agriculture

MDPI

Review

Integrated Nutrient Management of Fruits, Vegetables, and Crops through the Use of Biostimulants, Soilless Cultivation, and Traditional and Modern Approaches—A Mini Review

Awais Ali [1], Genhua Niu [2], Joseph Masabni [2], Antonio Ferrante [3] and Giacomo Cocetta [1,*]

[1] Department of Agricultural and Environmental Sciences, Università degli Studi di Milano, Via Celoria 2, 20133 Milano, MI, Italy; awais.ali@unimi.it
[2] Texas A&M AgriLife Research and Extension Center, Dallas, TX 75252, USA; genhua.niu@ag.tamu.edu (G.N.); joe.masabni@ag.tamu.edu (J.M.)
[3] Institute of Crop Science, Scuola Superiore Sant'Anna, Piazza Martiri della Libertà 33, 56127 Pisa, PI, Italy; antonio.ferrante@santannapisa.it
* Correspondence: giacomo.cocetta@unimi.it

Abstract: The increasing population, its requirements for food, and the environmental impact of the excessive use of inputs make crop production a pressing challenge. Integrated nutrient management (INM) has emerged as a critical solution by maximizing nutrient availability and utilization for crops and vegetables. This review paper highlights the potential benefits of INM for various vegetables and field crops and explores the conceptual strategies, components, and principles underlying this approach. Studies have shown that a wide range of vegetables and field crops benefit from INM, in terms of increased yield and improvements in yield attributes, nutrient contents and uptake, growth parameters, and various physiological and biochemical characteristics. This paper discusses biostimulants, their categories, and their impact on plant propagation, growth, photosynthesis, seed germination, fruit set, and quality. Additionally, this review explores modern sustainable soilless production techniques such as hydroponics, aeroponics, and aquaponics. These cultivation methods highlight the advancements of controlled-environment agriculture (CEA) and its contribution to nutrient management, food security and minimizing the environmental footprint. The review concludes by proposing methods and fostering discussions on INM's future development, while acknowledging the challenges associated with its adoption. Finally, this review emphasizes the substantial evidence supporting INM as a novel and ecologically sound strategy for achieving sustainable agricultural production worldwide.

Keywords: aeroponics; aquaponics; hydroponics; soil improvement; sustainable agriculture

check for updates

Citation: Ali, A.; Niu, G.; Masabni, J.; Ferrante, A.; Cocetta, G. Integrated Nutrient Management of Fruits, Vegetables, and Crops through the Use of Biostimulants, Soilless Cultivation, and Traditional and Modern Approaches—A Mini Review. *Agriculture* **2024**, *14*, 1330. https://doi.org/10.3390/agriculture14081330

Academic Editor: Peiyuan Cui

Received: 24 June 2024
Revised: 2 August 2024
Accepted: 6 August 2024
Published: 9 August 2024

1. Introduction

Efforts to satisfy the growing need for food (due to population growth and increased consumption) are placing unprecedented strain on current agriculture and natural resources, and this is exacerbated by shrinking acreage of arable land and other productive units [1]. In developing nations, achieving food security under sustainable systems is a major task that is vital to reducing poverty [2]. The already observable changes in the global environmental conditions and the related uncertainties make yield enhancement extremely challenging [3]. Modern cultures have ravenous needs for energy, water, wood products, land area for infrastructure, urbanization, and the removal of industrial and urban trash in addition to an endless supply of food [4]. Hence, the prime objective now should be optimization across a significantly complicated terrain of production, environmental, and social justice outcomes rather than just maximizing productivity. Farmers have used chemical fertilizers and pesticides excessively to overcome the problem of an insufficient yield, which has already begun to negatively impact the ecosystem. However, applying chemical fertilizer is now a crucial step in maintaining high and consistent crop yields, providing between 30 and 50% of crop output and over half of the global population's protein needs [5]. Today, food security is ensured by fertilizers and sustainable agricultural systems [6]. According to multiple reports, China is the world's greatest producer and consumer of fertilizers [7]. Between 1978 and 2019, China's consumption of chemical fertilizers rose from 8.84 to 54.0 metric tons, a 511% rise, while its grain output expanded from 305 to 664 Mt, a 118% increase, during the same period [8]. By 2050, the world's food supply must rise by 70% to meet the growing demand, where an average yearly increase in cereal production of 43 million metric tons is needed to fulfil this ambitious goal [9].

