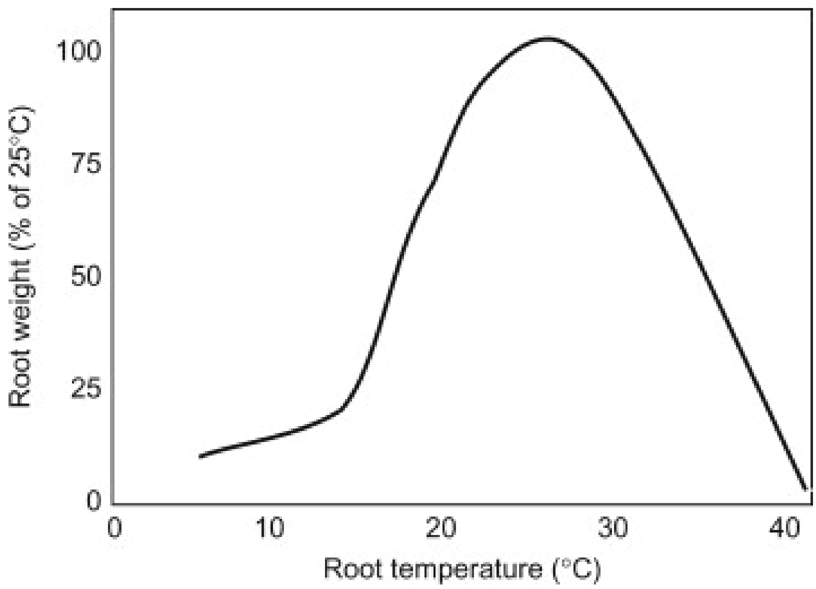
An Expanded View on Root Zone Temperature in Soilless and Hydroponic Systems

When we think about optimizing hydroponic systems, most growers focus on nutrient concentrations, pH levels, and lighting conditions. However, one of the most critical yet often overlooked factors that can dramatically impact plant performance is root zone temperature. Understanding the intricate relationship between temperature and root physiology can be the difference between a mediocre harvest and exceptional yields.

Root zone temperature (RZT) represents the thermal environment surrounding plant roots and serves as a fundamental driver of physiological processes in soilless cultivation systems. Unlike soil based agriculture where thermal mass provides natural temperature buffering, hydroponic and soilless systems expose roots to more dramatic temperature fluctuations, making active temperature management both more challenging and more important (1).



Relative root zone mass as a function of mass at the optimal temperature, taken from (9). Note that this is for a soil system, for soilless media system the response curves are similar while for DWC the curves are more shifted to the left because of oxygen solubility issues.

Optimal Root Zone Temperatures for Different Systems

The optimal root zone temperature varies significantly between deep water culture (DWC) and other soilless systems, primarily due to differences in oxygen availability and heat dissipation characteristics. Research has consistently demonstrated that temperature requirements differ based on the cultivation method employed.

Deep Water Culture Systems

In DWC systems, where roots are directly immersed in oxygenated nutrient solutions, optimal temperatures typically range from 18 to 22°C (64 to 72°F). This relatively narrow range reflects the critical balance between metabolic activity and dissolved oxygen availability (2). The inverse relationship between water temperature and oxygen solubility becomes particularly important in DWC, as warmer temperatures can quickly lead to hypoxic conditions that stress plant roots and promote pathogenic organisms.

Experienced DWC practitioners often target the lower end of this range, around 20°C (68°F), to maximize dissolved oxygen content while maintaining adequate metabolic rates (3). Temperatures above 25°C (77°F) in DWC systems frequently result in root browning, reduced nutrient uptake, and increased susceptibility to root rot pathogens.

Soilless Media Systems

Soilless systems utilizing growing media such as rockwool, perlite, or coco coir can tolerate slightly higher root zone temperatures due to improved aeration and thermal buffering properties of the growing medium. Optimal temperatures for these systems typically range from 20 to 28°C (68 to 82°F), with many commercial operations targeting 22 to 25°C (72 to 77°F) for optimal performance (1).

The growing medium provides several advantages over liquid culture systems. The air spaces within the substrate maintain higher oxygen levels even at elevated temperatures, while the thermal mass of the medium helps dampen rapid temperature fluctuations. This thermal stability allows for more forgiving temperature management while still maintaining excellent plant performance.

System Type	Optimal Temperature Range	Critical Considerations	Common Challenges
Deep Water Culture	18-22°C (64-72°F)	Dissolved oxygen levels	Limited thermal mass, rapid temperature changes
Rockwool Systems	20-26°C (68-79°F)	Media moisture retention	Uneven heating, thermal bridging
Coco Coir/Perlite	22-28°C (72-82°F)	Media thermal properties	Variable thermal conductivity
Nutrient Film Technique	18-24°C (64-75°F)	Flow rate and film thickness	Channel heating, pump heat

Impact on Hydraulic Transport and Water Relations

Root zone temperature profoundly influences hydraulic transport mechanisms within plants, affecting both water uptake rates and the efficiency of nutrient transport to aerial parts. The relationship between temperature and hydraulic conductivity follows predictable patterns that directly impact plant performance.

Water Uptake Mechanisms

Temperature affects water uptake through multiple pathways, including both passive and active transport mechanisms. Research on strawberry plants has shown that water absorption rates initially increase with rising root zone temperatures but subsequently decrease when temperatures exceed optimal ranges (4). This biphasic response reflects the competing effects of increased membrane fluidity and enzyme activity at moderate temperatures versus protein denaturation and membrane dysfunction at excessive temperatures.

Root pressure and hydraulic conductivity show particularly strong temperature dependence. Low root zone temperatures severely reduce both parameters, limiting the plant's ability to transport water and dissolved nutrients from roots to shoots (4). This effect becomes especially pronounced when root zones are maintained below 15°C (59°F), where hydraulic transport can be reduced by more than 50% compared to optimal temperatures.

Xylem Development and Function

Temperature also influences the development of xylem tissue, which serves as the primary pathway for water and nutrient transport. Studies have demonstrated that optimal root zone temperatures promote proper xylem differentiation and vessel development, enhancing long term transport capacity (5). Conversely, suboptimal temperatures can result in poorly developed vascular tissue with reduced transport efficiency.

Effects on Plant Growth and Development

The influence of root zone temperature on plant growth extends far beyond simple metabolic rate changes, affecting fundamental aspects of plant development including root architecture, shoot growth patterns, and reproductive development.

Root Development and Architecture

Root zone temperature significantly impacts root morphology and development patterns. Research with lettuce plants has shown that optimal temperatures (around 25°C/77°F) maximize both root and shoot dry weight accumulation, while temperatures of 15°C (59°F) or 35°C (95°F) result in reduced growth rates [(2)](). The relationship between temperature and root development follows a classical optimum curve, with growth rates increasing linearly from minimum temperatures to an optimum, followed by sharp declines at supra optimal temperatures.

Interestingly, recent studies have revealed that raising root zone temperature just 3°C (5.4°F) above air temperature can result in significant improvements in plant productivity. This approach increased shoot dry weight by 14 to 31% and root dry weight by 19 to 30% across different air temperature conditions [(1)](). These findings suggest that the optimal root zone temperature is not an absolute value but rather depends on the thermal environment of the aerial plant parts.

Shoot Growth and Biomass Accumulation

While root zone temperature directly affects root metabolism, its influence on shoot growth occurs through complex interactions involving nutrient uptake, hormone production, and resource allocation. Plants grown with optimal root zone temperatures show enhanced shoot growth rates, increased leaf area development, and improved overall biomass accumulation (6).

The mechanism underlying these growth improvements involves enhanced nutrient uptake and translocation from roots to shoots. When root zone temperatures are optimal, plants can more efficiently absorb and transport essential nutrients, leading to improved photosynthetic capacity and biomass production in aerial tissues.

Nutrient Uptake and Mineral Nutrition

Perhaps no aspect of plant physiology is more directly affected by root zone temperature than nutrient uptake. The temperature dependence of nutrient absorption reflects the fundamental biochemical nature of transport processes occurring in root tissues.

Macronutrient Absorption

The uptake of major nutrients including nitrogen, phosphorus, and potassium shows strong temperature dependence across all hydroponic systems. Classic research on tomato plants demonstrated that nutrient uptake for most elements peaks at approximately 26.7°C (80°F), with significant reductions in absorption rates at both higher and lower temperatures (7). This temperature optimum closely corresponds to the temperature range that maximizes plant growth and development.

Nitrogen uptake shows particularly interesting temperature responses, with both nitrate and ammonium absorption affected by root zone thermal conditions. At low temperatures, nitrate accumulation in roots increases while transport to shoots decreases, suggesting that cold stress impairs the translocation mechanisms responsible for moving absorbed nutrients to metabolically active tissues (8).

Pathogen Development and Root Health

Root zone temperature plays a crucial role in determining the microbial ecology of hydroponic systems, influencing both pathogenic and beneficial microorganisms. Understanding these temperature relationships is essential for maintaining healthy root systems and preventing disease outbreaks.

Pathogenic Microorganisms

Many of the most serious root pathogens in hydroponic systems show strong temperature preferences that overlap with optimal plant growth ranges. Pythium aphanidermatum, one of the most devastating hydroponic pathogens, causes severe root rot symptoms when root zone temperatures reach 23 to 27°C (73 to 81°F). This temperature range unfortunately coincides with optimal growing conditions for many crop plants, creating a challenging management situation.

The development of severe root browning and rot in greenhouse hydroponic crops often coincides with hot weather when nutrient solution temperatures rise above optimal ranges. Higher temperatures not only favor pathogen metabolism and reproduction but also stress plant roots, making them more susceptible to infection.

