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Waterlogging Stress in Ornamental Plants, Effects, Tolerance Mechanisms: A review

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Abstract

In recent years, the frequency and severity of floods have increased due to global warming associated with climate change. Flooding is a significant abiotic stress factor that directly affects plant growth, development, and survival, and it has considerable impacts on biodiversity. In agriculture, research on flooding stress has primarily focused on crops with high strategic importance. However, in ornamental plants, the amount of research remains limited. Flooding induces substantial morphological and physiological changes in plants, depending on the species, the duration of inundation, and the prevailing environmental conditions. The main objectives of this review are to examine the effects of flooding stress on ornamental plants and to highlight the morphological, physiological, biochemical, genetic, and molecular mechanisms involved in flood tolerance.

In recent years, several strategies have been explored to mitigate the adverse effects of flooding on plants. These include the selection of tolerant species and cultivars, nutrient supplementation, hormone treatments, and the application of biostimulants. Such mechanisms support plant survival by enhancing oxygen uptake, reducing toxic metabolite accumulation, and maintaining energy production under hypoxic conditions.

The findings of current studies are crucial for developing strategies to manage flood-induced stress, guiding the selection of suitable ornamental plants for flood-prone landscape areas, promoting sustainable landscape designs, and minimizing economic losses in the ornamental horticulture sector. Furthermore, it is essential for ornamental plant breeding programs to focus on the development of waterlogging-tolerant cultivars.

Key Words: Water flooding, abiotic stress, species selection, landscape

Süs Bitkilerinde Su Baskını Stresi, Etkileri, Tolerans Mekanizmaları: Bir inceleme

Özet

Son yıllarda iklim değişikliğinin neden olduğu küresel ısınma ile birlikte su baskınlarının sıklığı ve şiddeti de gittikçe artmaktadır. Su baskını, bitkilerin büyümesi, gelişimi ve hayatta kalmasını doğrudan etkileyen, biyoçeşitlilik üzerinde önemli etkiye sahip olan abiyotik stres faktörlerinden birisidir. Tarımda bu konuda yapılan araştırmalar daha çok stratejik değeri yüksek bitkiler üzerinde yoğunlaşmıştır. Süs bitkilerinde ise daha sınırlı sayıda araştırma mevcuttur. Su baskını bitkinin türüne, su altında kalma süresine ve çevresel koşullara bağlı olarak önemli morfolojik ve fizyolojik değişimlere neden olmaktadır. Bu incelemenin temel amaçları, su baskını stresinin süs bitkilerindeki etkilerini ortaya koyarak morfolojik, fizyolojik, biyokimyasal, genetik ve moleküler tolerans mekanizmalarını ele almaktır. Sel baskını stresinin bitkilerdeki olumsuz etkisini azaltmak için son yıllarda bazı uygulamalar üzerine yoğunlaşmıştır. Tolerant tür ve çeşit seçimi, bazı besin elementi uygulamaları, hormon ve biyostimulant uygulamaları bunlardan bazılarıdır. Bu mekanizmalar, bitkinin oksijen alımını artırarak, toksik birikimini önleyerek ve enerji üretimini sürdürerek hayatta kalmasını sağlar. Yapılan çalışmalar, sel kaynaklı stresi azaltmaya yönelik stratejilerin geliştirilmesi, sele meyilli peyzaj alanlarında süs bitkilerinin seçimine ilişkin değerli bilgilerin sağlanması, sürdürülebilir peyzaj tasarımlarının geliştirilerek süs bitkileri sektöründeki ekonomik kayıpların azaltılabilmesi bakımından önemlidir. Süs bitkileri yetiştiricileri için de su basmasına dayanıklı çeşitlerin geliştirilmesi gereklidir.

Anahtar Kelimeler: Su taşkını, abiotic stress, tür seçimi, peyzaj

Introduction

Waterlogging (flooding) is caused by environmental factors such as heavy rainfall, river overflow, storms, over-irrigation, poor soil drainage, and low soil permeability (Figure 1) (Manghwar et al., 2024). It has become increasingly common in many parts of the world due to global climate change and rapid urbanization (Pan et al., 2025). According to recent data, areas affected by flooding cover approximately 13% of the Earth's surface (Sangiorgio et al., 2020). In 2016, a total of \$217 million was spent on flood damage and control in the United States—3.4 times more than the costs associated with droughts (Jia et al., 2021). This trend has had a significant impact on urban ecosystems. In response, sponge city models—an innovative approach to mitigating waterlogging—have been adopted in many countries around the world in recent years (Pan et al., 2025). Examples



include Low Impact Development (LID) in the United States, Sustainable Urban Drainage Systems (SUDS) in France, and Water Sensitive Urban Design (WSUD) in Australia (Ning et al., 2017).

Waterlogging is one of the most critical abiotic stress factors that negatively affect plant growth and development. Flood stress manifests in two primary forms: complete submergence of the plant (both root and shoot), leading to anoxia, and partial submergence affecting only the root zone, resulting in hypoxia (Zhao et al., 2018). This stress directly impacts plant metabolism and survival, causing significant physiological, morphological, and biochemical changes. The extent and nature of these changes depend on the plant species, the duration of inundation, and environmental conditions. Plants develop various resistance mechanisms under waterlogging stress, and understanding these mechanisms is essential for selecting flood-tolerant species and guiding genetic improvement studies (Pan et al., 2025).

