Plant Stress Management in Fertigation

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Abstract— Fertigation is the most effective method of fertilizer application in plant nutrition and is among the most important components of sustainable agriculture. In fertigation applications, plants may be exposed to stress during the vegetation period for various reasons. In poorly managed applications, salt accumulation in the root zone, pH changes, oxygen deficiency, unbalanced nutrient combinations, and temperature stresses directly affect plant growth and crop performance. Various application strategies, automated control systems, and various biostimulant additives are widely used to increase stress tolerance in the management of these stress factors.

Keywords— Fertigation, Plant stress, Management Strategies

I. INTRODUCTION

Fertigation is a modern agricultural plant nutrition system based on the principle of directly supplying nutrients to plants by adding fertilizer to irrigation water. This combination provides significant technical advantages for precise and balanced mineral plant nutrition, both spatially and temporally. When optimal management techniques are applied, the fertilization and irrigation method ensures that agricultural products achieve high yields and quality and that producers earn high incomes. The main advantages of fertigation are the planning of fertilizer type and dosage according to the needs of the crop during its vegetation stages, better distribution of fertilizer in the root zone, ease of nutrient uptake by the plant, and minimization of fertilizer losses. It has been found that the use of fertigation reduces the leaching of mobile nutrients such as N from the soil by up to 70% compared to traditional fertilizer applications [1].

When applied correctly, fertigation increases water and fertilizer efficiency, but when not managed properly, plants can be exposed to physiological, chemical, and osmotic stresses. In addition, even when fertigation is well planned, unforeseen problems in soil-fertilizer interactions can occur in some soil conditions, causing stress in plants. In greenhouse or controlled environment conditions, it is critically important to identify and manage stress factors that negatively affect plant growth, yield, and quality in advance. Current research shows that many methods, ranging from sensor-controlled automation systems to various plant nutrition additives, can reduce these stresses.

This article examines the main types of stress encountered in fertigation, the effects of these stresses on plant physiology, current stress management strategies, and application recommendations.

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II. TYPES OF FERTIGATION-RELATED STRESS AND MANAGEMENT STRATEGIES

A. Osmotic/Salt Stress

When the electrical conductivity (EC) of the irrigation water or fertigation solution used in fertigation is very high, the salt concentration in the root zone increases. As the irrigation water evaporates, dissolved salts accumulate in the soil and increase the electrical conductivity (EC) around the roots. High EC values reduce the plant's water uptake capacity and create osmotic stress. This leads to salt stress, known as physiological drought in plants, and negatively affects water and nutrient uptake [2]. Salt stress affects plants through three main mechanisms:

- Osmotic stress: High salt concentration limits water uptake by roots and causes cells to shrink.
- Ion toxicity: Accumulation of Na^+ and Cl^- ions disrupts ion balance in the cell membrane, causing scorching and chlorosis on the edges of plant leaves.
- Nutrient imbalance: Excessive Na^+ inhibits the uptake of essential nutrients such as Ca^{2+} and K^+.
- Root development is suppressed, growth is stunted, and fruit size is reduced [3].

Management Strategy (EC control):

- EC values should be kept within the tolerance limits of the plant (e.g., 1.5–3.0 dS/m for tomatoes).
- 10–20% of the water applied daily should drain out; salt accumulation should be controlled.
- Weekly flushes (water application only) can remove accumulated salts from the root zone.
- If the irrigation water is highly saline, dilution or advanced filtration (e.g., reverse osmosis) should be considered.

B. pH Change and Decreases in Nutrient Availability

The pH of the solution affects the solubility of micro and macro elements. Deviating from the pH range of 5.5–6.5:

- Reduces the availability of microelements such as iron, zinc, and manganese.
- Creates a risk of phosphorus precipitation or Ca phosphate precipitation in calcareous soils.
- Prevents the uptake of certain elements, leading to nutritional imbalances.

Management Strategy (pH Control and Chelation):

- The pH of the solution should be maintained between 5.5–6.5 using phosphoric or nitric acid.
- If the irrigation water pH is above 7, automatic pH sensors and adjustment systems (acid/base dosing) can be used.

- Phosphate and calcium fertilizers should be kept in separate tanks, and attention should be paid to the risk of reaction before mixing.
- Microelements should be supplied in chelated form (Fe-EDDHA, Zn-EDTA, etc.).

