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Bridging soil-based and soilless nutrient management in horticulture: Mechanisms and technologies

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Abstract
Horticulture plays vital role for food security, rural employment and environmental protection. However, nutrient management in horticulture is divided into two main approaches. Integrated Nutrient Management (INM) focuses on nutrient cycling in soil systems. Secondary, hydroponic, aeroponic, aquaponic and vertical-farming systems depend on engineered nutrient solutions with little or no inclusion of rhizosphere science. This review summarizes recent work in both fields, contrasts their approaches to nutrient provision, and highlights a key research gap, which is the need to adapt and test the biological and rhizosphere-based principles of INM to soilless and controlled environment horticulture. The review also discusses biofertilizer and mycorrhizae application in soilless media, nano-fertilizer technology, decision support through the use of artificial intelligence and the influence of energy, economic and regulatory factors on adoption. The authors argue that the science of horticulture should include knowledge of soil-plant-microbe interactions with the same degree of precision as the application of nutrients in a controlled environment.

Keywords: Hydroponics; vertical farming; nutrient use efficiency; biofertilizers; precision horticulture

Introduction

The share of global agricultural land on which horticulture is practiced is rather modest, but the share that Horticulture represents in the global agricultural value, contribution to the nutrition and rural employment. [1]. Globally, food demand continues to increase (projected to grow by 35-56% by 2050 relative to 2010 levels) and will further stress nutrient supply chains, soil fertility and water resources [2]. The food and agriculture organization and its partner agencies report that elevated input costs and climate variability continue to erode access to nutritious food even as production intensifies [3]. The central issue in horticultural production is that crops (fruit, vegetable and ornamental), require significant levels of nutrients to satisfy high quality standards, often over very short production periods. [4].

Two research and practice approaches to meet this need have been developed. First is Integrated Nutrient Management (INM), in which organic, inorganic and biological sources of nutrients are combined so that nutrient supply can be matched to crop need in soil-based agriculture. [4]. Over the last 5 years, the INM science base has progressed significantly from being a mostly empirical exercise comparing crop yields to a mechanistic understanding of root exudation, rhizosphere pH changes, microbial nutrient cycling and the role of the mycorrhizal symbiosis [4]. The second has formed a nucleus of systems under managed circumstances. CEA (CEA systems that utilize water but not soil, such as water level culture, aeroponics, aquaponics, and also vertical farms) supply nourishment for roots with manufactured mechanisms instead than soil and have begun spreading quickly as a local climate-savvy action to reduce area prices as well as desire for locally grown winter-weather greens. [5].

These two approaches are rarely linked in the literature. Reviews of horticultural technology often mention precision agriculture, robotics, biotechnology, and controlled-environment systems together but do not discuss how their nutrient management methods differ or could be shared [1]. INM reviews indicate that digital as well as precision technologies are not well integrated into traditional nutrient management, and that rhizosphere biology remains underrepresented, even in soil-based INM studies [4]. Most of reviews for vertical farming address climate change adaptation, space-use, and urban food security, but usually neglect nutrient-use as an engineering issue; it's dealt as an engineering concern and represented with measurements like electrical conductivity, pH, and ion concentrations, not as a biological phenomenon. [5]. So far, no review has asked whether the microbial, root exudate, and soil organic matter mechanisms that make INM effective in the field can be adapted or redesigned for soilless and controlled-environment systems.

This review meets this gap by first explaining how INM works in soil-based horticulture, then examining nutrient-solution management and biological inputs in hydroponic, aeroponic, and aquaponic systems. It compares the two approaches in terms of nano- and digital-nutrient technologies, energy and economic issues, and certification policies. The review concludes with specific research priorities to develop an integrated nutrient management framework encompassing both soil-based and soilless horticulture.