Research in this area has largely concentrated on agricultural crops that are vital for human nutrition and health. In contrast, studies focusing on ornamental plants remain limited. Waterlogging stress can severely affect the morphology of leaves, flowers, and stems in ornamental species, thereby reducing their aesthetic and commercial value.

Increasing research on this topic may contribute to the development of flood-tolerant ornamental plants, offering practical solutions for waterlogging problems encountered in landscape design and urban green space planning. This review discusses the morphological, physiological, and biochemical effects of waterlogging on plant growth, yield, and quality, as well as the adaptive mechanisms plants employ in response to this stress.



Fig 1. Causes of waterlogging

A. Physiological, Morphological and Biochemical Effects of Waterlogging on Plant Growth and Development

A.1. Physiological Changes

The earliest physiological response of plants to water accumulation in the soil is stomatal closure.

A.1.1. Stomatal Closure

Under waterlogging conditions, plants perceive the stress signal and respond by closing their stomata to minimize water loss from the leaves. However, this adaptive response also limits carbon dioxide uptake, thereby reducing photosynthesis and negatively affecting plant growth (Ashraf, 2012; Yin et al., 2012; Zhang et al., 2024).

A.1.2. Decrease in Photosynthetic Capacity

When air-filled pores in the soil are occupied by water, gaseous exchange becomes restricted. Oxygen and other essential gases diffuse slowly through water-saturated soils, limiting their availability to both plant roots and soil microorganisms. This impaired gas exchange reduces the plant's photosynthetic efficiency (Sharma et al., 2021; Zhang et al., 2024; Pan et al., 2025).

A.1.3. Oxygen Deficiency (Hypoxia and Anoxia)

During waterlogging, plant roots experience oxygen deficiency. This inhibits aerobic respiration and shifts energy metabolism toward less efficient anaerobic pathways, leading to decreased ATP production. Fermentation processes increase, resulting in the accumulation of byproducts such as CO₂, methane, and volatile fatty acids in the rhizosphere. Additionally, high temperatures can accelerate oxygen depletion in saturated soils (Yavaş et al., 2011; Lindsey et al., 2024). In general, oxygen levels in waterlogged soils fall below critical thresholds for plant growth within approximately 45 to 96 hours (Özcan, 2020).

A.1.4. Decrease in Nutrient Uptake

Under waterlogging conditions, even in tolerant plant species, growth rate, nutrient uptake, and the root-to-shoot ratio are significantly reduced. Oxygen deficiency in the root zone disrupts ion balance by decreasing the uptake of potassium (K⁺) relative to sodium (Na⁺), and impairs the transport of K⁺ to aerial plant parts. Research has shown that the adverse effects of waterlogging are not primarily due to the toxic accumulation of Na⁺ or Fe²⁺, but



rather to reduced concentrations of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). Denitrification and nutrient leaching are key processes that decrease soil nitrogen availability under anaerobic conditions. Denitrification refers to the microbial conversion of nitrite (NO_2^-) or nitrate (NO_3^-) into gaseous nitrogen (N_2) compounds, which are released into the atmosphere, thereby leading to nitrogen deficiency in the soil. In response to nutrient scarcity, plants may remobilize internal nutrient reserves by degrading chlorophyll (Chl), which can impair chlorophyll biosynthesis. This disruption promotes the generation of reactive oxygen species (ROS), ultimately resulting in oxidative damage and cell death (Kudoh and Sonoike, 2002; Yavaş et al., 2011; Ashraf, 2012; Akhtar and Nazir, 2013). Soil pH generally increases during waterlogging, primarily due to the dissolution of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) compounds. In saline soils, this condition can exacerbate salt stress, often leading to rapid plant death under prolonged water accumulation (Yavaş et al., 2011; Panda and Barik, 2021).

A.2. Morphological Changes

A.2.1. Root Rot

In the absence of oxygen, root growth is restricted, and processes such as root elongation, thickening, and lateral root formation are either slowed or completely inhibited. Oxygen deficiency leads to the accumulation of toxic compounds such as ethanol and acetaldehyde, as well as mineral ions like nitrites and ferrous ions in root tissues (Sharma et al., 2021; Liu et al., 2021; Pan et al., 2025). These accumulations can cause root cell death and initiate tissue decay processes (Pan et al., 2025). The resulting damage impairs the plant's ability to absorb water and nutrients, ultimately leading to plant death. Under saline conditions, waterlogging further exacerbates stress by inhibiting the root's ability to exclude salts. This leads to excessive salt uptake and accumulation in the shoots, intensifying toxicity and physiological damage. Waterlogging responses and subsequent recovery strategies in *Paeonia* species are illustrated in Figure 2 (Zhou et al., 2024).