C. Oxygen Deficiency and Root Hypoxia

High temperatures, excessive watering, or insufficient air pockets in the substrate can cause oxygen depletion in the root zone. Additionally, if the fertigation tank or irrigation lines are exposed to sunlight, the solution temperature rises (above 30 °C). If the solution or root zone temperature exceeds 30 °C:

- The dissolved oxygen concentration in the nutrient solution decreases.
- Root respiration is impaired, and energy production decreases.
- The root surface may rot or weaken, and pathogen pressure increases.
- Plant metabolism slows down due to enzyme activity and nutrient uptake limitations.

Management Strategy (Oxygen and root environment management):

- The solution temperature should be maintained between 18–25 °C; the temperature should not exceed 30 °C. Shading, insulation, or cooling systems should be used to prevent excessive heating of the solution in tanks and pipes. Dissolved oxygen in the solution should be maintained at ≥ 5 mg/L.
- Cooling coils or night watering can be applied to the solution.
- Air voids in the soil or substrate should be maintained at an adequate level (20–30%).
- Ventilation techniques (periodic aeration) or pump-assisted oxygenation in hydroponic systems or optimization of the substrate mixture should be considered.

D. Nutrient Imbalance and Ion Competition

Errors in fertilizer combinations or excessive use of one element can suppress the uptake of other elements due to ion antagonism. Symptoms commonly seen in nutrient imbalance include abnormal leaf color, stunted growth, and fruit deformities (e.g., blossom end rot in calcium deficiency). In ion competition:

- Excess potassium can inhibit magnesium or calcium uptake.
- Excess ammonium can cause Ca and Mg deficiencies.
- Interactions between microelements Zn–Cu–Fe can have adverse effects.

Management Strategy (Fertilization optimization):

- Stress can be reduced with frequent and low-dose application strategies [4].
- Fertilizer doses should be gradually increased according to the plant's growth stage.
- Increase $Ca(NO_3)_2$ and reduce NH_4^+-containing sources during the fruit set period.
- The NH_4^+/NO_3^- ratio in nitrogen nutrition should be ≤ 0.1.
- Leaf analyses should be performed every 15 days to monitor the nutritional status of plants.

E. Water Stress (Insufficient Irrigation)

Failure to meet the plant's daily water requirements during the vegetation period causes stress. In addition, inadequate filtration in the fertigation system, sediment buildup in the dripper pipes, algae, Fe or $CaCO_3$ deposits cause dripper clogging, which in turn leads to insufficient irrigation water application due to low pressure and water stress in plants. In water stress:

- Insufficient nutrient uptake
- Leaf wilting are the most prominent symptoms.

Management Strategy (Removing clogs, monitoring soil moisture levels):

- The inlet water filter systems should be cleaned regularly.
- Drip lines should be periodically cleaned with acid (HNO_3 or H_3PO_4, 0.5–1%).
- Chlorination (2–3 ppm active chlorine) should be performed for microbial clogging.
- Irrigation times and intervals should be planned according to the plant's evapotranspiration (ETc) value.
- The moisture level of the soil or substrates should be monitored with moisture sensors. Automatic irrigation control can be performed with a moisture sensor.
- The air void in substrates (coconut fiber, perlite) should be at least 25–30%.

III. Current Applications in Fertigation Stress

A. Sensor-Based Automation

Sensor-based automation is defined as automatically managing water and fertilizer application processes based on real-time measurements (soil moisture, conductivity/EC, pH, temperature, nutrient levels, etc.) rather than fixed times in the fertigation system. With soil moisture and conductivity sensors, similar or better crop yields are achieved with less water and fertilizer use compared to time-based systems [5,6]. In addition, fertigation systems can save water and fertilizer through control and automation techniques, significantly reducing environmental pollution [7]. This approach provides real-time control rather than analysis-focused management. Sensors and automation components:

- The most commonly used sensors for soil or environment (greenhouse/hydroponics) are moisture sensors, electrical conductivity (EC) sensors, and pH sensors. For example, in a non-greenhouse system, substrate volumetric water content (VWC) and pore water EC were measured [5].
- Controllers (PLC, microcontrollers), injectors or dosing pumps, and valve systems are used for automation. Motor and pump control is possible by acquiring sensor data with Arduino + GSM module [8].
- In the software/algorithm part, "closed-loop" (feedback) control systems are used: sensor data is read in real time, compared with specified thresholds, and the system adjusts the water or fertilizer dosage accordingly [9].
- Advanced systems incorporate IoT (Internet of Things), cloud connectivity, and AI (artificial intelligence)-based optimization models [10].