2. Nutrient Management in Soil-Based Horticultural Systems

2.1 Components of Integrated Nutrient Management

INM focuses not on any one input, but a careful mix of inorganic fertilizers, organic manures, bio-fertilizers, micronutrient sources, green manures, crop residue, soil amendment and legume rotations [4]. Whereas Inorganic fertilizers release readily available macro- and micro-nutrients during crop demands while organic sources like FYM, compost and vermicompost releases nutrients slowly and concurrently build up soil organic carbon, cation exchange capacity, and water holding capacity of soil [4]. Meta-analyses in horticultural and vegetable production system have demonstrated that using organic inputs alone increases yields by approximately 42% compared to unfertilized soil, and a significant, albeit smaller, yield advantage over the full synthetic fertilizer inputs and soil organic matter, total N, P and K pools [11, 12]. Fertilization of any type (mineral or organic) across 551 field experiments globally boosts average yields of crops by approximately 31% and increases nutrient concentrations of foods by about 12%, and vegetables responded most significantly [10].

Green manures, bio-fertilizers and micro- nutrients fill up the INM package. The micronutrients-zinc, iron, boron, manganese (applied either on soil or foliar) correct the deficiencies responsible for the crop yield limitation on soils highly-cultivated and high-in-pH value, whereas bio-fertilizers containing Rhizobium, Azotobacter, phosphate-solubilizing bacteria, and mycorrhizal inoculants fix atmospheric nitrogen, solubilize phosphorus and produce siderophores and phytohormones thereby accelerating root-growth. Leguminous green manures including dhaincha and sesbania provide a bioavailable input of biologically-fixed nitrogen, significantly increasing yields in many fruit and vegetable crops from banana to lettuce. Soil amendments (e.g., lime, gypsum, biochar) remediate a variety of pH and salinity issues or cation-exchange limitations that hinder effective nutrient use in the soil. [4].

2.2 Rhizosphere processes contributing to INM's success

INM's mechanistic heart is the rhizosphere, an area in the soil surrounding roots, which, through exudation, microbial action and pH changes in a small locale, dictate nutrient access [8]. Root exudates, which consist of organic acids, sugars, amino acids and enzymes, increase iron, zinc, phosphorus, iron and nitrogen availability and, at the same time, promote populations of beneficial microbes (including disease-suppressive bacteria, nitrogen-fixing bacteria and phosphate-solubilising bacteria). [8]. Global meta-analysis of rhizosphere nutrient concentrations reported that typically plant-microbe activity results in approx. 10% increase in availability of nitrogen than in the bulk soil and an approx. 12% reduction in available phosphorus content, a result with obvious implications on the nutrient synchronization timing under INM [8]. Root-driven pH regulation enhances such phenomena - reducing rhizosphere pH by 1 unit increase 100-fold solubility of Zn and maximum availability for most macronutrients' ranges between pH 6.0 and 7.0 [4].

Arbuscular mycorrhizal fungi extend this biological machinery beyond the root surface itself. Their hyphal networks expand the effective absorptive area of roots and are particularly important for the acquisition of phosphorus, zinc, and copper in horticultural and vegetable crops, and also contributing to soil aggregation and carbon sequestration [9]. Soil enzymes, including urease, phosphatase, and dehydrogenase, and beta-glucosidase, act as sensitive indicators of this biological activity and closely correlate with nutrient mineralization rates and, ultimately, yield [4].

2.3 Demonstrated outcomes of soil-based INM

The cumulative effect of combining these mechanisms is well documented. Integrated nutrient management regimes based on organic, inorganic and bio-fertilizers in tomato, cauliflower, bottle gourd, strawberry and bitter gourd provided beneficial results of greater efficiency in the use of nutrients, stable yields throughout different cropping seasons and higher economic benefit-cost ratio than that of mineral fertilizers only in different crop fields as reported from the long-term field experiments. [4]. Partial replacement of mineral nitrogen with farmyard manure, green manure, and biofertilizers sustains or improves yield as substantially increasing nitrogen-use efficiency in cereal-vegetable rotations [14]. Our editing and synthesis of climate-smart nutrient management put INM front-and-center with respect to SDG target on hunger, responsible consumption and production, climate action, and soil biodiversity simply due to its reduction of dependency on artificial inputs at the level of yield. [6,7,16]. Cross-studies of INM also show that INM regimes aren't simply another version of organic farming: In general, purely organic regimes lag hybrid organic/inorganic/biological regimens regarding efficiency and yields, the type of synchrony effect for which the system is ideally tailored [18]. Controlled greenhouse trials that directly manipulate nitrogen-sulphur ratios and multi-year organic-fertilizer trials in greenhouse vegetable production in China both confirm that the yield and soil-fertility benefits of INM continue under intensively managed, semi-controlled conditions, not only in open fields [13, 19]. A more inclusive meta-analysis, integrating across all cropping systems, attributes much of their on-average 27% yield increase, in part through "enhanced microbe-mediated functions of soils, instead of by only nutritional addition. This indicates that nutrient supply itself is not directly responsible for increased INM effectiveness, and rather, that the mechanism operating via the rhizosphere-microbiome link explains increased INM effectiveness." [15, 51].