A significant rise in global greenhouse gas emissions (GHGs) by the agriculture sector is evident, which primarily is due to the use of synthetic fertilizers and pesticides, both of which have been increasing in use quickly in recent years. One of the main contributors of environmental damage, including eutrophication and GHGs, is the use of fertilizer, particularly nitrogen [10]. In Europe, the quality of drinking water and the safety of the environment were threatened when the overall amount of nitrogen used for agricultural production reached 200 million tons in the 1980s, leading to excessive nitrate (N) in the water, eutrophication, and GHGs [11]. To prevent excessive fertilizer inputs, the European Union (EU) passed several pieces of legislation and regulations, such as the EU Nitrates Directive [12] and the EU Water Framework Directive [13]. In accordance with national conditions and legal requirements, member nations implemented equivalent fertilizer reduction control policies. From 2000 to 2008, the Nitrate Directive's implementation reduced N leaching by 16%, NH_3 by 3%, and N_2O emissions by 6% [14]. However, studies comparing fertilizer use to crop nutrient requirements have not been conducted extensively. For example, China's crop N use efficiency is only about 25%, well behind the global average of 42%, the 52% average in Europe, the 68% average in the US and Canada, and the 72% average in sub-Saharan Africa [7]. The partial factor productivities of N, P, and K fertilizers are 20 kg grain/kg N, 98 kg grain/kg P, and 61 kg grain/kg K in China, where average wheat grain yields are approximately 4.9 t/ha. This is less than the 2.9 t/ha in North America and the 7.5 t/ha in Western Europe (55 kg grain/kg N, 724 kg grain/kg P, 275 kg grain/kg K), 2.9 t/ha in North America (48 kg grain/kg N, 332 kg grain/kg P, 193 kg grain/kg K), and 1.7 t/ha in Australia (76 kg grain/kg N, 211 kg grain/kg P, 478 kg grain/kg K) [15]. Thus, to increase production, agricultural programs must embrace sustainable agricultural development by adopting agro-ecological approaches that prioritize resource conservation, environmental impact mitigation, and global climate change mitigation. For example, in regions with specialized cropping, well-planned crop rotations are believed to improve agricultural sustainability, increase soil fertility, reduce insect life cycles, and maximize resource utilization. These approaches also aid modern agriculture in addressing environmental, human nutrition, and socioeconomic concerns; for instance, growers can increase revenue by introducing high-value crops [16]. Previous research suggested that reducing the cropping intensity and rotating water-efficient species can help slow the depletion of the groundwater table [17]. Additionally, low-input rotations—such as those including legumes—lessen the need for synthetic fertilizers, which lowers related pollution and greenhouse gas emissions [18]. Legumes are the most varied and widely distributed group of plants that can fix nitrogen from the atmosphere. They are an essential part of terrestrial ecosystems and a source of nutrients and proteins for humans and animals. Leguminous crops, for instance, provide half of the nitrogen required by agricultural systems, reducing the need for chemical N fertilizer inputs into the soil and the associated environmental harm [19]. They also help in decomposing litter more quickly and have higher N concentrations than non-leguminous species, which ultimately increases the availability of N in the soil and improves the conditions for coexisting plant growth by raising the levels of soil organic carbon (C), soil nutrients, and humus [20].

For the last two decades, there has been a relatively new approach to boosting agricultural production in addition to alleviating the negative effects of climate change. This approach includes the use of biostimulants, an easy-to-use, inexpensive, and organic or artificial extract [21]. The definition and idea of plant biostimulants is still developing based on the consortia of two leading biostimulant regions, the European Union and North America. The European Biostimulant Industry Council (EBIC) defined biostimulants as follows: "Plant biostimulants contain substance(s) and/or micro-organisms whose function when applied to plants or the rhizosphere is to stimulate natural processes to enhance/benefit nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop quality" (reported in the European regulation n. 2009/2019) [22]. Meanwhile, the North American definition of biostimulants is the following: "Substances, including micro-organisms, that are applied to plant, seed, soil or other growing media that may enhance the plant's ability to assimilate applied nutrients, or provide benefits to plant development. Biostimulants are not plant nutrients and therefore may not make any nutrient claims or guarantees" [23]. The two primary categories of biostimulants are non-microbial and microbial biostimulants. Plant and seaweed extracts, humic compounds, protein hydrolysates, and substances such as plant growth regulators (PGRs) are among the non-microbial biostimulants. Phytohormones, chemicals (melatonin), and biostimulants derived from various sources (such as organic materials from vermicompost) are examples of the latter. In addition to other natural polymers, chitosan, chitin, or chitosan oligosaccharides can be employed as biostimulants. Because of their elemental makeup, inorganic elements (NO and H_2S) can also be regarded as biostimulants if they have positive effects on plants without directly increasing nutrient concentrations. Trichoderma, mycorrhizal and non-mycorrhizal fungi, and plant growth-promoting rhizobacteria (PGPR) are examples of microbial biostimulants [24]. The categories of biostimulants used in agriculture are represented in Figure 1.

