, J. and Ke Y. (1991). Study on determination of wet tolerance of 4572 barley germplasm resources. *Acta Agriculturae Shanghai*, **7**, 27-32.

Rhine, M.D., Stevens G., Shannon G., Wrather A. and Sleper D. (2010). Yield and nutritional responses to waterlogging of soybean cultivars. *Irrigation Science*, **28(2)**, 135-142.

Sarma, H.H. and Kakoti M. (2024). Significance of weather forecasting in crop production with respect to Indian scenario. *Vigyan Varta*, **5(7)**, 95-102.

Sarma, H.H., Das B.C., Deka T., Rahman S., Medhi M. and Kakoti M. (2024). Data-driven agriculture: Software innovations for enhanced soil health, crop nutrients, disease detection, weather forecasting, and fertilizer optimization in agriculture. *Journal of Advances in Biology & Biotechnology*, **27(8)**, 878-896.

Sarma, H.H., Paul A., Kakoti M., Talukdar N. and Hazarika P. (2024). Climate resilient agricultural strategies for enhanced sustainability and food security: A review. *Plant Archives*, **24(1)**, 787-792.

Sarma, H.H., Paul A., Kakoti M., Talukdar N. and Hazarika P. (2024). Climate resilient agricultural strategies for enhanced sustainability and food security: A review. *Plant Archives*, **24(1)**, 787-792.

Sarma, H.H., Borah S.K., Chintey R., Nath H. and Talukdar N. (2024). Site specific nutrient management (SSNM): Principles, key features and its potential role in soil, crop ecosystem and climate resilience farming. *Journal of Advances in Biology & Biotechnology*, **27(8)**, 211-222.

Sayama, T., Nakazaki T., Ishikawa G., Yagasaki K., Yamada N., Hirota N., Hirata K., Yoshikawa T., Saito H. and Teraishi M. *et al.*, (2009). QTL analysis of seed-flooding tolerance in soybean (*Glycine max* [L.] Merr.). *Plant Science*, **176(4)**, 514-521.

Sayre, K., van Ginkel M., Rajaram S. and Ortiz-Monasterio I. (1994). Tolerance to water-logging losses in spring bread wheat: Effect of time of onset on expression. *Annual Wheat Newsletter*, **40**, 165-171.

Setter, T.L. and Waters I. (2003). Review of prospects for germplasm improvement for waterlogging tolerance in wheat, barley, and oats. *Plant and Soil*, **253(1)**, 1-34.

Shimamura, S., Yamamoto R., Nakamura T., Shimada S. and Komatsu S. (2010). Stem hypertrophic lenticels and secondary aerenchyma enable oxygen transport to roots of soybean in flooded soil. *Annals of Botany*, **106(2)**, 277-284.

Singh, S.P. and Setter T.L. (2017). Effect of waterlogging on element concentrations, growth and yield of wheat varieties under farmer's sodic field conditions. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, **87(4)**, 513-520.

Soltani, A., MafiMoghaddam S., Oladzad-Abbasabadi A., Walter K., Kearns P.J., Vasquez-Guzman J., Mamidi S., Lee R., Shade A.L., Jacobs J.L. *et al.*, (2018). Genetic analysis of flooding tolerance in an Andean diversity panel of dry bean (*Phaseolus vulgaris* L.). *Frontiers in Plant Science*, **9**, 767.

Sundgren, T.K., Uhlen A.K., Waalen W. and Lillemo M. (2018). Field screening of waterlogging tolerance in spring wheat and spring barley. *Agronomy*, **8(1)**, 38.

van Dongen, J.T. and Licausi F. (2015). Oxygen sensing and signaling. *Annual Review of Plant Biology*, **66**, 345-367.

Van Ginkel, M., Rajaram S. and Thijssen M. (1991). Waterlogging in wheat: Germplasm evaluation and methodology development. In *Proceedings of the Seventh Regional Wheat Workshop for Eastern, Central and Southern Africa* (115-124). Nakuru, Kenya.

VanToai, T.T., St. Martin S.K., Chase K., Boru G., Schnipke V., Schmitthenner A.F. and Lark K.G. (2001). Identification of a QTL associated with tolerance of soybean to soil waterlogging. *Crop Science*, **41(4)**, 1247-1252.

Velmurugan, A., Swarnam T., Ambast S. and Kumar N. (2016). Managing waterlogging and soil salinity with a permanent raised bed and furrow system in coastal lowlands of humid tropics. *Agricultural Water Management*, **168**, 56-67.

Voesenek, L.A.C.J. and Sasidharan R. (2013). Ethylene- and oxygen signaling drive plant survival during flooding. *Plant Biology*, **15(3)**, 426-435.

Wu, Y.S. and Yang C.Y. (2016). Physiological responses and expression profile of NADPH oxidase in rice (*Oryza sativa*) seedlings under different levels of submergence. *Rice*, **9**, 1.

Yamauchi, T., Colmer T.D., Pedersen O. and Nakazono M. (2018). Regulation of root traits for internal aeration and tolerance to soil waterlogging-flooding stress. *Plant Physiology*, **176(2)**, 1118-1130.

Yijun, G., Zhiming X., Jianing G., Qian Z., Rasheed A., Hussain M.I. and Jian W. (2022). The intervention of classical and molecular breeding approaches to enhance flooding stress tolerance in soybean: A review. *Frontiers in Plant Science*, **13**, 1085368.

Zarembinski, T.I. and Theologis A. (1997). Expression characteristics of OS-ACS1 and OS-ACS2, two members of the 1-aminocyclopropane-1-carboxylate synthase gene family in rice (*Oryza sativa* L. Cv. Habiganj Aman II) during partial submergence. *Plant Molecular Biology*, **33(1)**, 71-77.

Zhang, X., Shabala S., Koutoulis A., Shabala L. and Zhou M. (2017). Meta-analysis of major QTL for abiotic stress tolerance in barley and implications for barley breeding. *Planta*, **245(2)**, 283-295.

Zhou, Z., Engler J.A., Rouan D., Michiels F., van Montagu M. and van der Straeten D. (2002). Tissue localization of a submergence-induced 1-aminocyclopropane-1-carboxylic acid synthase in rice. *Plant Physiology*, **129(1)**, 72-84.