3. Managing Nutrient Solutions in Soilless and Controlled-Environment Agriculture Systems

3.1 Nutrient Solution Engineering

Hydroponics, aeroponics and the like: the soil-rhizosphere continuum is substituted by an explicitly-designed nutrient solution and such substitution alters the mechanics of, and language of, nutrient management. Although growers use conductivity and pH as indices of total ionic strength and nutrient content, respectively, a recent review of the topic suggests that conductivity values cannot predict individual ion concentration, which may result in concealed nutrient deficits or excesses even when the total conductivity value looks fine [20]. To overcome these shortcomings, scientists have tried ion-selective sensors for detecting concentrations of nitrates, calcium, and potassium, and also the control strategies based on nitrogen that employ the level of the nutrient depletion of nitrogen as the signal for refilling the total nutrient mixture [20]. Even small, deliberate shifts in nutrient-solution pH measurably change lettuce physiology, antioxidant activity, and mineral uptake, showing that pH management in soilless culture requires the same precision as pH management in the rhizosphere, even though the underlying mechanism, namely the buffering capacity of a circulating solution rather than of a soil colloid, is entirely different [21]. In closed coir-substrate systems for, for example, paprika, there is also a definite threshold for electrical conductivity (EC) that has significant effects on crop yield and plant development; the required recipes vary from season to season. [22, 23].

3.2 Aeroponics, vertical farming, and urban controlled-environment systems

Aeroponic systems have roots suspended in the air where nutrients are applied to them with periodic mists. This creates greater air space around the root systems, speeding up plant growth over the more conventionally known submersed hydroponics [1]. Vertical farming further consolidates and elevates many of these soil-less systems, such as nutrient film technique, deep water culture, tower systems, and aeroponic misting, to multi-level, climate-controlled facilities that can be built in urban centers [1, 5]. In one recent abstract to a sky-high veg farming seminar: "With urban land space diminishing, rooftop agriculture, the ‘newest skyscraper vegetable gardens,’ indoor farming and any high-rise systems that incorporate vegetative elements, have been promoted as the future for an adaptive strategy for climate challenges that includes a new urban farming niche- the ‘vertical hydroponic farms’ built on rooftops that has proved to improve nutritional yield over 10 to 20% compared to field plots that are similarly stressed in the same climatic zone [5]. However, reviews of the literature about controlled-environment agriculture largely agree that while vertical farms and greenhouses do cut down on the impacts on food transportation and postharvest waste, they do bring their own unique set of resource challenges. [24, 44].

3.3 Aquaponics: nutrient cycling without a rhizosphere or a synthetic solution

The Aquaponic system sits between soil farming and chemical hydroponics: waste water from the fish, provides nitrogen and phosphorus to the plants. The plants filter the water from the hydroponics system, before feeding it back to the fish. New critique of aquaponic systems: 'overall retention rate was only 30 to 41 percent of the nitrogen input and 46 to 62 percent of the phosphorus input that end up being retained as biomass or plant residue. The remainder of the nitrogen and phosphorus is lost as denitration, or effluent, or waste solids, indicating nutrient-use efficiency continues to be an unsolved challenge even in a system developed based on nutrient cycling principles [27]. These losses mirror, in a different technical form, the nitrogen and phosphorus use-efficiency losses that INM research treats as a major problem in soil-based systems, which suggests that the underlying mass-balance challenge of matching nutrient supply to plant demand while limiting loss pathways is shared across soil, hydroponic, and aquaponic systems even though the loss pathways differ.