Oxygen Availability and Pathogen Suppression

The relationship between temperature and dissolved oxygen creates additional challenges for pathogen management. As temperatures increase, oxygen solubility decreases, creating anaerobic conditions that favor certain pathogenic organisms while simultaneously stressing plant roots. This dual effect explains why temperature management is so critical in hydroponic systems, particularly those with limited aeration capacity.

Maintaining root zone temperatures in the lower portion of the optimal range (18 to 22°C/64 to 72°F) helps maximize dissolved oxygen levels while providing adequate metabolic activity for plant growth. This approach represents a compromise that optimizes the balance between plant performance and disease suppression.

Beneficial Microorganisms

While pathogenic organisms often receive the most attention, root zone temperature also affects beneficial microorganisms that can enhance plant growth and disease resistance. Many beneficial bacteria and fungi have temperature optima that align with ideal plant growing conditions, suggesting co evolutionary relationships that can be exploited in hydroponic systems.

The use of beneficial microorganisms as biological control agents requires careful temperature management to maintain viable populations while preventing pathogen development. This balance represents one of the most sophisticated aspects of modern hydroponic management.

Metabolic and Biochemical Responses

Root zone temperature influences numerous metabolic pathways within plants, affecting everything from primary metabolism to secondary metabolite production. These biochemical responses help explain the growth and quality improvements observed with optimal temperature management.

Primary Metabolism

Optimal root zone temperatures enhance protein synthesis and amino acid metabolism in root tissues. Research has shown that raising root zone temperature by just 3°C (5.4°F) above air temperature significantly increases total soluble protein concentrations in both roots and leaves (1). This enhanced protein synthesis reflects improved metabolic activity and contributes to better plant growth and development.

The production of specific amino acids also responds to temperature management. Ten different amino acids, including alanine, arginine, aspartate, and others, show increased concentrations in root tissue when temperatures are maintained in optimal ranges (1). These amino acids serve as building blocks for proteins and as precursors for numerous other metabolic compounds.

Secondary Metabolite Production

Root zone temperature also affects the production of secondary metabolites that contribute to plant quality and nutritional value. Optimal temperatures increase the concentrations of important compounds including carotenoids, chlorophyll, and ascorbic acid (1). These improvements in secondary metabolite production enhance both the visual quality and nutritional value of harvested crops.

Interestingly, stress temperatures can sometimes increase certain secondary metabolites. Higher temperatures (35°C/95°F) in lettuce production significantly increase pigment contents including anthocyanins and carotenoids, though this comes at the cost of reduced plant growth (2). This relationship suggests opportunities for strategic temperature manipulation during specific growth phases to optimize product quality.

Practical Management Strategies

Implementing effective root zone temperature management requires understanding both the technical aspects of temperature control and the practical constraints of different growing systems. Successful temperature management strategies must balance plant requirements with economic and energy considerations.

Temperature Monitoring and Control

Accurate temperature monitoring represents the foundation of effective root zone management. Unlike air temperature, which can be measured at any convenient location, root zone temperature must be measured at the actual root interface. This requires placing sensors directly in the growing medium or nutrient solution where roots are actively growing.

For DWC systems, temperature sensors should be placed directly in the nutrient reservoir at root level. In media based systems, sensors should be buried in the growing medium at the depth where the majority of roots are located. Multiple sensors may be necessary in large systems to account for thermal gradients and ensure uniform temperature management.

Heating and Cooling Strategies

Heating strategies for root zone temperature management vary considerably based on the type of hydroponic system and local climate conditions. In DWC systems, submersible aquarium heaters provide reliable and precise temperature control. For media based systems, heating cables or mats can be installed beneath growing containers to provide bottom heat.

Cooling presents greater challenges, particularly in warm climates or heated growing environments. Water chillers represent the most reliable solution for DWC systems but require significant energy investment. For smaller operations, the use of insulation, reflective materials, and strategic shading can help moderate temperature extremes.

Some innovative approaches include using waste heat from LED lighting systems to warm root zones during cooler periods, or incorporating thermal mass materials to buffer temperature fluctuations. These strategies can improve energy efficiency while maintaining optimal growing conditions.

Conclusion

Root zone temperature management represents one of the most impactful yet underutilized tools available to hydroponic growers. The evidence clearly demonstrates that maintaining optimal temperatures can significantly improve plant growth rates, enhance nutrient uptake efficiency, and increase crop quality. However, successful implementation requires careful attention to system specific requirements and the balance between plant needs and pathogen management.

The differences between DWC and soilless media systems necessitate different temperature targets and management strategies. While DWC systems require more restrictive temperature control due to oxygen limitations, soilless media systems offer greater flexibility and thermal stability. Understanding these differences allows growers to optimize their specific systems for maximum productivity.

Perhaps most importantly, the research reveals that root zone temperature should not be considered in isolation but as part of an integrated environmental management strategy. The relationship between root zone and air temperatures, the interaction with dissolved oxygen levels, and the impact on microbial communities all require careful consideration when developing temperature management protocols.

Growing Soilless Crops Without Nitrates: Practical Options When Nitrate Salts Are Unavailable

For growers in regions where geopolitical conflicts or economic constraints limit access to nitrate fertilizers like calcium nitrate and potassium nitrate, the question arises: can you grow hydroponic or soilless crops using only alternative nitrogen sources? The short answer is yes, but with important limitations and necessary substrate modifications. This post explores the science behind nitrate-free soilless growing and practical strategies for growers facing nitrate scarcity.

Figure 1. Effects of nitrate concentration (25, 50, 75, 100 and 150% of the recommended dose) and proportion of nitrate/ammonium (0:100, 25:75, 50:50, 75:25 and 100/0) in the nutrient solution for hydroponics, on the development of lettuce Iceberg type.

The above image is sourced from (8).

Why Nitrates Dominate in Hydroponics

In conventional hydroponics, 85-95% of nitrogen is supplied as nitrate (NO_3^-) rather than ammonium (NH_4^+). This preference exists for good reasons. Plants can safely store nitrate in vacuoles without toxicity, while ammonium accumulation in plant tissues causes rapid damage (1). In soil, nitrifying bacteria convert ammonium to nitrate before plant uptake, but most soilless substrates lack these microbial communities. Without this conversion, ammonium concentrations that would be harmless in soil become highly toxic in hydroponics.

Research on tomatoes shows that plants supplied with 112 ppm nitrogen as ammonium developed severe toxicity symptoms and produced only one-third the biomass of nitrate-fed plants (1). Even at 14 ppm nitrogen, ammonium-only nutrition suppressed growth compared to mixed nitrogen sources. For lettuce, similar effects occur, with crown discoloration and biomass reductions appearing at 50 ppm ammonium nitrogen (2).

Maximum Safe Ammonium Levels

The tolerance threshold varies by species and conditions, but general guidelines exist:

Crop Type	Maximum Safe Ammonium (% of total N)	Maximum Concentration (ppm N)
Most crops (standard)	10-15%	15-30 ppm
Sensitive crops (tomato, pepper, lettuce)	5-10%	10-20 ppm
Cold conditions (<15°C)	0-5%	0-10 ppm
High light, fast growth	15-20%	20-40 ppm

These limits exist because ammonium uptake is passive and rapid, plants cannot regulate it effectively, and it disrupts calcium and magnesium uptake while acidifying the root zone (3).

Substrate Amendments: Creating Artificial Soil

The key to using higher ammonium levels or organic nitrogen sources is establishing nitrifying bacteria in the substrate. Recent research demonstrates that soilless substrates can be inoculated with microbial communities that convert organic nitrogen to nitrate (4).

Effective substrates for nitrification include rockwool, vermiculite, polyurethane foam, oyster shell lime, and rice husk charcoal. The process requires:

1. **Inoculum source**: Bark compost or mature vermicompost provides ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB). Add 1g per 100mL substrate initially.
2. **Temperature**: Nitrifying bacteria function optimally at 25-42°C. Below 15°C, nitrification slows dramatically, causing ammonium accumulation (5).
3. **Humidity and aeration**: Substrates need >50% relative humidity and adequate oxygen. Waterlogged conditions inhibit nitrification and promote denitrification.
4. **Establishment period**: Allow 2-3 weeks for bacterial colonization before planting. Daily additions of dilute organic fertilizer (6 mg N per 100mL substrate) accelerate establishment.

Practical Nitrogen Sources

Ammonium Salts

Ammonium sulfate ($(NH_4)_2SO_4$) is the most accessible ammonium source globally. At 21% nitrogen, it provides both N and sulfur. However, use caution:

- Never exceed 20% of total nitrogen as ammonium in solution
- Monitor substrate pH closely, as ammonium uptake releases protons and acidifies the root zone
- Increase ratios only under high light and warm temperatures (>20°C)
- Sensitive crops like lettuce, tomato, and pepper tolerate lower ratios

Ammonium phosphate (MAP or DAP) offers nitrogen plus phosphorus but requires even more careful management due to rapid pH shifts.

Urea

Urea ($CO(NH_2)_2$) at 46% nitrogen is economical and widely available. In water, urease enzymes (either from bacteria or added exogenously) hydrolyze urea to ammonium. However, hydroponic studies on various crops show that urea performs poorly as a sole nitrogen source (6). Plants fed only urea exhibited nitrogen deficiency symptoms at low concentrations and toxicity at high concentrations. The primary issues are:

- Insufficient uptake of intact urea by most crop species
- Variable conversion rates without soil bacteria
- pH instability during hydrolysis

Combined applications of urea with nitrate showed better results than urea alone, but if nitrates are unavailable, urea offers limited benefit beyond what ammonium salts provide (6).