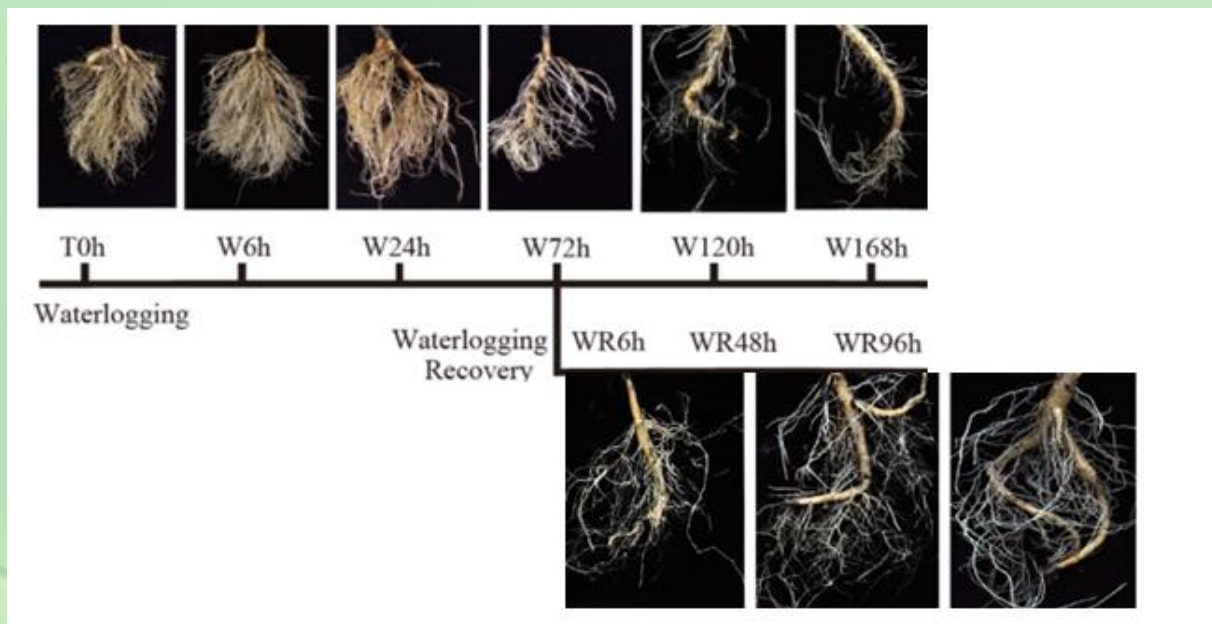


Fig 2. Waterlogging and recovery application in peony plants (Zhou et al., 2024-changed)

A.2.2. Growth Retardation and Decrease of Flowering

Under prolonged flooding conditions, the above-ground parts of plants are also adversely affected. Stem thickening, growth inhibition, or excessive elongation may occur as physiological responses to stress (Pan et al., 2025). In a study on narrow-leaved zinnia (*Zinnia angustifolia*), plants exposed to flooding exhibited significantly reduced height compared to the control plants; however, they retained a high ornamental value. Such morphological responses may represent an adaptive mechanism to reduce flooding-induced damage (Yang et al., 2020). Flooding stress also impacts reproductive development. Flowering may be delayed, reduced, or completely suppressed as the plant prioritizes energy conservation over reproduction (Butsayawarabat et al., 2019; Jacob and Sumiya, 2022).

A.2.3. Leaf Yellowing and Dropping

Due to chlorophyll degradation, plants subjected to waterlogging often exhibit visible symptoms such as yellowing, wilting, and leaf curling. In addition, increased ethylene production under stress conditions may lead to premature leaf abscission and inhibit the formation of new leaves (Zhao et al., 2018; Zhang et al., 2023).

In chrysanthemum (*Chrysanthemum morifolium*), prolonged exposure to waterlogged conditions significantly increased the thickness of palisade and spongy parenchyma layers (Yin et al., 2012). However, in *Celosia spp.* and



Amaranthus spp.—commonly referred to as medallion flowers—leaf thickness was found to decrease under water-saturated conditions (Yang et al., 2020). Short-term waterlogging did not significantly affect the plant height, leaf length, or leaf area of the herbaceous peony (*Paeonia lactiflora*), but it did significantly reduce the root-to-shoot ratio (Liu et al., 2021).

A.3. Biochemical Changes

A.3.1. Increase in Reactive Oxygen Species (ROS)

Under waterlogging stress, oxygen deficiency leads to elevated levels of reactive oxygen species (ROS), which disrupt various cellular metabolic processes in plants. Molecular oxygen is gradually reduced within the cell, resulting in the formation of different types of ROS. These include singlet oxygen (1O_2), superoxide anion (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radical ($OH\cdot$). Under normal physiological conditions, the concentrations of these reactive species are tightly regulated and remain at low levels (Büyük et al., 2012).

ROS are produced in plants even under non-stress conditions; however, their accumulation is limited by enzymatic and non-enzymatic antioxidant defense systems that maintain cellular redox homeostasis. Under stress conditions such as waterlogging, the efficiency of these antioxidant systems declines, thereby promoting ROS overproduction and leading to their accumulation within plant tissues (Yin et al., 2009; Ashraf, 2012).