B. Stress-Resistant Additives

The most commonly applied additives to plants during stressful periods are seaweed extracts, humic/fulvic acids, silicon, osmoregulators (proline, glycine betaine), plant hormone applications (e.g., salicylic acid, jasmonates), antioxidants, beneficial microorganisms (PGPR, mycorrhiza), and these increase the plant's tolerance to different types of stress (drought, salinity, heat stress, oxidative stress, heavy metals, etc.).

3.2.1. Seaweed Extracts: As a biostimulant, it promotes root and shoot growth, improves drought/salinity tolerance by affecting stomatal behavior and osmoprotectant production; increases nutrient uptake and antioxidant responses [11]. Available in liquid form for fertigation or foliar spraying. Concentration/application frequency varies depending on the product and product label.

3.2.2. Humic and Fulvic acids: Improve soil/medium physical-chemical properties, increase root development and nutrient uptake; reduce stress damage by regulating antioxidant enzyme activities in plants. They can be applied to the soil or via fertigation; they can be used in solution in hydroponic systems. Their effect is directed both at the plant itself and at the rhizosphere microflora [12].

3.2.3. Silicon (Si): Strengthens cell walls, helps control water loss by regulating stomatal behavior; protects the photosynthetic apparatus and stimulates antioxidant systems — thereby increasing tolerance to drought and salt stress [13]. Silicon is applied in fertigation as dissolved silicates or as foliar silicon solutions. It is particularly effective in Si-accumulating/utilizing plant species [14].

3.2.4. Osmoprotectants / Amino acids (proline, glycine betaine, glutamate, etc.): Protect the plant against salt and drought stress by maintaining intracellular osmotic balance, preserving cell water, and providing protein and membrane stabilization. They also support antioxidant systems: they can increase the activity of free radical scavenging enzymes and play a protective role against protein and membrane damage (Hosseinifard et al., 2022). They are generally applied at low concentrations via foliar application or seed coating. They can be used in fertigation with a suitable formulation. It targets the rhizosphere microflora [12].

3.2.5. Plant hormones/signaling molecules (salicylic acid (SA), jasmonic acid (JA), abscisic acid (ABA), melatonin, etc.): They regulate the plant's stress response pathways: they have the function of increasing antioxidant activity, stomatal closure (ABA), systemic resistance (SA), and in some cases activating defense pathways (JA). They are generally applied by spraying on leaves or coating seeds. While the external application of these compounds increases tolerance in plants, dosage and timing are critical [15].

3.2.6. Antioxidants/metabolites (ascorbic acid, etc.): When plants are subjected to abiotic stresses such as drought, salinity, and temperature extremes, a series of metabolic reactions intensify in their cells, resulting in the accumulation of reactive oxygen species (ROS). While these ROS perform signaling functions at low levels, their excessive accumulation can damage cell membranes, proteins, DNA, and the photosynthetic system. Exogenous antioxidant applications can support the plant's defense against this ROS accumulation, thereby improving criteria such as photosynthesis, water status, nutrient uptake, and root development, and reducing stress-induced yield or quality losses [16]. Foliar application is the most common form; their stability or solubility should be controlled in fertigation applications.

3.2.7. Beneficial microorganisms (PGPR, mycorrhiza): They enhance the plant's nutrient uptake and tolerance to water stress; some microorganisms stimulate osmoprotectant/antioxidant pathways in the plant. They are applied through soil/environment inoculation, and some liquid inoculants can be administered via fertigation [17].

CONCLUSION

Although fertigation is a highly efficient and resource-saving plant nutrition method when properly managed, it is necessary to minimize the various stresses that plants may be exposed to during the growing season using appropriate strategies. Salt accumulation, pH deviation, oxygen deficiency, unbalanced nutrient combinations, and temperature stresses can directly affect plant performance. Strategies that optimize these stress factors, such as sensor-controlled systems, biostimulant support, and correct dosage-frequency, must be considered as a whole. In practice, a culture of continuous monitoring, analysis, and improvement is essential. Recent research shows that sensor-based automation can provide more balanced environments, and that additional strategies such as additive applications can help increase stress tolerance

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