Compost and Organic Extracts

Compost leachates and vermicompost teas contain nitrogen primarily as proteins, amino acids, and ammonium. Direct use in inert hydroponics fails because plants cannot efficiently absorb complex organic nitrogen. However, two approaches work:

Aerobic nitrification method: Add organic nitrogen sources like corn steep liquor (1g/L) or fish emulsion plus bark compost (0.5g/L) as bacterial inoculum. Aerate for 12 days, during which bacteria convert organic N and ammonium to nitrate, reaching 100-130 ppm N as nitrate (7). This creates a low-cost, nitrate-containing solution from readily available materials.

Substrate-based mineralization: Inoculate substrates with compost microbes and apply dilute organic fertilizers daily. The substrate acts as a biofilter, mineralizing organic N to nitrate before plant uptake (4). This method requires 2-3 weeks establishment and careful moisture management.

Expected Yield Impacts

When managed properly with substrate amendments and bacterial communities, yields can approach conventional hydroponic levels. Studies show that tomatoes grown with nitrified organic solutions performed comparably to mineral fertilizer controls when adequate nitrate was generated (7).

However, several factors reduce yields in poorly managed nitrate-free systems:

- **Ammonium toxicity**: High ammonium causes 30-70% yield reductions across most crops (1)

- **Nutrient imbalances**: Ammonium competes with Ca^{2+} and Mg^{2+} uptake, inducing deficiencies
- **pH instability**: Root zone acidification from ammonium uptake reduces nutrient availability
- **Incomplete mineralization**: Organic N sources may not fully convert to plant-available forms

Realistic expectations for growers transitioning to nitrate-free systems:

- First crop cycle: 50-70% of conventional yields while optimizing conditions
- Established systems with functioning bacterial communities: 80-95% of conventional yields
- Cold season growing (<15°C): 40-60% due to impaired nitrification

Nutrient Solution Modifications

Without calcium nitrate, calcium must come from chloride or sulfate sources rather than nitrate. Calcium chloride is highly soluble but adds chloride. Gypsum (calcium sulfate) doesn’t have the solubility needed to make concentrated stock solutions and therefore can only be added to the final solutions or added to the media as an amendment. Calcium chloride can add unwanted high amounts of chlorides as it’s therefore best avoided. If you are doing composting amendments then limestone amendments might be the most desirable way to supply Ca to the crop.

Critical Success Factors

To successfully grow soilless crops without nitrate fertilizers:

1. **Establish nitrifying bacteria**: This is non-negotiable for using organic N or high ammonium levels
2. **Monitor pH constantly**: Ammonium acidifies solutions; maintain pH 5.8-6.5 through buffering or base addition
3. **Provide adequate calcium**: Use calcium chloride or sulfate since calcium nitrate is unavailable
4. **Keep temperatures warm**: >20°C substrate temperature for bacterial activity
5. **Start conservatively**: Begin with 10% ammonium and increase gradually as plants adapt
6. **Choose tolerant species first**: Leafy greens like pak choi are more tolerant than tomatoes or peppers

Conclusion

Growing soilless crops without nitrates is achievable but requires different management than conventional hydroponics. The approach depends on creating conditions that mimic soil processes, establishing microbial communities to convert ammonium and organic nitrogen to nitrate within the substrate. While yields may initially be lower, proper substrate inoculation, temperature management, and careful nitrogen source selection can produce acceptable results. For growers with limited access to nitrate salts, combining small amounts of ammonium sulfate (20-30 ppm N) with aerobically nitrified compost teas or inoculated substrates offers the most practical path forward.

Comparing Nutrient Solutions

for Hydroponic Strawberry Production

Getting the right nutrient solution for strawberries in hydroponics can feel like trying to solve a puzzle where every piece matters. Unlike many crops where you can get away with a generic formula, strawberries are particularly responsive to nutrient composition, especially when it comes to the balance between nitrogen and potassium. Today, we will explore how different nutrient formulations affect both yield and fruit quality in soilless strawberry production.

A hydroponic strawberry production greenhouse

The Modified Steiner Approach

When researchers at the Technological Institute of Torreón tested different nitrogen and potassium combinations in strawberries, they discovered something important about how these two nutrients interact. Using a [(1)](#) modified version of Steiner's Universal Nutrient Solution, they evaluated twelve different formulations with nitrogen ranging from 126 to 210 ppm and potassium from 195 to 430 ppm.

The results were revealing. Plants receiving 168 ppm nitrogen combined with 430 ppm potassium achieved yields of 114 grams per plant, which was significantly higher than lower nitrogen treatments. However, here is where it gets interesting: while high nitrogen boosted yield, it actually decreased fruit quality. The highest soluble solids content (10.5 degrees Brix) occurred at the lowest nitrogen level of 126 ppm. This creates a real dilemma for growers who want both high yields and premium quality fruit.

Solution Type	**N (ppm)**	**P (ppm)**	**K (ppm)**	**Ca (ppm)**	**Mg (ppm)**	**Yield**	**Quality Impact**
Modified Steiner (Low N)	126	46	195	449	121	89.3 g/plant	Highest Brix (10.5°)
Modified Steiner (Medium N)	168	32	273	360	97	108 g/plant	Moderate Brix (10.0°)
Modified Steiner (High N)	210	19	194	413	111	111 g/plant	Lowest Brix (9.5°)

The Critical Role of Potassium

What emerged from this study was potassium's profound impact on fruit quality. When potassium was increased to 430 ppm, the soluble solids climbed to 10.6 degrees Brix, and phenolic compounds reached their peak as well. The (1) research showed that the optimal combination for maximizing both yield and nutraceutical quality was 168 ppm nitrogen with 430 ppm potassium, resulting in antioxidant capacity of 6305 microequivalents of Trolox per 100 grams.

This makes physiological sense. Potassium plays a fundamental role in sugar transport through the phloem, and when potassium availability is adequate, more sugars accumulate in the fruit. Meanwhile, excessive nitrogen tends to promote vegetative growth and the synthesis of nitrogen containing compounds like proteins and amino acids, rather than the accumulation of secondary metabolites that contribute to fruit quality.

Optimizing NPK Ratios for Chinese Greenhouses

A comprehensive study from China Agricultural University took a different approach by examining the combined effects of nitrogen, phosphorus, potassium, and water on strawberry production. Using a (2) quadratic regression design with 36 treatments, researchers determined that nitrogen was by far the most important factor, followed by water, then phosphorus, with potassium having the least impact on the sweetness to acidity ratio.

Their optimal formulation for achieving yields above 110 grams per plant with excellent fruit quality included nitrogen at 156 to 172 ppm (supplied as calcium nitrate), phosphorus at 54 to 63 ppm (as sodium dihydrogen phosphate), and potassium at 484 to 543 ppm (from potassium sulfate). This represents significantly higher potassium levels than the Steiner based formulations, suggesting that when other nutrients are optimally balanced, strawberries can benefit from even more potassium.

Nutrient	Optimal Range (ppm)	Impact on Yield	Impact on Quality (SSC/TA)
Nitrogen (N)	156 to 172	Most significant positive effect	Most significant factor

Phosphorus (P)	54 to 63	Moderate positive effect	Second most important
Potassium (K)	484 to 543	Significant positive effect	Minimal impact
Water	12.0 to 13.1 L/plant	Second most important	Third most important

The Calcium and Electrical Conductivity Question

While much attention focuses on NPK ratios, calcium concentration matters enormously in strawberry production. In the modified Steiner solutions, calcium ranged from (1) 244 to 449 ppm depending on the treatment. Higher calcium levels corresponded with lower nitrogen and potassium concentrations, maintaining appropriate osmotic potential.

Research has shown that the electrical conductivity (EC) of the nutrient solution significantly impacts strawberry performance in soilless culture. Studies using different EC levels found that (3) 1.3 mS/cm was optimal for spring production, while 2.2 mS/cm proved better during winter months. This seasonal adjustment reflects the plant's changing water use and nutrient demand patterns throughout the growing cycle.

Micronutrient Considerations

While macronutrients get most of the attention, micronutrient composition matters too. The (1) modified Steiner formulations included iron at 5 ppm, manganese at 1.6 ppm, boron at 0.865 ppm, zinc at 0.023 ppm, copper at 0.11 ppm, and molybdenum at 0.048 ppm. These concentrations remained constant across all treatments, suggesting that within reasonable limits, macronutrient balance has a more pronounced effect on yield and quality than micronutrient variation.

Making Practical Choices

So what should you actually do with this information? If you are growing strawberries hydroponically and want to maximize both yield and quality, consider starting with a solution containing approximately 160 to 170 ppm nitrogen, 55 to 60 ppm phosphorus, and 400 to 500 ppm potassium. Maintain the K:Ca ratio near 1-1.4:1 and the K:Mg ratio near 4:1. This matches some of my previous publications on the K:Ca ratio.

Remember that these recommendations assume you are maintaining appropriate pH (around 5.5 to 6.0) and EC levels suitable for your growing conditions. The (2) research demonstrated that excessive nutrients actually decreased both yield and quality, so more is definitely not better. You will need to adjust based on your specific cultivar, climate, and growing system, but these ranges provide a solid starting point backed by peer reviewed research.

The key takeaway is that strawberry nutrition in hydroponics requires a delicate balance. While nitrogen drives yield, potassium enhances quality, and the interaction between these two nutrients determines your ultimate success. Monitor your plants carefully, conduct tissue analysis when possible, and do not be afraid to adjust your formulation based on what the plants are telling you.

Comparing Nutrient Solutions for Hydroponic Tomatoes

When growing tomatoes hydroponically, one of the most critical decisions you'll make is choosing the right nutrient solution. The composition of your nutrient solution can dramatically affect both the quantity and quality of your harvest. In this post, I'll examine different nutrient formulations that have been tested in scientific studies and discuss how they impact tomato production in soilless systems.