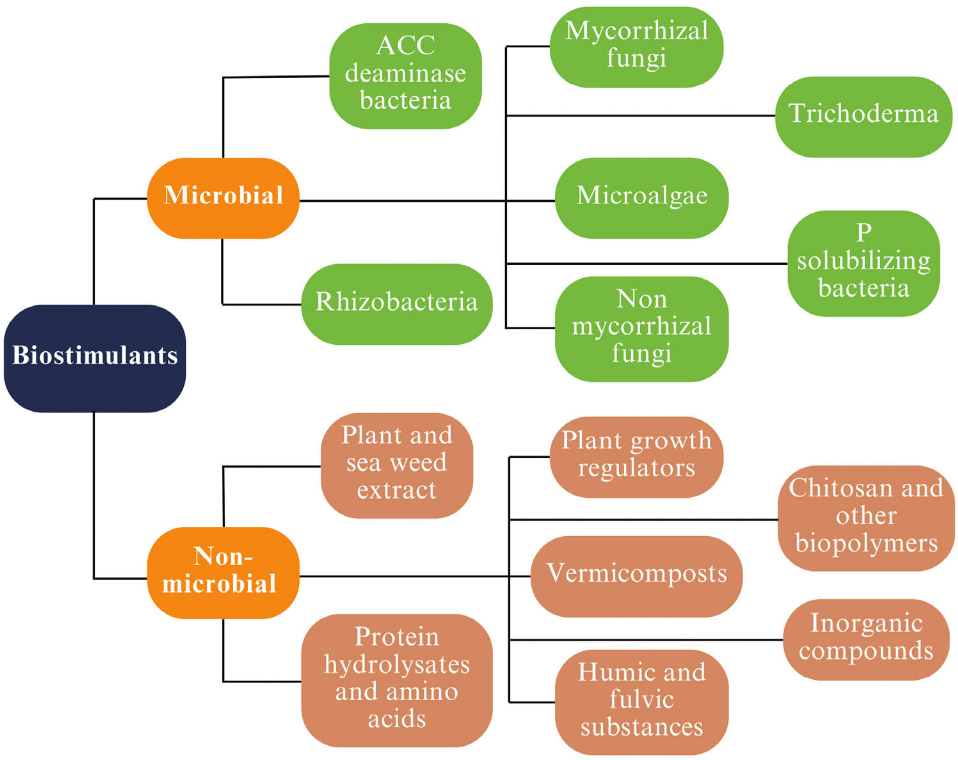

Figure 1. Biostimulants and their different categories employed in agriculture.

Integrated nutrient management (INM) is an approach to preserving the environment for posterity while simultaneously improving the quality of the output where it depends on the application and preservation of nutrients, the development of new technologies to increase nutrient availability to plants, and the dissemination of information between farmers and researchers [25]. It has been demonstrated that INM significantly increases crop yields by controlling the nutrient supply and minimizing nutrient losses to the environment. This leads to a high resource utilization efficiency, lower costs, and better tolerance of biotic and abiotic challenges [26]. A few of the primary objectives of INM include controlling and maintaining agricultural productivity while simultaneously increasing farmers' profitability through the rational and effective use of its components such as chemical fertilizers, organic manures, green manures, compost, including vermicompost, crop residues, and biofertilizers, as shown in Figure 2. But this does not mean adding nutrients randomly; rather, it demands highly calculated, effective, and practical combinations of several nutrient sources that can deliver required yields and sustain soil health over time. The INM system aids in preventing new micronutrient shortfalls as well as assisting in maintaining and restoring the crop output [27].

Figure 2. Components of INM.