Table 1: Nitrogen and phosphorus mass balance in aquaponic production systems

Nutrient	Fate / Pathway	Share of Total Input	Reference
Nitrogen	Retained in biomass (fish + plants)	30-41% (21-24% fish; 9-17% plants)	[27]
Nitrogen	Lost to denitrification	45-50%	[27]
Nitrogen	Lost via aquaculture effluent discharge	14-20%	[27]
Nitrogen	Lost as solid waste	0.7-2%	[27]
Phosphorus	Retained in biomass (fish + plants)	46-62% (35-45% fish; 11-25% plants)	[27]
Phosphorus	Lost via effluent discharge	22-28%	[27]
Phosphorus	Lost via precipitation	8-25%	[27]
Phosphorus	Lost as solid waste	2-7%	[27]

3.4 Biological inputs in soilless media: transferring, not replicating, rhizosphere science

The most direct point of contact between INM and soilless horticulture is the growing use of biofertilizers and plant-growth-promoting rhizobacteria in hydroponic and other soilless systems. Editorial reviews of soilless culture note that root surfaces in hydroponic systems remain biologically active even without a traditional soil rhizosphere, and that plant-growth-promoting rhizobacteria can colonize these surfaces when added directly to the nutrient solution [28]. Trials in floating and nutrient-film hydroponic systems report that biofertilizers reduce the need for mineral fertilizer in capia pepper, improve leaf quality and reduce nitrate accumulation in hydroponically grown baby spinach, and raise basil yield, mineral content, and antioxidant levels when substituted for a portion of the synthetic nutrient solution [29, 30, 31]. Broader reviews of plant-growth-promoting rhizobacteria show that these organisms enhance nutrient availability, produce growth hormones, and improve stress tolerance across a wide range of crops, though most of the mechanistic evidence base for nitrogen fixation, phosphorus solubilization, and siderophore-mediated iron acquisition was generated in soil systems rather than soilless media [32, 33, 34]. Microalgae-derived biostimulants and biofertilizers represent a further, less-studied input with demonstrated potential in floating hydroponic culture [31, 35].

Direct transfer from soil to soilless systems doesn't work easily as evidenced by the case of the arbuscular mycorrhizal fungi. In soil these are the dominant organisms of uptake for P and micronutrients and of soil aggregation [9]. In hydroponic systems, for instance, root colonization by mycorrhizal fungi is lower than in soil, and the addition of high levels of P into the nutrient solution to ensure fast growth deliberately hinders fungal colonization, thus making many soil-based mycorrhizal management techniques not directly transferable to hydroponic and vertical agriculture settings. [9]. This isolated instance illustrates a more important conclusion, namely that soil-validated biological nutrient management tools cannot be expected to work exactly the same in soilless systems where media composition, aeration levels, nutrient availability and levels differ from soil and every tool must be independently validated in soilless media rather than borrowed directly from INM literature.

Table 2: Reported effects of biofertilizers and microbial inoculants on crop performance in hydroponic and other soilless systems

Crop / System	Biological Input	Reported Effect vs. Synthetic-Only Nutrient Solution	Reference
Capia pepper (soilless-grown)	Commercial biofertilizer blend	Reduced requirement for mineral fertilizer while maintaining growth	[29]
Baby spinach (hydroponic)	Biofertilizer inoculant	Improved leaf quality; reduced nitrate accumulation	[30]
Basil (floating culture)	Biofertilizer inoculant	Increased leaf yield, mineral content, and antioxidant levels	[31]
Multiple vegetable crops	Plant-growth-promoting rhizobacteria (root-surface colonization)	Enhanced nutrient availability, growth-hormone production, and stress tolerance	[32, 33]
Ornamental and vegetable crops (soil-derived evidence)	Microalgae-derived biostimulants	Improved growth response; potential for floating hydroponic culture	[31, 35]
Multiple crops (hydroponic media)	Arbuscular mycorrhizal fungi	Lower root colonization than in soil; suppressed by high solution phosphorus	[9]

3.5 Soilless cultivation as an emerging, still-fragmented research field

Recent reviews characterize soilless cultivation as a distinct field of nutrient management that should integrate precise, engineered nutrient allocation with established biological insights from soil science [25, 26]. While these reviews advocate for increased use of biostimulants and soil-derived biological concepts in soilless and substrate systems, they do not offer a consolidated framework. This confirms the necessity for the cross-system synthesis addressed in this review [25, 26].