A.3.2. Increase in Lipid Peroxidation

Lipid peroxidation in plants is promoted by reactive oxygen species (ROS), leading to elevated levels of oxidative damage. Increased lipid peroxidation compromises cell membrane integrity, impairs photosynthetic activity, and reduces overall stress tolerance. One of the key byproducts of lipid peroxidation, malondialdehyde (MDA), can bind to proteins and DNA, thereby disrupting their structural and functional integrity (Liu et al., 2021). Zhou et al. (2019) reported that, under waterlogging conditions, leaf pigment content decreased in all tested poplar cultivars, while the levels of MDA and proline (Pro) increased. Similarly, in a comparative study of flood-susceptible and flood-tolerant chrysanthemum cultivars, MDA content was significantly higher in the susceptible cultivar, whereas it remained relatively stable in the tolerant one (Yin et al., 2009). Elevated MDA levels are considered indicative of weaker antioxidant defense systems and higher oxidative stress (Zhang et al., 2019).

A.3.3. Protein Oxidation and Impairment of Enzyme Activity

Protein oxidation occurs as a result of damage caused by reactive oxygen species (ROS), such as superoxide anion (O_2^-) and hydrogen peroxide (H_2O_2), which alter the structure and function of proteins. This oxidative damage impairs enzymatic activity, thereby disrupting key biochemical reactions. When photosynthetic enzymes are affected, energy production through photosynthesis is significantly reduced.

Under conditions of severe oxidative stress, the accumulation of oxidized or misfolded proteins can trigger the activation of programmed cell death (PCD) pathways, ultimately leading to plant cell death (Manghwar et al., 2024; Pan et al., 2025).

A.4. Hormonal Changes

Ethylene is a phytohormone that promotes plant growth at low concentrations. Under stress conditions, ethylene levels generally increase due to the accumulation of 1-aminocyclopropane-1-carboxylic acid (ACC), a key precursor in the ethylene biosynthetic pathway. ACC accumulation is thought to negatively affect plant growth, particularly by inhibiting root development (Nadaem et al., 2014). Elevated ethylene production can lead to premature leaf abscission and contribute to root damage under hypoxic stress.

In a study conducted on two waterlogging-tolerant *Chrysanthemum* (syn. *Dendranthema spp.*) cultivars, ethylene was reported to accelerate the onset of programmed cell death (PCD) under waterlogged conditions (Yin et al., 2013). Waterlogging also elevates abscisic acid (ABA) levels, which induces stomatal closure to minimize transpirational water loss (Akhtar and Nazir, 2013). Conversely, the levels of growth-promoting hormones such as gibberellic acid (GA_3) and cytokinins are typically reduced under waterlogged conditions (Sanghera and Jamwal, 2019).

B. Mechanisms of Plant Resistance to Waterlogging

The ability of plants to survive waterlogging is associated with their developed resistance to the stress factor, which consists of morphological, physiological, biochemical, genetic, and molecular tolerance mechanisms (Figure 3).

B.1. Morphological and Anatomical Adaptation

Morphological and anatomical adaptations developed by plants in response to waterlogging include the formation of aerenchyma tissue, adventitious root development, internode elongation, gas film formation, and the development of radial oxygen loss (ROL) barriers. These adaptations help reduce oxygen demand and improve gas exchange under hypoxic conditions.

B.1.1. Elongation of Apical Meristems



Rapid internode elongation is a key adaptation to waterlogging, enabling plants to escape the anoxic zone by reaching above the water surface and restoring access to atmospheric oxygen for aerobic respiration (Pan et al., 2021).

B.1.2. Formation of Aerenchyma

Under waterlogged conditions, some plants develop specialized air-filled tissues called aerenchyma in their roots and stems to facilitate internal oxygen transport (Akhtar and Nazir, 2013; Zhang et al., 2023; Pan et al., 2025). Aerenchyma channels deliver oxygen to the root system while simultaneously allowing the removal of CO₂ and toxic metabolites from water-saturated tissues (Pan et al., 2021).

B.1.3. Adventitious Root Growth

Plants exposed to flooding often form adventitious roots along the stem to enhance oxygen uptake. This response is especially prominent in aquatic and semi-aquatic species and helps compensate for impaired function of the primary root system (Ashraf, 2012; Pan et al., 2025). The formation of adventitious roots is influenced by factors such as water depth, oxygen availability, light penetration, and dissolved CO₂ concentration (Sharma et al., 2021).

B.1.4. Gas Film Formation

In certain aquatic or semi-aquatic plants, a thin gas film forms on the leaf surface under submerged conditions (Figure 4). This gas film facilitates more efficient gas exchange between the plant and its environment, thereby supporting continued aerobic respiration and photosynthesis (Pan et al., 2021).