Picture of a soilless tomato greenhouse

Understanding Nutrient Solution Basics

Before diving into specific formulations, it's important to understand that tomato plants have changing nutritional needs throughout their growth cycle. Research has shown that early in the season, excessive nitrogen can cause plants to become too vegetative, resulting in bullish growth that produces misshapen fruits and increases susceptibility to disease (1). High potassium levels can also create problems by interfering with calcium and magnesium absorption, leading to blossom end rot.

Most successful nutrient programs divide the growing season into distinct stages. The seedling stage requires lower concentrations of nutrients, particularly nitrogen, while mature fruiting plants need substantially higher levels of most nutrients to support both vegetative growth and fruit development (2).

Comparing Two Common Formulations

Research has established several effective nutrient formulations for hydroponic tomatoes. I'll compare two well documented approaches that represent different philosophies in nutrient management.

Nutrient	Arizona Formula (Seedling)	Arizona Formula (Fruiting)	Florida Formula (Early)	Florida Formula (Late)
Nitrogen (N)	113 ppm	144 ppm	60 to 70 ppm	150 to 200 ppm
Phosphorus (P)	62 ppm	62 ppm	39 ppm	39 ppm
Potassium (K)	199 ppm	199 ppm	200 ppm	300 to 400 ppm
Calcium (Ca)	122 ppm	165 ppm	150 to 200 ppm	150 to 200 ppm
Magnesium (Mg)	50 ppm	50 ppm	48 ppm	48 ppm

The Arizona formulation (2) maintains relatively consistent macronutrient levels between growth stages, with only modest increases in nitrogen and calcium as plants mature. In contrast, the Florida approach (1) uses much lower nitrogen during early growth to prevent bullishness, then dramatically increases both nitrogen and potassium during fruit production.

Micronutrient Requirements

While macronutrients often receive the most attention, micronutrients are equally essential for healthy tomato production. These elements remain fairly constant throughout the growing cycle (2). Standard micronutrient concentrations for hydroponically grown tomatoes include iron at 2.5 ppm, manganese at 0.62 ppm, boron at 0.44 ppm, zinc at 0.09 ppm, copper at 0.05 ppm, and molybdenum at 0.06 ppm.

Micronutrient	Concentration (ppm)
Iron (Fe)	2.5
Manganese (Mn)	0.62
Boron (B)	0.44
Zinc (Zn)	0.09
Copper (Cu)	0.05
Molybdenum (Mo)	0.06

The Impact of Nitrogen Supply on Quality

Research on nitrogen management has revealed some surprising findings. A study examining nitrogen supply at different growth stages found that increasing nitrogen from 140 to 225ppm during the vegetative stage increased protein, vitamin C, and sugar content in fruits (3). However, the effect on lycopene and beta-carotene depended heavily on the potassium supply during the reproductive stage.

Other research examining lower nitrogen levels has shown that minimal nitrogen supply can actually enhance lycopene content in tomato fruits, particularly when coupled with sufficient water supply (4). Studies in hydroponic culture have demonstrated that either the lowest or medium levels of nitrogen application produced the best lycopene content, suggesting that optimal nitrogen levels for antioxidant production may be lower than those for maximum yield.

Potassium’s Role in Fruit Quality

Potassium plays a fundamental role in determining tomato fruit quality. Research has demonstrated that increasing potassium supply during the reproductive stage significantly enhances sugar concentration, vitamin C content, protein levels, lycopene, and beta-carotene in tomato fruits (3). The effect is particularly pronounced when potassium levels increase from 200 to 500ppm.

Another comprehensive study found that high proportions of potassium in the nutrient solution increased quality attributes including fruit dry matter, total soluble solids content, and lycopene content (5). However, these same researchers found that high proportions of calcium improved tomato fruit yield and reduced the incidence of blossom end rot, highlighting the importance of balancing these two nutrients.

Electrical Conductivity Management

One of the most innovative approaches to nutrient management involves carefully controlling the electrical conductivity (EC) of the nutrient solution. A study in closed NFT (Nutrient Film Technique) systems examined three different EC replacement set points: 5, 7.5, and 10 mS/cm (6). Remarkably, the highest EC replacement set point produced yields equivalent to lower EC treatments while significantly improving fruit quality.

The higher EC replacement threshold resulted in better dry matter content and total soluble solids in berries. Additionally, it demonstrated superior environmental sustainability by reducing total nutrients discharged into the environment by 37% compared to the medium EC treatment and 59% compared to the low EC treatment (6). This approach challenges conventional thinking about salinity stress in tomato production.

Calcium Management and Blossom End Rot

Calcium nutrition presents one of the most common challenges in hydroponic tomato production. Blossom end rot, characterized by dark lesions on the blossom end of fruits, results from calcium deficiency in developing fruits. However, this deficiency often occurs even when calcium levels in the nutrient solution appear adequate (1).

The problem frequently stems from antagonism between nutrients. Excessive potassium in the nutrient solution can interfere with calcium uptake by plant roots. This is particularly problematic early in the season when using pre-mixed fertilizers that contain high potassium levels. Growers working with water containing less than 50 ppm calcium need to be especially cautious about potassium concentrations.

To minimize blossom end rot, it’s critical to maintain calcium levels between 150 and 200 ppm while keeping early season potassium levels moderate. Some growers supplement calcium nitrate with calcium chloride to increase calcium availability without adding more nitrogen. Each pound of calcium chloride (36% Ca) in 30 gallons of stock solution increases calcium concentration by approximately 14 ppm in the final nutrient solution when injected at a 1% rate (1).

Effects on Yield and Quality Parameters

The differences between nutrient formulations can significantly impact both yield and fruit quality. Research consistently shows that inadequate nitrogen during fruiting stages produces lower yields, though the fruits may have better sugar content and flavor. Conversely, excessive nitrogen can produce abundant foliage at the expense of fruit production (4).

Potassium levels have a pronounced effect on fruit quality parameters. Adequate potassium improves fruit firmness, color development, and sugar content (3). However, excessive potassium can lead to calcium and magnesium deficiencies that compromise both yield and quality.

The timing of nutrient adjustments also matters significantly. Studies have shown that gradually increasing nutrient concentrations as plants transition from vegetative to reproductive growth produces better results than sudden changes in formulation. Plants that experience consistent, appropriate nutrition throughout their lifecycle typically show improved yields and more uniform fruit quality (6).

Practical Considerations

When implementing a nutrient program, several practical factors deserve consideration. Water quality plays a fundamental role in determining how much of each nutrient to add. Wells in many regions naturally contain significant calcium and magnesium, sometimes providing 40 to 60 ppm calcium (1). These naturally occurring nutrients should be factored into your formulation calculations.

The pH of your nutrient solution also affects nutrient availability. Research has established that maintaining pH between 5.5 and 6.0 ensures optimal nutrient uptake (2). Water with high alkalinity requires acidification, which can be accomplished using phosphoric acid or sulfuric acid depending on your phosphorus requirements.

The type of hydroponic system you're using may also influence your nutrient concentrations. Systems requiring fewer daily irrigation cycles may need higher nutrient concentrations to ensure plants receive adequate nutrition. The general principle is that nutrient concentrations should be higher in systems with less frequent fertigation compared to those with continuous or very frequent feeding (1).

Advanced Management: The Transpiration-Biomass Ratio

One of the most sophisticated approaches to nutrient management involves calculating a recovery solution based on the transpiration-biomass ratio (6). This method recognizes that the relationship between water use and dry matter production changes throughout the growing cycle.

Research has shown that the transpiration-biomass ratio is high early in the crop cycle (approximately 300 liters per kilogram of dry weight), decreases during mid-season to a relatively stable phase, and then increases again late in the season (up to 400 liters per kilogram). This pattern suggests that nutrient concentrations should be adjusted accordingly: lower concentrations in the first and last phases, and higher concentrations during the middle phase when biomass accumulation is most rapid.

Conclusion

Successful hydroponic tomato production requires careful attention to nutrient solution composition. While several proven formulations exist, the research clearly shows that no single approach works best for all situations. The Florida formulation with its conservative early nitrogen levels may be ideal for preventing bullishness in greenhouse production, while higher EC strategies can improve fruit quality in closed systems.

Key takeaways from the scientific literature include: maintain nitrogen between 60 and 70 ppm early in the season to prevent excessive vegetative growth, increase potassium substantially during fruiting to enhance quality parameters, keep calcium between 150 and 200 ppm throughout the season while monitoring potassium levels to prevent antagonism, and consider that higher EC values (up to even 10 mS/cm) may be feasible limits for nutrient solution replacement in recirculating systems.

Starting with a well researched base formulation and making careful adjustments based on plant response, tissue analysis, and your specific growing conditions provides the most reliable path to optimizing both yield and quality in your hydroponic tomato crop. The scientific evidence demonstrates that nutrient management is not a one-size-fits-all proposition, but rather a dynamic process that should respond to both plant developmental stage and environmental conditions.

Calcium silicate (wollastonite) in soilless crops

Silicon in media is not a magic switch. In soilless systems it can help, it can do nothing, and at the wrong rate or pH it can hurt. Calcium silicate sources such as wollastonite release plant-available Si into inert substrates and typically raise pH, which is useful in peat but potentially more risky in coir or already alkaline systems. A recent substrate study quantified this clearly: wollastonite steadily released Si for months and increased media pH about 0.5 to 1 unit depending on substrate composition (1). With that in mind, here is the evidence for tomatoes and cucumbers grown without soil, focusing only on media or root-zone applications.

Vansil CS-1, one of the most common forms of calcium silicate (wollastonite) used as an amendment in soilless crops.