4. Nano-enabled and digital nutrient technologies across systems

4.1 Nano-fertilizers in soil-based horticulture

Nano pesticides- nano urea, nano-zinc, nano-phosphorus, encapsulated micronutrients which slow the release rate of nutrient and deliver nutrient on site. Fertiliser nutrient release time is between 4 to 10 days when in the presence of irrigation. [39]. When integrated with lower doses of traditional nitrogen in field trials with nano-nitrogen and nano-zinc, these approaches have led to over 60% improvement in maize and wheat yield when compared with unfertilized treatments, and large reviews indicate improvements of between 13% and 55% in wheat, potato, maize and rice as a result of using different nanoparticle compositions and application modes. [65]. Zeolite- and calcium phosphate-based carriers are being developed specifically to control the release rate and reduce leaching losses associated with conventional fertilizers [40, 41]. This further shows how nano-enabled applications are intrinsically tied into the biology of the rhizosphere and that understanding what occurs with nano-particles in the vicinity of the root system can complement and interfere with how conventional INM works via roots exudation and microbial activity. [36].

Table 3: Reported yield effects of nano-fertilizer formulations in soil-based field crops

Crop	Nano-Fertilizer Treatment	Yield Response vs. Unfertilized / Conventional Control	Reference
Maize	Nano-N + nano-Zn at 100% recommended nitrogen rate	Grain yield increased 66.2-68.8%	[38]
Wheat	Nano-N + nano-Zn at 100% recommended nitrogen rate	Grain yield increased 61.9-62.6%	[38]
Wheat (multi-study range)	Various nano-fertilizer formulations	Yield increase of approximately 20-55%	[64]
Potato (multi-study range)	Various nano-fertilizer formulations	Yield increase of approximately 20-35%	[64]
Maize (multi-study range)	Various nano-fertilizer formulations	Yield increase of approximately 20-40%	[64]
Rice (multi-study range)	Various nano-fertilizer formulations	Yield increase of approximately 13-25%	[64]
Multiple crops	Zeolite- and calcium-phosphate-based nano-carriers	Slower, more controlled nutrient release; reduced leaching loss	[40, 41]

4.2 The unresolved question of nano-fertilizers in soilless media

Although there has been significant progress in soil-based systems, nano-fertilizer research has not been extensively applied to hydroponic, aeroponic, or aquaponic nutrient solutions. In the absence of soil, the slow-release functions and microbial interactions that facilitate nanoparticle efficacy are lacking. This indicates a distinct research gap: it remains unclear whether the benefits of nano-fertilizersobserved in soil environments will persist, diminish, or alter when implemented in recirculating nutrient solutions.

4.3 Artificial intelligence and decision-support systems for nutrient management

In separate developments for soil- and soilless-based crops, the design and implementation of nutrient management decision support systems in the digital area have occurred with little mutual exchange. For precision agriculture in field-scale settings, fuzzy-logic-and machine learning-based decision support systems advise on the timing of, type of, and amount of fertilizer to be applied using inputs including crop growth status, forecast weather conditions, and the latest soil analysis reports; more recent additions integrate blockchain-based traceability with explainable AI to enhance the transparency of recommendations. [42, 43]. In hydroponic and aquaponic systems, machine-learning models developed using sensor data, including electrical conductivity, pH, dissolved oxygen, and ion-selective electrode outputs, predict nutrient uptake and automatically adjust nutrient solution composition in near real time [20]. In ion-selective electrode systems, when tested against an ion chromatograph in a laboratory, there was excellent linear correlation with nitrate, although less accuracy in potassium and calcium, implying fully automated nutrient-solution control systems are still not yet technically perfect but within reach [20]. As in the case of biofertilizers and nanotechnology, these two decision-support literatures, namely soil-based fuzzy and AI systems and soilless sensor-driven control systems, have developed in parallel with limited cross-pollination of algorithms, sensor architectures, or validation datasets.