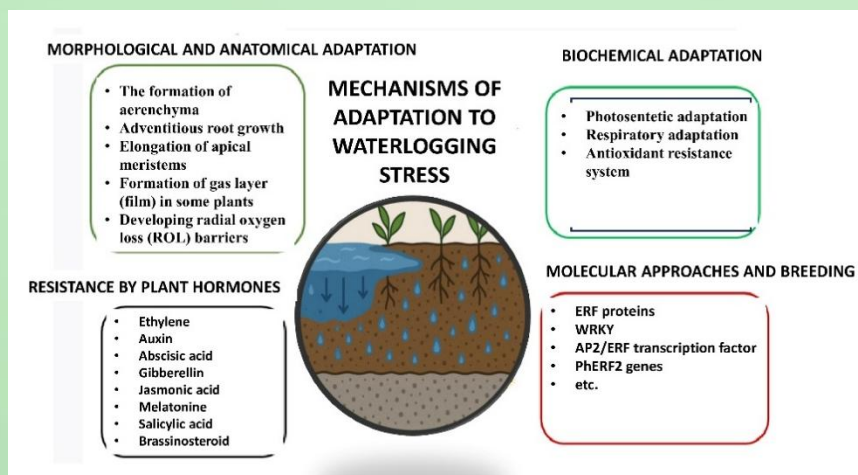


Fig 3. Mechanisms of resistance developed by plants against waterlogging stress

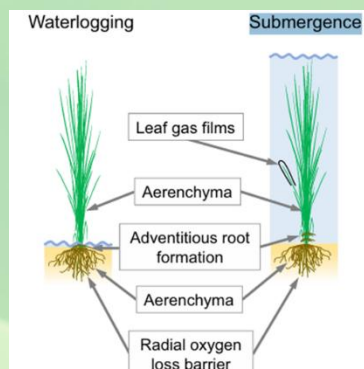


Fig 4. Gas film formation in submergence plants (Kuroha and Ashikari, 2020)

B.1.5. Developing radial oxygen loss (ROL) barriers

Oxygen produced in the leaves—the primary site of photosynthesis—is transported to the roots via specialized air-filled tissues known as **aerenchyma**. Upon reaching the root tip or other root zones, this oxygen can diffuse radially from the root into the surrounding environment. This process, termed **radial oxygen loss (ROL)**, occurs especially in hypoxic or anoxic soils where oxygen is scarce.

ROL can offer several physiological benefits. It creates an oxygenated zone around the root surface, which reduces the toxicity of harmful substances such as reduced sulfur compounds (e.g., hydrogen sulfide) and supports the survival of beneficial aerobic microorganisms (Figure 5). However, when significant amounts of oxygen are lost to the environment before reaching the root tip, it can result in oxygen deficiency at the root apex, thereby limiting root growth. To mitigate this, some plant species develop a physical barrier composed of substances like **suberin**



or **lignin** within the outer layers of the root. This barrier restricts radial oxygen leakage, allowing more oxygen to reach the root tip and enhancing root survival and growth under flooded conditions (Pan et al., 2021).

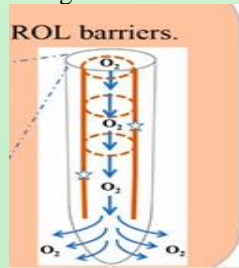


Fig 5. Radial O₂ loss (ROL) (Jia et al., 2021).

B.2. Biochemical Adaptation

Biochemical adaptations under waterlogging stress include the activation of protective enzymes that detoxify harmful substances and support essential metabolic functions, enabling plant survival in oxygen-deprived environments.

B.2.1. Photosynthetic Adaptation

Photosynthetic adaptation refers to the plant's ability to adjust its photosynthetic processes in response to environmental variables such as light intensity, water availability, temperature, and CO₂ concentration. These adaptations help plants maintain energy production under stress conditions.

Photosynthetic pigments—chlorophyll a, chlorophyll b, total chlorophyll (a+b), and carotenoids—play a crucial role in light absorption, and changes in their concentrations directly influence photosynthetic efficiency. The enzyme **Rubisco** (*ribulose-1,5-bisphosphate carboxylase/oxygenase*) is central to the carbon fixation process in photosynthesis. Under flooding conditions, Rubisco activity typically declines, impairing photosynthetic performance. Therefore, maintaining or enhancing Rubisco activity is essential for sustaining carbon assimilation during waterlogging (Pan et al., 2021).

B.2.2. Respiratory Adaptation

Under waterlogging stress, reduced oxygen availability inhibits mitochondrial respiration and leads to a significant decline in adenosine triphosphate (ATP) production. To compensate, plants increase anaerobic metabolic pathways such as glycolysis and ethanol fermentation to meet the minimal ATP requirements for cellular maintenance. In the absence of oxygen, the activities of enzymes such as pyruvate decarboxylase (PDC), alcohol dehydrogenase (ADH), and lactate dehydrogenase (LDH) are upregulated to support continued ATP synthesis. PDC catalyzes the initial step in fermentation, converting pyruvate into acetaldehyde, which is then further processed to ethanol by ADH. It converts pyruvate into acetaldehyde. Afterwards Alcohol dehydrogenase (ADH) then converts acetaldehyde to ethanol (Pyruvate $\xrightarrow{\text{PDC}}$ Acetaldehyde $\xrightarrow{\text{ADH}}$ Ethanol) (Figure 6). This conversion regenerates NAD⁺, allowing glycolysis to proceed under anaerobic conditions and enabling the cell to continue producing limited amounts of ATP (Pan et al., 2021). While aerobic respiration yields approximately 36 ATP molecules per one molecule of glucose, only 2 ATP molecules are generated through anaerobic fermentation pathways. Despite this low energy yield, it is crucial for maintaining essential metabolic functions and ensuring the short-term survival of the plant under waterlogged conditions (Lamsfus-Prieto et al., 2016; Aslam et al., 2023).