Tomatoes

Two independent Brazilian groups that amended substrate with calcium silicate found quality benefits but also rate-sensitivity. In a factorial test across Si sources and doses, calcium silicate treatments improved postharvest durability and maintained physicochemical quality of fruits; the effect size depended on the source and the dose used (2). A protected-environment pot study that mixed calcium silicate into the substrate before transplanting reported reductions in gas exchange and chlorophyll at midcycle at higher rates, a warning that more is not always better (3). Earlier yield work that compared sources also detected response to silicon fertilization in tomatoes, but the magnitude varied with rate and material (4).

Cucumbers

When wollastonite was incorporated into the soilless substrate, 3 g L^{-1} increased yield by ~25% under moderate moisture restriction, with no penalty to soluble solids or fruit size. Lower doses or excessive irrigation did less (5). A separate work that applied a calcium-silicate solution into the substrate showed small gains in biomass under specific moisture regimes and no change in soluble solids, again pointing to context and dose as the deciding factors (6).

Practical takeaways for media use

1. Treat calcium silicate like a weak liming Si source. Expect a pH rise. In peat this can be helpful, in coir or high-alkalinity waters it can push you out of range (1).
2. Dose conservatively, then verify with tissue Si or leachate pH before scaling. Tomatoes show rate-sensitive physiology (3).
3. Target crops and situations with the strongest evidence. Cucumbers under moderate moisture restriction and strawberries in organic substrates show the clearest yield and quality benefits (5), (7).

Summary table – media or root-zone Si only

Crop	Medium and Si source	Application rate	Positive effects on yield or quality	Reported negatives	Ref
Tomato	Substrate mix, calcium silicate among Si sources	Field-equivalent 0 to 800 kg SiO_2 ha^{-1} mixed pre-plant	Improved postharvest durability and maintained physicochemical quality vs control; effect depended on dose and source	None specified at optimal rates	(2)
Tomato	Substrate, calcium silicate mixed before transplant	0, 150, 300, 450, 600 kg ha^{-1}	–	Reduced gas exchange and chlorophyll at midcycle at higher rates, indicating potential performance penalty	(3)
Tomato	Substrate, silicon sources including calcium silicate	Multiple rates	Yield responded to Si fertilization depending on source and rate	–	(4)
Cucumber	Soilless substrate, wollastonite	3 g L^{-1} of substrate under 75-85% container capacity	+24.9% yield vs untreated; fruit size and soluble solids unchanged	None noted at that rate	(5)

Crop	Medium and Si source	Application rate	Positive effects on yield or quality	Reported negatives	Ref
Cucumber	Substrate drench, calcium silicate solution	50-100 mg L^{-1} SiO_2 applied to substrate	Biomass gains under specific moisture regimes; quality unchanged	No quality gain at tested doses; response moisture-dependent	(6)
Any	Peat or coir mixes, wollastonite	~1 g L^{-1} media typical in study	Steady Si release over months supports long crops	Raises media pH by about 0.5-1 unit depending on substrate	(1)

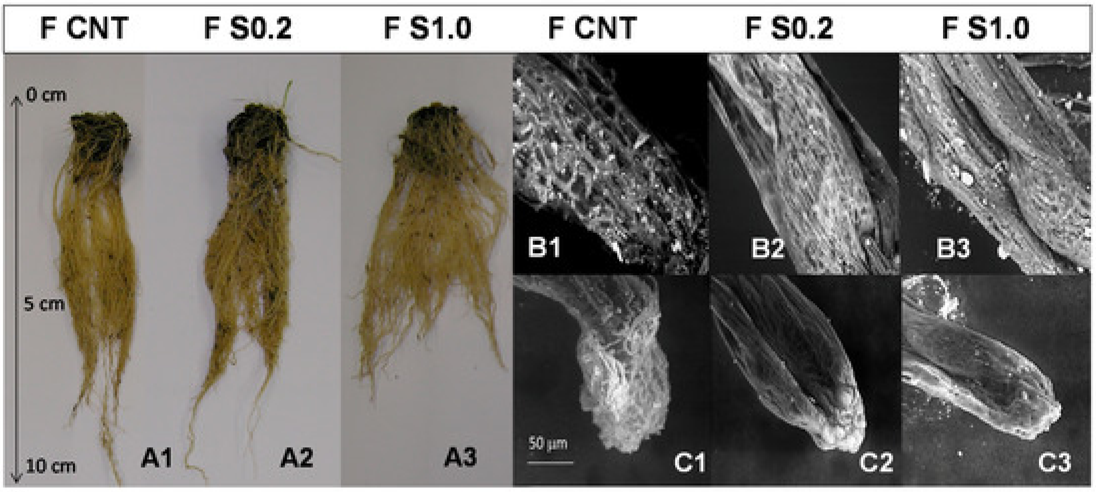
Bottom line

Use calcium silicate where the crop and context justify it, not by default. For cucumbers and strawberries the upside on yield and quality is most consistent when Si is in the root zone. For tomatoes, treat calcium silicate as a quality tool with a narrow window and verify plant response; higher rates can backfire physiologically. If you want to try calcium silicate, mix wollastonite with your media at a rate of 3g L^{-1}, then test the effect on pH and Si in tissue.

Exogenous Root Applications of Wetting Agents in Soilless Media

Introduction

Dry peat, coir, rockwool or bark mixes can become water repellent, which creates uneven moisture and nutrient delivery around roots. Wetting agents reduce surface tension and restore wettability by improving water contact with hydrophobic surfaces, an effect well documented for organic growing media used in horticulture (6). In soilless systems, exogenous root applications are used to correct dry-back, stabilize irrigation performance, and improve nutrient distribution. This post reviews what has been tested, how these agents affect mineral nutrition, water uptake, yield and quality, known toxicity limits, and realistic application rates.



Effect of surfactants on roots. Taken from (7)

Evidence and discussion

Types tested

Most root-zone wetting agents in horticulture are nonionic surfactants such as alcohol ethoxylates, block copolymers, or organosilicone derivatives; anionic formulations are less common for routine root use due to higher phytotoxic risk, while cationic types are generally avoided; amphoteric agents are used less frequently but appear in some products. The role of wetting agents to counter water repellency in organic media is supported by a comprehensive review of wettability mechanisms and amendments (6).

Water uptake and distribution

In rockwool and coir, adding a nonionic surfactant to the fertigation stream at doses from 2 to 20 000 ppm showed that a **minimal** dose could be sufficient: **2 ppm** increased easily available water by more than 600 percent, while higher concentrations gave no extra benefit (1). Across peat, coir, and bark, wetting agents improved hydration efficiency, although severely dry materials retained some hydrophobic pockets that were not fully overcome by surfactant treatment (2).

Mineral nutrition

In a melon crop on rockwool and reused coco fiber, weekly fertigations with a nonylphenol ethoxylate at about **1000 ppm** reduced nitrate and potassium losses in drainage and increased potassium uptake, while leaving total water use and pH unchanged (3). In lettuce, fertigation with a nonionic organosilicone-type surfactant at **200 ppm** and **1000 ppm** improved nutrient use efficiency without increasing yield, indicating better capture of applied nutrients for the same biomass and specifically in field trials with a methyl-oxirane nonionic surfactant. Direct lettuce evidence of improved nutrient use efficiency and root-zone wetting with **~200–1000 ppm** doses comes from an in-field trial using a nonionic methyl-oxirane surfactant (6) and is detailed further under quality effects below.

Yield and quality

Yield responses depend on whether water distribution was limiting. In lettuce, the nonionic surfactant improved nutrient use efficiency but did **not** increase marketable yield under well-watered conditions. Quality can benefit: lettuce fertigated with a nonionic methyl-oxirane surfactant at **~1000 ppm** showed a significant reduction in leaf nitrate accumulation compared with controls, alongside indications of shallower, more uniform wetting of the upper root zone (6).

Persistence and accumulation

Repeated use matters. In sand models, a polyoxyalkylene polymer surfactant (PoAP) sorbed to particles and **increased hydrophobicity** after repeated applications, whereas an alkyl block polymer (ABP) maintained or improved wettability and did not leave a hydrophobic residue. Chemistry dictates long-term behavior, so product choice is critical (4).

Toxicity

There is a hard ceiling for some agents. Hydroponic lettuce exposed to the anionic detergent Igepon showed acute root damage at **≥250 ppm**, with browning within hours and growth suppression, although plants recovered after the surfactant degraded in solution (5). Practical takeaway: avoid harsh anionic detergents and keep any surfactant well below known toxicity thresholds.

Tables

Table 1. Water behavior in soilless substrates after root-zone wetting agents

Study (Ref)	System and media	Surfactant and dose	Key outcome
(1)	Rockwool and coir, new and reused	Nonionic surfactant, 2–20 000 ppm	**2 ppm** raised easily available water by >600 percent; higher doses gave no additional gain

Study (Ref)	System and media	Surfactant and dose	Key outcome
(2)	Peat, bark, coir under different initial moistures	Commercial wetting agent, low to high	Hydration efficiency improved across materials, but extremely dry media retained some hydrophobic zones

Table 2. Nutrient dynamics, yield, quality, and safety

Study (Ref)	Crop and system	Regime and dose	Observed effect
(3)	Melon in rockwool and reused coco	Weekly fertigation at ~1000 ppm	Lower nitrate and potassium leaching, higher K uptake, no change in water use or pH
(6)	Lettuce, fertigated field context	Nonionic surfactant ~200–1000 ppm	Improved nutrient use efficiency; neutral yield response; reduced leaf nitrate at higher dose
(4)	Sand columns, repeated applications	PoAP vs ABP, repeated dosing	PoAP accumulated and increased hydrophobicity; ABP maintained or improved wettability
(5)	Lettuce in hydroponics	Anionic detergent ≥250 ppm	Acute root phytotoxicity at and above 250 ppm; recovery after degradation of the agent

Practical rates

In closed hydroponic or recirculating fertigation, start conservatively. Research showing benefits without injury typically used **~50–1000 ppm**, with several studies centering on **~1000 ppm** weekly pulses in drip systems, or **~200–1000 ppm** continuous-equivalent dosing in trials on leafy greens (3) (6). Very low concentrations can already fix wettability issues, as the 2 ppm result illustrates (1). Always monitor for foaming, root browning, or oily films. Avoid cationic disinfectant-type surfactants at the root zone and keep anionic detergents far below the **250 ppm** lettuce toxicity threshold (5). Choose chemistries that do not accumulate with repeated use (4).