5. The Dimensions of energy, economy and policy

5.1 The energy-nutrient efficiency trade-off in controlled-environment systems

Controlled-environment and vertical-farming systems achieve high water- and nutrient-use efficiency, yet at a high energy cost that soil-based INM does not achieve. Life-cycle assessments of commercial vertical farms find that such operations consume around 10 kWh of electricity for every kg of lettuce and produce greenhouse gas emissions that are several times higher than in open-field agriculture once their electricity consumption is considered, depending on how the grid is fuelled [46]. Analyses that weigh land-use savings against the renewable-energy infrastructure required to power vertical farms find a genuine trade-off rather than a straightforward environmental win: vertical farming reduces the land area required for crop production but increases the land area required for renewable electricity generation to power it [47]. Earlier plant-factory case studies reached a similar conclusion, showing that energy technology choices, not nutrient-solution management, dominate the ecological burden of indoor production [45]. Studies of CEA using systematic reviews showed that electricity for climate and lighting rather than managing the nutrient solution accounts for most environmental impact in vertical-farm life-cycle assessments [24, 44]. Land-use analyses that build on this assessment to include short-cycle crops such as microgreens further indicate that the land savings indoor farms provide may lead to an increased burden on renewable-energy infrastructure and construction resources - a trade-off that nutrient delivery alone cannot justify [48]. This energy burden has no direct analog in soil-based INM, where the main environmental costs are nutrient leaching, volatilization, and emissions rather than electricity demand, and there is currently no framework that collectively optimizes nutrient-use efficiency and energy-use efficiency across both system types.

Table 4: Reported resource-use and environmental trade-offs of controlled-environment and vertical farming versus open-field cultivation

System / Study Focus	Key Metric	Reported Finding	Reference
Commercial vertical farm (lettuce)	Electricity use	Approximately 10 kWh consumed per kg fresh weight produced	[46]
Vertical farming vs. open field	Land-use trade-off	Reduces crop-production land footprint but increases land needed for renewable-energy generation	[47]
Plant factory (Japan case study)	Environmental hotspot	Energy technology choice, not nutrient-solution design, dominates footprint	[45]
Vertical farms and greenhouses (systematic review)	Environmental hotspot	Electricity for lighting and climate control identified as dominant impact category	[24, 44]
Indoor vertical farm (microgreens)	Land-use trade-off	Reduced agricultural land demand offset by increased renewable-infrastructure and construction land demand	[48]
Soil-based INM systems	Primary environmental cost	Nutrient leaching, volatilization, and emissions rather than electricity demand	[4]

5.2 Economic barriers to adoption in both systems

Though different, barriers to adopting soil-based INM and controlled-environment nutrient management is just as severe. While poor information awareness on the part of farmers, varying nutrient quality of organic inputs, the labor intensity of composting and the lack of strong extension services limit adoption, these constraints were most significant for smallholder farmers. [4]. Controlled-environment agriculture is shackled by a different, equally tough, set of restrictions-a massive capital expenditure for buildings, light, and controls, plus volatile energy costs that led many high-profile vertical-farming businesses to go bust even as demand for local food has soared. [63, 64]. The few more general studies of horticultural technology uptake highlight that a similar basic problem faces traditional and controlled-environment technology adopters - the cost of precise inputs and infrastructure often exceeds what smallholder farmers or fledgling companies can afford to implement - regardless of the nutrient-delivery system. [1, 62].