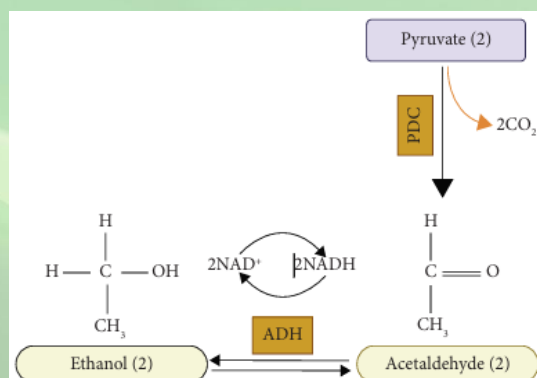


Fig 6. Metabolic pathway of ethanol metabolism in waterlogging (PDC: pyruvate decarboxylase; ADH: alcohol dehydrogenase) (Ali et al., 2023).

B.2.3. Antioxidant Resistance System

Under waterlogging stress, plants activate their antioxidant defense system to prevent cellular damage caused by the accumulation of reactive oxygen species (ROS). This system comprises both enzymatic and non-enzymatic components. Enzymatic antioxidants include superoxide dismutase (SOD), catalase (CAT), peroxidase (POD),



ascorbate peroxidase (APX), dehydroascorbate reductase (DHAR), monodehydroascorbate reductase (MDHAR), and glutathione reductase (GR). Non-enzymatic antioxidants consist of ascorbic acid (AA), glutathione (GSH), tocopherols (lipid-soluble), and carotenoids (Figure 7) (Manghwar et al., 2024). In addition, plants accumulate osmoprotectants such as proline, soluble sugars, free amino acids, and soluble proteins to counteract the toxic effects of waterlogging (Aslam et al., 2023). Yin et al. (2009) compared the physiological and biochemical responses of flood-tolerant and flood-sensitive *Chrysanthemum* cultivars under waterlogging stress. They reported that the activities of alcohol dehydrogenase (ADH), pyruvate decarboxylase (PDC), and lactate dehydrogenase (LDH) increased in both cultivars, with a greater increase observed in the flood-sensitive one. In contrast, the activities of SOD, APX, and POD were significantly higher in the flood-tolerant cultivar, indicating a more effective antioxidant defense system.

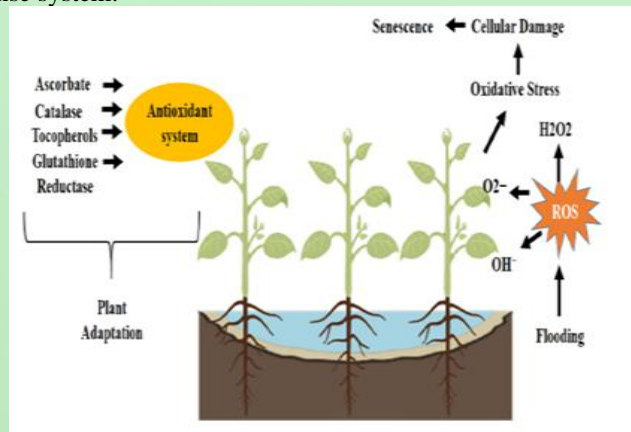


Fig 7. Reactive oxygen species (ROS) production and antioxidant enzyme activity under waterlogging conditions (Nasrullah Ali et al., 2022).

B.3. Resistance Mechanism Induced by Plant Hormones or Biostimulants

Plant hormones, which play key roles in growth and development, also contribute significantly to waterlogging tolerance. A schematic representation of the effects of plant growth regulators under waterlogging conditions is provided in Figure 8.

Ethylene accumulates under waterlogging stress but also regulates several physiological processes that facilitate adaptation. For instance, its interaction with auxin (IAA) promotes the formation of adventitious roots (ARs) (Aslam et al., 2023). Although waterlogging leads to substantial carbohydrate consumption and energy deficiency, light-supported photosynthesis continues to supply sugars that assist auxin transport and AR formation in the hypocotyl (Pan et al., 2021). Furthermore, ethylene interacts with gibberellin (GA₃) to stimulate stem elongation in wetland species (Pan et al., 2025). In a study on different soybean genotypes, GA content was found to be higher in waterlogging-tolerant lines compared to sensitive ones (Pan et al., 2021).

Abscisic acid (ABA) levels increase under waterlogging, activating the antioxidant defense system and inducing stomatal closure. This helps reduce oxidative damage, delay senescence, and enhance waterlogging tolerance. However, in plants exposed to prolonged submergence, ABA levels tend to decrease due to elevated gibberellin activity (Pan et al., 2021).

Although research on melatonin and flood stress is still limited, existing studies indicate that melatonin can enhance tolerance by stimulating antioxidant enzyme activity, reducing ROS levels, and supporting normal growth (Huo et al., 2022). Melatonin application has also been shown to mitigate the effects of anaerobic respiration and reduce MDA and ROS-induced chlorosis (Pan et al., 2021).