Conclusion

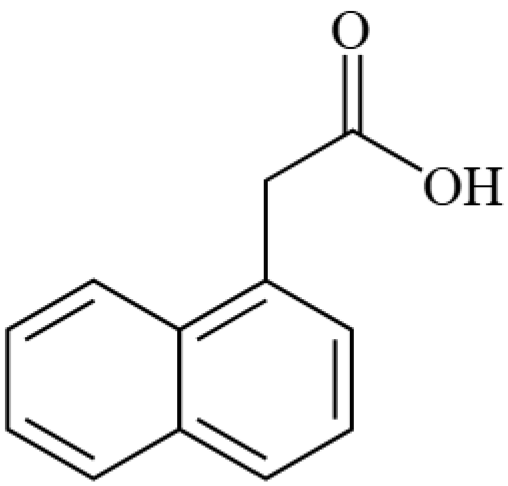
For soilless production, exogenous root applications of wetting agents are a precise way to restore uniform wetting, stabilize nutrient delivery, and improve nutrient use efficiency. Expect neutral yield when irrigation is already optimal, but better quality in leafy greens via lower leaf nitrate, and less nutrient loss in drain when media are reused or prone to channeling. Use the lowest effective ppm, prefer nonionic chemistries validated in horticultural systems, and be wary of products that persist or sorb to media. Done right, wetting agents are a small, high-leverage tweak that keeps the entire root zone working for you, not against you.

Root-applied auxins in

hydroponics: where they help, where they don’t

Introduction

Auxins can modulate root architecture, fruiting and stress responses. In hydroponic and substrate soilless systems, exogenous **root-zone** applications at very low ppm sometimes boost yield or quality. Push the dose and you flip the response. Below I review peer-reviewed work on widely grown crops, focusing on species, timing, exact dosages converted to ppm, and toxic thresholds. Where possible I prioritize reviews to frame context, but yield data come from primary trials.



Model representation of the NAA molecule, a very commonly used auxin in plant culture.

Evidence & discussion

Sweet pepper. Two lines of evidence exist. First, fertigation with a commercial IBA product at **0.4 percent** active (4000 ppm in the stock) applied **weekly from early fruit development** at **0.5 L ha^{-1}** outperformed **1.0 L ha^{-1}**, increasing marketable yield while improving root mass and water and nutrient uptake in perlite culture (1). Second, a separate trial compared **root**

fertigation vs foliar using a formulation containing **6.75 g L^{-1} NAA** and **18 g L^{-1} NAA-amide**. The fertigation rate was **0.6 mL L^{-1}** of product in the solution, equal to **~4 ppm NAA** plus **~10.8 ppm NAA-amide** per application; foliar used **0.4 mL L^{-1}** or **~2.7 ppm NAA** plus **~7.2 ppm NAA-amide**. Early and total yield were higher with fertigation, while foliar favored some quality traits like firmness and soluble solids (5). Practical read: peppers respond to root-zone auxin in the **single-digit ppm** range, but more is not better.

Melon. The same IBA approach that helped pepper flopped in melon. In perlite greenhouse culture, **0.4 percent IBA** applied **weekly** at **0.5 or 1.0 L ha^{-1}** did **not** improve yield or water or nutrient relations. Authors concluded it is not an effective tool for commercial melon in soilless culture (2). Species matter.

Strawberry. In long recirculating systems, autotoxic phenolics depress growth and fruiting. A **one-time root or crown dip** in NAA **before transplant** at **5.4 µM** NAA, which is **~1 ppm**, mitigated autotoxicity and restored flower and fruit numbers compared with untreated plants. A higher **54 µM** dose, about **10 ppm**, was less effective (3). Timing was everything.

Toxic thresholds from hydroponic seedlings. While not a yield trial, maize in nutrient solution shows the margins. IBA at **10^{-11} M** is **~0.000002 ppm** and stimulated root growth, but **10^{-7} M** is **~0.02 ppm** and significantly stunted primary root elongation and biomass. The same hormone switches from helpful to harmful across four orders of magnitude (4). That narrow window explains why melon trials can miss and pepper trials can hit. For broader context on root-zone biostimulation via fertigation programs, see this review (6).

Tables

Table 1. Positive responses to exogenous auxin at the root zone in soilless crops

Crop & system	Auxin and delivery	Dose in root zone (ppm)	Timing	Outcome
Sweet pepper, perlite	IBA 0.4 percent product via fertigation	Stock is **4000**; applied **0.5 L ha⁻¹ weekly**	From early fruit development	Higher marketable yield at 0.5 vs 1.0 L ha⁻¹; improved root mass and water and nutrient uptake (1)
Sweet pepper, soilless	NAA + NAA-amide via fertigation	**~4** NAA + **~10.8** NAA-amide per application	Weekly during production	Higher early and total yield vs foliar; foliar favored firmness and °Brix (5)
Strawberry, recirculating hydroponics	NAA root or crown dip	**~1** optimal; **~10** less effective	One time at transplant	Mitigated autotoxic yield loss; restored flower and fruit counts under closed reuse (3)

Table 2. Null results and toxic thresholds

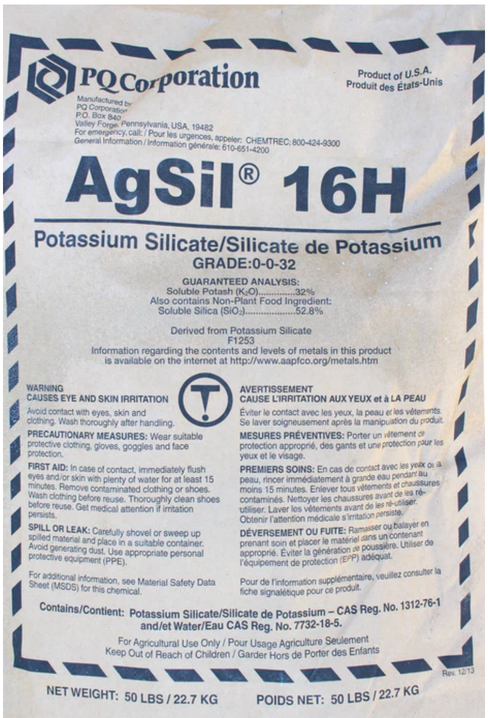
Crop or context	Auxin & delivery	Threshold or tested dose (ppm)	Timing	Result
Melon, perlite greenhouse	IBA 0.4 percent via fertigation	Stock **4000**; **0.5 or 1.0 L ha⁻¹ weekly**	Season-long	No improvement in yield or water or nutrient relations (2)
Maize seedlings, hydroponic assay	IBA in solution	**0.000002** stimulatory vs **0.02** inhibitory	Continuous exposure	Root growth stimulation at ultra-low ppm but marked stunting by **0.02 ppm** (4)

Conclusion

Root-applied auxins are not a silver bullet. They can raise yield or preserve quality, but only when dose and timing line up with the crop's physiology. Peppers respond to **single-digit ppm** root fertigation with higher early and total yields, while melons do not. Strawberries benefit from a **~1 ppm** pre-plant dip that preempts autotoxicity, whereas **~10 ppm** underperforms. Hydroponic seedling work reinforces the risk: **~0.02 ppm** IBA already suppresses maize roots. The safe play is to trial low, crop-specific ppm near published values, apply at the stage that matters, and stop if marketable yield does not move. If you treat auxins like a nutrient and "turn them up," they will punish you. If you treat them as a precise signal, they can pay off.

How to easily lower the costs of your Athena nutrient regime

You can make your Athena schedule much cheaper by replacing the pH up products with simple raw salts. Branded pH management and buffering products like Athena Balance and Athena Pro Balance are, at their core, just sources of potassium bases delivered in carbonate or silicate form. They are however, very over priced for what they are and can be a high percentage of the overall cost of running these nutrient regimes. By understanding their labels and safety data sheets, we can replicate these formulations with commodity salts, achieving equivalent nutritional and pH adjusting outcomes at a fraction of the cost.



AgSil 16H, a very common base used to prepare potassium silicate solutions.

Athena Pro Balance can be replaced with Potassium Carbonate
The powdered Pro Balance product is likely nothing more than high-purity potassium carbonate (K_2CO_3), usually 98.5–100% pure. Chemically, K_2CO_3 contains ~68% K_2O-equivalent by weight, which is exactly what the Athena Pro Balance label reflects. This means you don't need to blend or dilute anything to make a replacement, simply sourcing food-grade or fertilizer-grade potassium carbonate is sufficient. You can dose it directly as you would the branded powder, bearing in mind it is strongly alkaline and should be added to water with care. Storage should be in sealed HDPE containers to avoid caking from atmospheric moisture.