5.3 Certification and regulatory divergence

Nutrient-management policy has also evolved along separate soil-based and soilless tracks. Organic certification standards, developed around the principle of building soil fertility through organic inputs, have faced a extended legal and regulatory dispute over whether hydroponic and other soilless systems, which, by definition, do not build soil fertility, can legitimately bear an organic label [49, 50]. Although American courts have endorsed regulatory decisions allowing hydroponics facilities to maintain their organic certifications, in policy terms, the tension between a soil-based understanding of organic production and nutrient-centric engineering persists, while scientific knowledge on soilless biology is expanding. [49, 50]. This difference illustrates that policy models, like nutrient-science research itself, have not caught up with the reality that biological, INM-style nutrient management is now technically feasible within soilless systems.

5.4 Broader technology adoption context

There is also no way that Nutrient Management Research is growing in a vacuum away from the bigger technology transformation occurring in Horticulture, which I hope can explain why Nutrient Management Research is split into soil and soilless subcategories. Overviews of precision farming describe sensor networks, satellite imagery, and GPS-guided input application as a single, integrated toolkit, without distinguishing between the soil-based and soilless contexts in which that toolkit is deployed [57]. Similarly reviews on remote sensing suggest that both plant indices and monitoring water-status are transferable across whole of production system, also not taking into account that nutritional specific monitoring will vary between a soil and a circulating nutrient system [58]. Historical accounts of greenhouse development show that controlled-environment structures were originally built around climate control rather than nutrient science, which may explain why nutrient-solution engineering developed as an engineering discipline rather than as an extension of soil-plant-microbe research [59]. Reviews of high-tech horticultural innovation, vertical farming, and landscaping catalogue these developments as a single technological wave, again without separating out which innovations are nutrient-specific and which are climate- or structure-specific [60]. Reviews of nanotechnology that were specifically dedicated to crops in horticultural fields covered only applications using nano-fertilizer, nano-pesticide and smart-coating in orchards and in an open-field scenario and their soilless applications, discussed above, remained unexplored [55]. Water management review in horticulture is often framed similarly with fertigation and irrigation considered a joint water and nutrient problem in the case of soil-grown crops, but this hasn't been formalized into a closed-loop hydroponic recirculating culture. [56]. Harvest, weeding, and irrigation robots are characterized in robotics and automation reviews as implements that improve productivity-but none mention integrating them to nutrient-status monitoring-despite the inherent suitability of robot platforms to the real-time, site-specific nutrient management demanded by both INM and soilless methods [54, 61]. Economic viability analysis of protected cultivation reiterates that success of improved livelihoods and profitability achieved by switching to the greenhouse or shade-net based production is contingent upon prudent control of input costs thereby suggesting that efficiency of nutrient supply is equally an economic factor as a biological one [1, 62].

The most recent trade reports underscore these concerns. There were numerous well-capitalized vertical farm companies that declared bankruptcy or shuttered operations during 2023-2024 due to the high energy and capital expenditures required in producing what have been characterized as “premium priced produce.” [63]. Investment in new controlled-environment farming systems declined sharply in 2024, despite rising consumer demand for fresh, locally grown produce. Industry specialists attribute this to still unresolved energy-cost and scaling issues, not deficiencies in nutrient-delivery technology [64]. This underscores that precision in nutrient application alone cannot ensure economic viability in controlled-environment horticulture unless energy use is also optimized.

6. The Research Gap

Table 5: Nutrient-management strategies, major costs, and evidence in soil-based INM vs. Soilless / CEA horticulture

Dimension	Soil-Based Integrated Nutrient Management	Soilless / Controlled-Environment Systems	Reference
Primary nutrient-delivery mechanism	Rhizosphere: root exudation, microbial solubilization, mycorrhizal uptake	Engineered nutrient solution: electrical conductivity, pH, ion-selective control	[4,8,20]
Biological inputs	Mature evidence base for biofertilizers, PGPR, mycorrhizae in soil	Emerging evidence; colonization and efficacy differ from soil and require separate validation	[4,9,29,30,31,32,33]
Nano-fertilizer evidence	Substantial field-trial evidence of yield and nutrient-use-efficiency gains	Essentially untested in recirculating nutrient solutions	[37,38,]
Digital decision support	Fuzzy-logic and AI fertilizer-recommendation systems using soil-test data	Sensor- and machine-learning-driven real-time solution control	[20,42,43]
Dominant environmental cost	Nutrient leaching, volatilization, and greenhouse-gas emissions	Electricity demand for lighting and climate control	[4,24,44,46]
Principal adoption barrier	Farmer awareness, input-quality inconsistency, weak extension support	High capital cost and volatile energy prices	[4,63,64]
Certification / policy status	Well-established organic and INM-compatible standards	Contested organic-certification status; standards still evolving	[49,50]