Brassinosteroids (BRs) are plant-derived steroids that enhance tolerance to waterlogging by promoting the translocation of carbohydrates from leaves to roots, increasing antioxidant enzyme activity, and reducing ROS production (Pan et al., 2021).

Salicylic acid (SA), a common phenolic compound, enhances plant adaptation to stress by modulating antioxidant pathways (Pan et al., 2021). These hormones reduce ROS accumulation, regulate proline levels, and improve stress tolerance (Hasanuzzaman et al., 2022).

Jasmonic acid (JA) is another growth regulator; however, its role in waterlogging tolerance is less well understood. In a study conducted on soybean, JA application improved flood tolerance by increasing phenolic compounds, flavonoids, and sugar content (Manghwar et al., 2024).



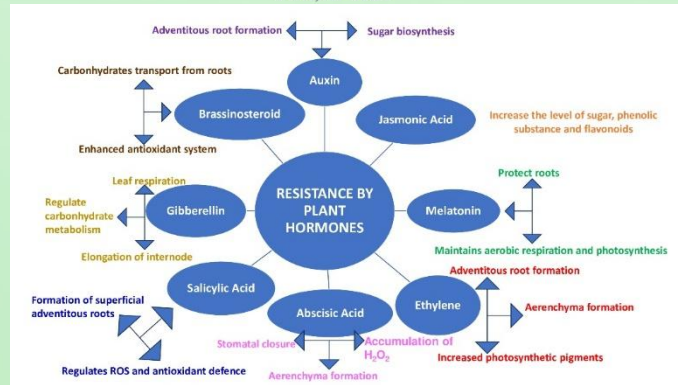


Fig 8. Schematic representation of hormonal resistance mechanisms in plants against waterlogging stress (Manghwar et al., 2024- changed)

B.4.Molecular approaches and breeding

In recent years, molecular techniques have increasingly been employed to assess plant tolerance to abiotic stress factors. The identification of novel genes and proteins is crucial for understanding plant responses to waterlogging stress (Manghwar et al., 2024). Genes associated with flood tolerance can be utilized in genetic modification, gene silencing, and overexpression strategies, thereby forming the basis for molecular breeding programs aimed at improving flood tolerance in horticultural crops (Pan et al., 2025).

Numerous studies have demonstrated that various genes exhibit significant responses to waterlogging stress. For instance, ethylene response factor (ERF) proteins play a critical role in regulating plant responses to environmental stresses. Additionally, the WRKY transcription factor family, one of the largest families in plants, has been shown to be involved in both biotic and abiotic stress responses.

Although chrysanthemum (*Chrysanthemum spp.*) is one of the most economically important ornamental plants, it is relatively sensitive to waterlogging. As a result, it has become one of the most extensively studied ornamental species with regard to flooding tolerance. Several transcription factors and genes, particularly from the AP2/ERF family, have been implicated in waterlogging response pathways in chrysanthemum. In another genetic study, the SOS1 gene was shown to enhance waterlogging tolerance in chrysanthemum (Manghwar et al., 2024).

Furthermore, Su et al. identified single nucleotide polymorphism (SNP) loci associated with waterlogging tolerance in chrysanthemum and developed derived cleaved amplified polymorphic sequences (dCAPS) markers based on PCR technology for SNP detection (Pan et al., 2025).

In petunia, plants carrying the PhERF2 gene demonstrated increased flooding tolerance and faster recovery following submergence (Yin et al., 2019). Other ornamental species that have been investigated for their waterlogging tolerance mechanisms include *Prunus cerasifera*, *Populus spp.*, *Iris pseudacorus*, *Begonia spp.*, and *Tropaeolum majus* (Pan et al., 2025).

There is a great need to develop flood-tolerant plant varieties, especially in the face of increasing instances of waterlogging stress (Sharma et al., 2021). Recent advances include the development of two double haploid line (DHL) populations through crosses between submergence-tolerant and submergence-sensitive rice cultivars (Ahmad et al., 2013). These DHL populations offer valuable genetic material for identifying loci associated with flood tolerance and accelerating breeding efforts through molecular and classical selection approaches.

C. Researches on Ornamental Plants Against Waterlogging and Applications in Urban Landscape

Flood stress primarily affects landscape plants by reducing their ornamental value. Pan et al. (2025) identified 50 flood-tolerant plant species with high ornamental potential, including 27 herbaceous plants (*Alternanthera philoxeroides*, *Hedychium coronarium*, *Hydrocotyle verticillata*, *Ophiopogon bodinieri*, *Dianella ensifolia*, *Phormium tenax*, *Zinnia angustifolia*, *Echeveria cuspidata*, *Cladium mariscus*, *Carex secta*, *Schenoplectus scirpoides*, *Melilotus sulcatus*, *Melilotus indicus*, *Sesbania virgata*, *Iris tectorum*, *Stachys byzantina*, *Salvia officinalis*, *Thamnochortus insignis*, *Scirpus tabernaemontani*, *Angelonia salicariifolia*, *Zizania latifolia*, *Phragmites mauritianus*, *Fimbristylis sinensis*, *Elymus nutans*, *Typha orientalis*, *Canna spp.*, *Alpinia zerumbet*), 7 shrubs (*Ruellia brittoniana*, *Calotropis procera*, *Cistus creticus*, *Jatropha curcas*, *Pteris ensiformis*, *Lavandula angustifolia*, *Myricaria laxiflora*), and 15 tree species (*Alnus spp.*, *Casuarina obesa*, *Leucaena leucocephala*, *Dalbergia odorifera*, *Acacia auriculiformis*, *Dalbergia sissoo*, *Pterocarya stenoptera*, *Ficus altissima*, *Eucalyptus camaldulensis*, *Cleistocalyx operculatus*, *Prunus padus*, *Prunus cerasus*, *Populus alba*, *Populus deltoides*, *Tamarix chinensis*).