Athena Blended Balance (liquid) can be replaced with an AgSil 16H solution
The liquid Balance label shows 2% K_2O. AgSil 16H, a common potassium silicate source, contains 32% K_2O and ~53% SiO_2. To reproduce the K_2O content of Athena Balance, you need to dilute AgSil at the correct ratio:

- Target is 2% K_2O.
- Required fraction = 2 / 32 = 0.0625.
- This means 6.25% (w/w) AgSil in water.

Translated to a practical recipe, this equals **236.6 g of AgSil 16H per US gallon of solution** (3.785 L), topped up with RO water (must be RO or distilled water). Dissolve the AgSil slowly with vigorous mixing, as potassium silicate is highly viscous and alkaline. The result is essentially identical in potassium concentration to the branded Balance, with the added benefit of supplying soluble silica (~1.55% Si in the solution).

Improving stability with KOH
One common issue with potassium silicate solutions is their tendency to polymerize or precipitate over time, especially at lower concentrations or in the presence of divalent cations.

To mitigate this, adding a small amount of potassium hydroxide (KOH) helps maintain a strongly alkaline environment that discourages silica gelation. For the recipe above, **adding 1 g of KOH per gallon** of solution is a simple way to improve stability during storage. This will not significantly change the K_2O content but will keep the solution more stable and easier to handle.

Cost Analysis

Beyond the chemistry, cost is the main driver for making these substitutions. Let's look at a ballpark comparison based on typical retail prices (USD, 2025):

Product	Retail Price	Equivalent Raw Material	Raw Material Price	Cost per Gallon of Finished Equivalent
Athena Pro Balance (powder)	~$7 per lb	Potassium carbonate	~$2 per lb	Replacement is more than 3x cheaper
Athena Balance (liquid)	~$20-40 per gallon	AgSil 16H + 1 g KOH	~$6.4 per lb AgSil, ~$5 per lb KOH (~3$ AgSil + 1c of KOH per gal)	Replacement costs is around 10x cheaper

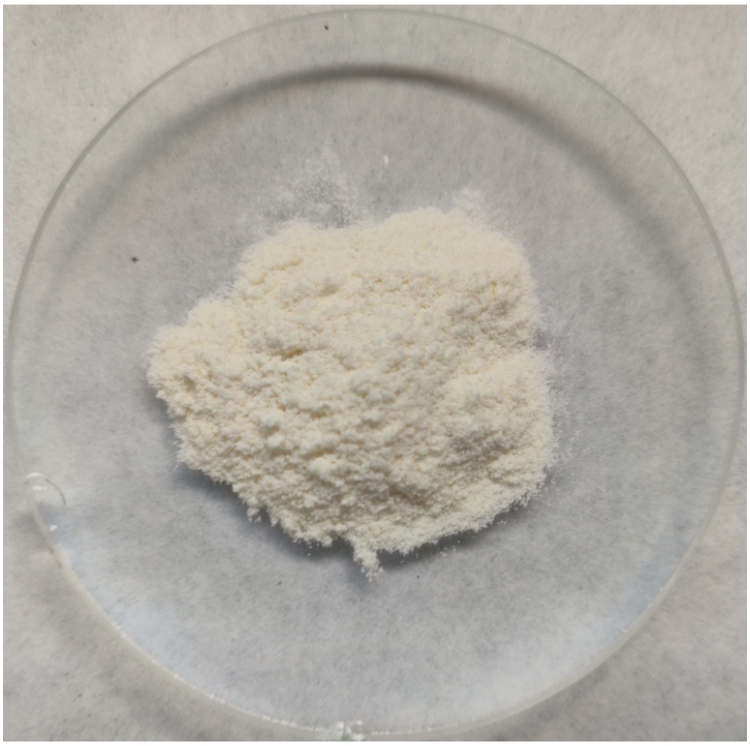
For the Balance liquid in particular, the price difference is striking: the branded gallon runs around $20-40, while the equivalent solution made from AgSil 16H plus a pinch of KOH comes out to under $3 per gallon, even at retail chemical pricing. The Pro Balance substitution is less dramatic in absolute terms but still represents substantial savings over time.

Take-home message

Replacing Athena Pro Balance is as simple as sourcing potassium carbonate, while Athena Balance can be reliably reproduced with a potassium silicate solution prepared from AgSil 16H plus a small stabilizing addition of KOH. For growers comfortable working with raw salts, this substitution strategy provides full control, predictable composition, and significant cost savings while providing a drop-in replacement for one of the most expensive parts of the Athena nutrient line.

Chitosan in hydroponic and soilless crops: what actually works

In hydroponic and substrate systems chitosan can help, but only inside fairly narrow windows of dose, molecular traits, and crop context. Here is what the strongest hydroponic and soilless evidence shows for common greenhouse crops, with doses in ppm and forms that have actually been tested in peer-reviewed trials.



Chitosan powder, used as a biostimulant in soilless cultivation

What matters before you dose

Form and solubility. Most horticultural studies use acid-solubilized chitosan, typically chitosan acetate prepared by dissolving chitosan in dilute acetic acid. Solubility improves as degree of deacetylation increases and molecular weight decreases. That changes biological activity and leaf penetration, which is why not all chitosans behave the same in crops grown without soil. Review data across crops confirms that activity depends on origin, degree of deacetylation, molecular weight and derivative used, not just “chitosan” on the label (1).

Degree of deacetylation and molecular weight. Higher deacetylation increases positive charge density and solubility in the acidified sprays most growers use. Lower to mid molecular weight generally penetrates tissues better; very high molecular weight tends to act more at surfaces. Reviews focused on crop plants note these relationships and explain why different products show inconsistent results if DD and MW are not controlled (1).

Application route. Foliar and rootzone applications are not interchangeable. Foliar sprays in hydroponics commonly use 50 to 200 ppm for stress mitigation and quality endpoints. Rootzone dosing inside recirculating solutions can work for disease suppression at similar or higher ppm, but the tolerance window is tighter and crop-dependent. A 2024 root-focused review flags that root exposure can inhibit growth if dose and MW are off, even while defense responses go up (2).

Source. Commercial material is generally crustacean-derived, with fungal-derived chitosan available at smaller scale. Origin mainly matters through DD, MW and impurities like ash and protein. Again, agronomic performance maps back to those properties rather than source alone (1).

What the hydroponic and soilless studies actually show

Leafy greens and fruiting vegetables most tested in soilless settings

- **Lettuce, deep-flow hydroponics, foliar.** In a controlled deep-flow system, foliar chitosan at 100 ppm mitigated salt stress, improved relative water content and chlorophyll, and reduced membrane damage markers. The trial used exogenous chitosan applied to leaves while plants grew in circulating nutrient solution, so the result is directly relevant to recirculating NFT or DFT growers (3).
- **Cucumber, hydroponic rootzone, disease control.** In a classic hydroponic study, adding 100 to 400 ppm chitosan to the nutrient solution suppressed Pythium aphanidermatum root rot and induced host defenses without visible phytotoxicity at those doses. This is

one of the best-controlled demonstrations of rootzone efficacy in a soilless system (4).

- **Tomato, soilless substrate, chitosan-based material at the rootzone.** A soilless peat and perlite greenhouse system received a chitosan polyvinyl alcohol hydrogel with copper nanoparticles placed in the rootzone. The treatment improved growth, antioxidant capacity and yield relative to the untreated control. This is not a simple chitosan salt spray and the dose was delivered as a solid material rather than a ppm solution, but it shows chitosan-based materials can be integrated into substrate programs in practice (5).
- **Context across crops.** A comprehensive review of chitosan for plant protection and elicitation explains the defense activation seen above and why responses are dose and MW dependent. It also documents successful use patterns that generalize to greenhouse crops treated by foliar or root routes (6).

Practical dose ranges that align with the hydroponic evidence

If you want the odds on your side in hydroponics or inert substrates, stay inside these lanes and confirm on a small block first.

- **Foliar, leafy greens and fruiting vegetables in hydroponics or inert substrate.** 50 to 150 ppm per spray, usually every 7 to 10 days around stress periods. The deep-flow lettuce result sits at 100 ppm and delivered physiological benefits under salinity (3).
- **Rootzone, recirculating hydroponics.** 100 to 400 ppm in the circulating solution only when you have a clear disease target like Pythium in cucumber. For general biostimulation, root dosing is higher risk. The

hydroponic cucumber study used 100 and 400 ppm to suppress Pythium effectively (4). Outside this range you are more likely to see growth penalties than benefits according to root-focused syntheses (2).
- **Chemistry targets when purchasing.** Prefer DD around 80 to 90 percent and low to mid MW material for foliar work. Verify supplier certificates rather than marketing bullets. The crop reviews explaining DD and MW effects are clear that these traits determine outcomes (1).