Three independent bodies of evidence converge on the same conclusion. First, horticultural technology reviews catalogue soil-based and soilless innovations side by side without examining how their nutrient-management mechanisms relate to one another [1]. Second, INM reviews themselves emphasize the persistent and inadequate attention devoted to the biology of the rhizosphere, even within the literature that does address soil aspects of nutrient management, and the poor integration of digital and precision technologies with standard INM approaches [4]. Third, the conventional controlled-environment and vertical-farming literature generally frames nutrient supply as a problem in solution chemistry and sensor engineering, and mostly separate from the biological processes - such as root exudation, microbial solubilization and mycorrhizal symbiosis - that INM research has devoted the past 10 years to describing in soil. [5, 24, 44].

This has led to a real, unresolved research gap: there is no published framework that systematically applies INM’s rhizosphere-based, microbial, and nutrient-synchronization principles to soilless, aeroponic, aquaponic, or vertical farming systems. There is also no framework that looks at digital, nano-enabled, energy, and economic aspects of nutrient management across both soil-based and soilless horticulture. This review points out five clear research priorities to help close this gap.

First, mechanistic validation of soil-derived biological inputs, including biofertilizers, plant-growth-promoting rhizobacteria, and mycorrhizal inoculants, is needed specifically in hydroponic, aeroponic, and aquaponic media, since colonization rates, nutrient-solubilization pathways, and optimal nutrient concentrations differ measurably from those in soil [9, 32, 33].

Second, nano-fertilizer research needs to be extended from soil trials to recirculating nutrient solutions to determine whether slow-release and targeted-delivery benefits persist once the soil matrix with which nanoparticles were designed to interact is removed [36, 37, 39].

Joint valuation of trade-offs among energy-nutrient use: to-date, life-cycle assessments evaluate efficiency of use for energy and for nutrients separately, yet no system currently optimizes efficiency of both use in soils and soilless cultivation [45, 46, 47].

The independently designed digital decision-support systems for field-scale fuzzy logic fertilizer application and online sensor-controlled hydroponic nutrient supply must be merged within a unified management architecture to control both the soil and the soilless crop nutrient requirements in one agricultural enterprise [20, 42, 43].

Fifth, certification and policy frameworks must have updated criteria to evaluate the sustainability of soilless, biologically enhanced nutrient management on its own technical merits, rather than being adjudicated solely by soil-centered organic standards that predate the biological innovations now available to soilless growers [49, 50].

7. Conclusion

Soil-based Integrated Nutrient Management and soilless controlled-environment nutrient engineering have both advanced into evidence-rich fields over the past five years, but have mostly developed separately. INM has built a strong understanding of rhizosphere biology, nutrient timing, and soil-plant-microbe interactions. In contrast, hydroponic, aeroponic, and vertical-farming research has focused on precise, sensor-based nutrient-solution control. Sufficient evidence exists today to integrate these: - Bio-fertilizers & mycorrhizal inoculants (proven effectiveness in soilless systems), Nano-fertilizer technology (targeted delivery in soil which could potentially apply to nutrients solutions) and Artificial intelligence-based decision making (used in both field & hydroponic systems). However, careful, cross-system research is still needed to test these tools together, not just side by side. Building an integrated framework would help horticulture choose the best nutrient-management strategy, whether soil-based, soilless, or hybrid, based on local land, water, energy, and market needs. This would improve food security, resource use, and adapting to a changing environment- rural and urban. Research on climate-resilient farming and soil resilience already emphasizes that agriculture should be judged by its power to handle environmental shocks, not just by yield in good years. Closing the nutrient-management gap discussed in this review is a practical step toward that goal [52, 53].

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