Yang et al. (2020) applied 10 days of waterlogging followed by 7 days of recovery to *Zinnia angustifolia*, *Angelonia salicariifolia*, *Celosia argentea*, and *Melampodium paludosum*. The effects of control and waterlogging treatments on these species are illustrated in Figure 9.





Fig 9. Effects of waterlogging on the performances of *Angelonia salicaliifolia*, *Zinnia angustifolia*, *Celosia argentea* and *Melampodium paludosum* plants. CK: Control WL: Well irrigated condition (60% soil moisture) (Yang et al., 2020).

Plants were subjected to 36 days of waterlogging followed by 12 days of recovery in a study comparing waterlogging-tolerant (*Sedum spectabile* ‘Carl’) and waterlogging-sensitive (*Sedum spectabile* ‘Rosenteller’) cultivars (Figure 10). In conclusion, *S. spectabile* ‘Carl’ demonstrated the ability to withstand waterlogging stress for up to 36 days and exhibited a superior recovery capacity following soil drainage when compared to *S. spectabile* ‘Rosenteller’. The ability to form adventitious roots significantly contributed to recovery after stress and adaptation to prolonged waterlogging. Additionally, researchers reported that the improved waterlogging tolerance of *S. spectabile* ‘Carl’ may be closely associated with a more effective antioxidant enzyme system, including superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), which help to mitigate oxidative stress caused by ROS (Zhang et al., 2019).



Fig 10. Morphological responses of waterlogging-tolerant *Sedum spectabile* ‘Carl’ and susceptible *S. spectabile* ‘Rosenteller’ cultivars. Water saturated for 0, 7, 14, 21, 28 and 36 days and *S. spectabile* ‘Carl’ treated for 12 days (C0, C7, C14, C21, C28, C36 and RC12) and *S. spectabile* ‘Rosenteller’ treated on the same days (R0, R7, R14, R21, R28, R36 and RR12) (Zhang et al., 2019).

In recent years, with global climate change, a concept known as “Sponge City” has begun to be implemented in many urban areas around the world. This concept refers to a set of green architectural and ecological strategies designed to absorb and retain excess rainwater—much like a sponge—rather than draining it quickly during periods of heavy rainfall (Figure 11). This approach has proven to be highly effective in improving urban flood resilience, and plant selection plays a critical role in the successful design and functionality of sponge cities (Pan et al., 2025).

One key component of sponge cities is the use of rain gardens, which are vegetated depressions that collect and infiltrate stormwater. Francini et al. (2022) described several plant species suitable for use in rain gardens, grouped as follows:

- Trees: *Metasequoia glyptostroboides* Hu & W.C. Cheng, *Salix babylonica* L., *Paulownia tomentosa* Steud., *Acer palmatum* Thunb. ‘Atropurpureum’
- Shrubs: *Fatsia japonica* Decne. & Planch., *Aucuba japonica* Thunb. ‘Variegata’, *Loropetalum chinense* Oliv.
- Medicinal and herbaceous plants: *Hemerocallis fulva* (L.) L., *Farfugium japonicum* (L.) Kitam., *Stipa tenuissima* Trin.
- Aquatic or wetland plants: *Phragmites australis* (Cav.) Steud., *Gladiolus gandavensis* Van Houtte, *Iris pseudacorus* L., *Iris tectorum* Maxim., *Lythrum salicaria* L., *Cyperus alternifolius* L.



These species contribute not only to flood mitigation and water regulation but also enhance the aesthetic and ecological value of urban green spaces

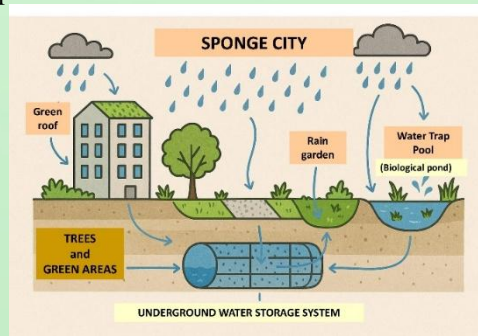


Fig 11. Sponge City Concept

Conclusions

This study provides valuable insights for the selection of ornamental plants suited for flood-prone areas by identifying species and cultivars with demonstrated waterlogging tolerance.

In addition to increased research on advanced breeding approaches for improving waterlogging resistance, further studies are needed to elucidate the molecular mechanisms of stress tolerance in ornamental plants. Therefore, future research should focus on both molecular and applied aspects of waterlogging resistance and aim to translate promising findings into practical applications in urban landscape design and planning.

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