Summary tables

Table 1. Trials in hydroponic or soilless systems with chitosan

Crop	System	Application route	Chitosan form	Dose used (ppm)	Reported effect	Reference
Lettuce	Deep-flow hydroponics	Foliar spray	Acid-solubilized chitosan solution	100	Mitigated salinity stress, higher RWC and chlorophyll, lower oxidative damage	(3)
Cucumber	Hydroponics	Rootzone in nutrient solution	Chitosan solution in recirculating feed	100 to 400	Suppressed Pythium root rot, induced defense enzymes, no visible phytotoxicity at tested doses	(4)

Crop	System	Application route	Chitosan form	Dose used (ppm)	Reported effect	Reference
Tomato	Soilless substrate, peat plus perlite	Rootzone material in substrate	Chitosan PVA hydrogel with Cu nanoparticles	not applicable as ppm	Improved growth, antioxidant capacity and yield versus control in substrate culture	(5)

Table 2. Chemistry traits that move the needle

Trait	Why it matters in soilless culture	Practical target
Degree of deacetylation	Higher DD increases solubility in dilute acids used for sprays and increases cationic charge for leaf interaction	80 to 90 percent DD for foliar sprays (1)
Molecular weight	Lower to mid MW improves penetration and reduces viscosity. Very high MW can sit on surfaces and act mainly as an elicitor	Low to mid MW for foliar, avoid very high MW for root dosing (1)
Source	Crustacean and fungal sources both work. Performance depends on DD, MW and impurities, not source alone	Buy on spec sheet, not species label (1)

Table 3. Foliar versus root applications in hydroponics and substrates

Dimension	Foliar application	Root application
Typical working range	50 to 150 ppm per spray	100 to 400 ppm in the solution when disease control is the objective
Primary targets	Stress mitigation, quality traits, mild growth stimulation	Pathogen suppression in roots and elicitation of defenses
Risk profile	Low when DD and MW are appropriate and pH is controlled	Higher. Dose and MW errors can reduce root growth and yield
Evidence base in soilless settings	Deep-flow lettuce shows clear physiological benefits at 100 ppm (3)	Hydroponic cucumber shows robust Pythium control at 100 to 400 ppm (4)

How to deploy without shooting yourself in the foot

1. **Start with foliar at 100 ppm on a small block.** If your chitosan is low to mid MW and 80 to 90 percent DD, you are in the same ballpark as the effective lettuce hydroponic protocol (3).
2. **Reserve root dosing for disease pressure.** If you are chasing Pythium in cucumber, 100 to 400 ppm in the solution is supported. For general "growth promotion", root dosing is more likely to backfire than help in recirculating systems (4), (2).
3. **Verify product specs.** Ask for DD and MW. If the vendor will not provide them, find one who will. The variability you see in practice maps to those two numbers (1).
4. **Do not stack unknowns.** Mixing chitosan with copper, acids, or surfactants without a clear recipe can change

activity. That can help in substrate programs where materials are embedded, as in the hydrogel example, but it is not a blank check (5).

5. **Measure the outcome that pays.** Run a side-by-side block with your limiting stress in view. If you cannot tie chitosan to a measurable gain in yield, quality or loss avoidance in your system, move on. Elicitation without payoff is just cost (6).

Iodine in Hydroponic Crops: An Emerging Biostimulant

Introduction

Iodine sits in a weird spot in plant nutrition. It is essential for humans, not officially essential for higher plants, yet low, well chosen doses often push crops to perform better in controlled systems. The key is dose and form. Get either wrong and you tank growth. Get them right and you can see yield and stress-tolerance gains that are economically meaningful. Recent reviews lay out both the promise and the pitfalls, so let's cut through the noise and focus on agronomically relevant hydroponic and soilless work only. (1)

Potassium iodide, one of the most common forms used to supplement iodine in hydroponic culture.

Why iodine can behave like a biostimulant

Mechanistically, iodine at trace levels appears to influence redox balance and stress signaling and can even become covalently bound to plant proteins. Proteomic evidence has shown widespread protein iodination, and plants deprived of iodine under sterile hydroponics grow worse until micromolar-range iodine is restored. That does not make iodine “essential” in the strict sense, but it explains why tiny doses can trigger outsized responses. (2)

Form matters

Across multiple hydroponic tests, iodide is absorbed faster and is more phytotoxic than iodate. In basil floating culture, growth was unaffected by roughly 1.27 ppm iodine as KI or 12.69 ppm iodine as KIO_3, but KI above about 6.35 ppm iodine cut biomass hard, while KIO_3 needed far higher levels to do the same. That is a practical takeaway for nutrient solution design. Favor iodate when you are exploring a new crop or cultivar. (3)

Evidence from hydroponic and soilless crops

Lettuce

A classic water-culture study ran 0.013 to 0.129 ppm iodine in solution and saw no biomass penalty while leaf iodine rose predictably. Iodide enriched tissue more than iodate at equal iodine, which is useful if your target is biofortification, not just a biostimulant effect. (4)

Under salinity, iodate becomes more interesting. In hydroponic lettuce with 100 mM NaCl, about 2.54 to 5.08 ppm iodine as KIO_3 increased biomass and upregulated antioxidant metabolism, which is exactly what you want in salty recirculating systems. Push higher and the benefits fade. (5)

Strawberry

Hydroponic strawberry responded to very low iodine. Iodide at or below 0.25 ppm and iodate at or below 0.50 ppm improved growth and fruit quality, while higher levels reduced biomass and hurt fruit quality metrics. You do not have much headroom here. (6)

Basil

Greenhouse floating culture trials on sweet basil showed cultivar-specific tolerance but the same pattern every time. KI starts biting growth above single-digit ppm iodine, while KIO_3 is far gentler at comparable iodine. Antioxidant capacity trends are cultivar dependent, so do not generalize “more phenolics” as a guarantee of better growth. (7)

Tomato

Tomato is where yield effects get real. In growth-chamber work, fertigation with iodate at roughly 6.35 to 12.69 ppm iodine increased fruit yield by about 30 to 40 percent in a small-fruited cultivar. In a greenhouse trial with a commercial hybrid, much lower iodine in solution, around 0.025 to 1.27 ppm as KIO_3, still improved plant fitness and mitigated part of the salt penalty. Dose tolerance depends on the system and the genotype, so copy-pasting numbers between cultivars is a bad idea. (8)

Cabbage

Hydroponic Chinese cabbage tested 0.01 to 1.0 ppm iodine as KI or KIO_3. Uptake and partitioning behaved differently by species and form. The practical read is that both forms work for biofortification within that band, but I would still lean iodate first for safety. (9)

Working ranges seen in hydroponic or soilless trials

Crop	System	Iodine form used	Dose range tested in literature (ppm as I)	Observed direction of effect
Lettuce	Water culture	Iodide and iodate	0.013 to 0.129	Neutral on biomass, strong tissue enrichment at all doses tested

Crop	System	Iodine form used	Dose range tested in literature (ppm as I)	Observed direction of effect
Lettuce under salinity	Hydroponic with 100 mM NaCl	Iodate	~2.54 to 5.08	Biomass increased, antioxidant system activation
Strawberry	Hydroponic	Iodide and iodate	Beneficial at or below 0.25 (I−) and 0.50 (IO3−)	Growth and fruit quality improved at low doses, declines above
Basil	Floating culture	Iodide and iodate	Safe near 1.27 as KI, 12.69 as KIO_3; toxicity above ~6.35 as KI	KI far more phytotoxic than KIO_3 at equal iodine
Tomato	Substrate fertigation and growth chamber	Iodate	~0.025 to 12.69 depending on setup	Yield and stress tolerance improved within study-specific bands
Cabbage	Hydroponic	Iodide and iodate	0.01 to 1.0	Both forms accumulated; response form-dependent

Practical setup that does not wreck

a crop

Start with iodate. It is consistently less phytotoxic in solution culture than iodide at the same iodine level. Use iodide later only if you have a clear reason. (7)

Leafy greens
Conservative exploratory band: 0.03 to 0.10 ppm iodine in solution during vegetative growth. If you are running saline conditions, you can test up to about 2.5 to 5.1 ppm as iodate for stress mitigation, but do not do this blind outside a salinity trial. (4) (5)

Strawberry
Keep solution iodine low. Try 0.05 to 0.25 ppm as iodide or 0.10 to 0.50 ppm as iodate. Expect quality shifts alongside biofortification, and expect penalties if you push higher. (6)

Basil
If you work with KI, do not exceed about 1.3 ppm iodine without a reason and tight monitoring. With KIO3, you have more headroom, but benefits are not guaranteed at the higher end. (7)

Tomato
In substrate systems, exploratory fertigation bands that have shown positive responses run roughly 0.025 to 1.27 ppm iodine as iodate for commercial cultivars. Higher doses around 6.50 to 12.50 ppm have improved yield in small-fruited genotypes under controlled conditions, but those are not starting points for a commercial house. (8)

Cabbage and other Brassicas
0.01 to 1.0 ppm works for biofortification trials in solution culture. Track form-specific uptake. (9)

Common failure modes

1. **Using iodide when you should have used iodate.** Iodide is more phytotoxic in water culture. If you switch to iodide, cut the ppm accordingly and watch plants closely. (7)
2. **Copying doses between crops or between stress contexts.** Lettuce under salt stress tolerated and benefited from multi-ppm iodate that would be overkill in non-saline runs. (5)
3. **Chasing biofortification at the expense of growth.** Strawberry is very sensitive; the window for improvement is narrow and easy to overshoot. (6)
4. **Assuming universality.** Tomato shows real yield gains, but the best range depends on cultivar and system. Validate locally. (8)

Crop	Best form to start	Trial band to test next (ppm as I)	Notes you should not ignore
Lettuce	KIO_3	0.03–0.10 for routine runs; up to 2.5–5.1 only in salinity trials	Tissue enrichment is easy at sub-ppm; benefits need stress context
Strawberry	KI or KIO_3	0.05–0.25 as KI; 0.10–0.50 as KIO3	Quality improved at low levels; penalties above
Basil	KIO_3	0.5–3.0	KI becomes risky above low single digits

Crop	Best form to start	Trial band to test next (ppm as I)	Notes you should not ignore
Tomato	KIO_3	0.025–1.27 in commercial substrate; leave 6.5–12.5 to controlled trials	Verify by cultivar; watch fruit quality metrics
Cabbage	KIO_3	0.05–0.5	Uptake is efficient; track partitioning by organ

Final word

Iodine can behave like a biostimulant in hydroponics and soilless systems, but only if you respect its razor-thin margin between helpful and harmful. Start small, prefer iodate, and validate on your own cultivars and systems instead of trusting a one-size-fits-all recipe. If you need a broader framework for running precise biofortification trials in soilless production, recent reviews are clear about why controlled systems are the right place to do this work. (9)