A few of the benefits offered by INM are presented in Figure 3. With the continuous increase in both the quantity and quality of experimental data, researchers are now able to properly integrate, evaluate, and conclude on approaches for the betterment of crops and the environment. Smallholder farmers could benefit more from technology transfer centers that encourage the adoption of modern agricultural management techniques including the use of sensors, drones, and inexpensive satellite imaging for better fertilization and pest control [28]. Machine learning (ML) and ML algorithms can forecast yields based on genetic information, environmental and land management variables, fertilizer rates, and genetic data [29]. It is feasible to combine and interpolate several pieces of information in the field of nutrient management that have never been investigated before. These advances facilitate the inclusion of economic factors in decision-making and enhance our general understanding of agricultural systems, including fertilizer requirements. A precise assessment of the crop nutritional status and nutrient requirements is essential to overall farm management, and it affects the farm's economic viability as well as the environment.

Soilless farming is a cultivation technique that dispenses with the use of soil as a rooting medium. In this approach, nutrients are absorbed by the roots, provided through irrigation water. The methods include aeroponics, aquaponics, and hydroponics. Reduced water consumption/loss, less soil exploitation, and reduced land usage may be achieved with the disciplined resource conservation approaches of soilless farming [30]. In soilless farming, careful nutrient monitoring and nutrient solution modifications are carried out to suit the unique requirements of many plant species, and success is highly dependent on accurate nutrition management [31]. On the other hand, poor nutrient management can result in stunted growth, low yields, and in severe situations, plant death. Hence, with a resource optimization approach, this technique reduces waste and increases efficiency by delivering nutrients in a controlled manner straight to the plant roots in addition to lessening the negative effects on the environment [32].

Thus, in this article, we review the importance of INM in agriculture, its concepts and objectives, procedures, and principles apart from sustainable agricultural production, and its potential for reducing the overall environmental impact. This review paper explores the scientific research from the literature found in the Google Scholar, Scopus, and Web of Science repositories. The use of biostimulants, their categories, and their potential impacts on vegetative as well as reproductive phases are discussed. Fruits/vegetables such as tomatoes and field crops such as wheat and rice are presented as separate tables since these crops have been extensively studied and possess sufficient nutrient management data. Soilless agricultural production through hydroponics, aeroponics, and aquaponics is highlighted, and their potential as excellent resource utilization and conservation practices is discussed. The goal of this review is to demonstrate how resilient various agricultural systems are in the face of environmental crises and climate change. Moreover, the information gathered may be used to create environmentally friendly farming methods that are sustainable; in the future, we can maximize the usage of these methods and create climate-smart farming policies for a more sustainable future. Additionally, in creating this review, we have tried to compile work carried out on various crops and fruits/vegetables using traditional nutrient management approaches and modern approaches, which account for both micro- and macronutrient management strategies and improvements in both indoor and outdoor crops and fruits/vegetables.

Canva software (Canva Pro version 4.49.0, Perth, Australia) was used to construct the schematic diagrams and figures (https://www.canva.com/en_gb/, accessed on 30 May 2024).

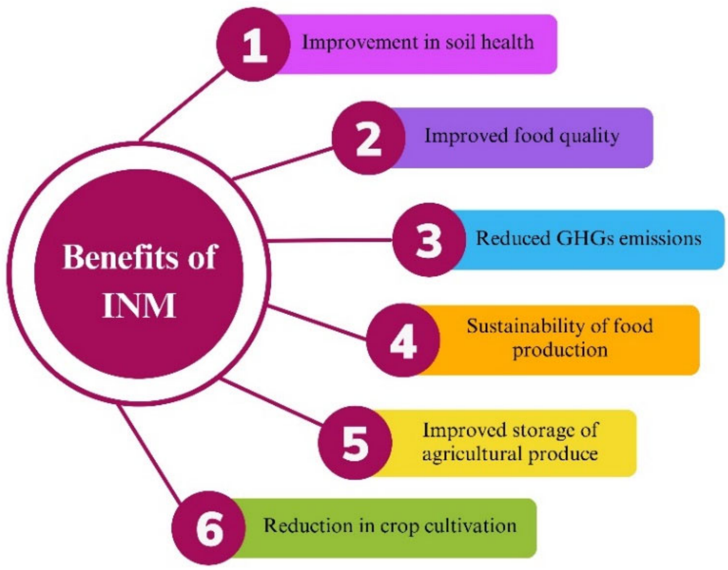

Figure 3. Flow sheet diagram highlighting the advantages offered by integrated nutrient management.

2. Conceptual Basis and Principles of INM

INM primarily refers to the integration of traditional and contemporary nutrient management techniques into an environmentally sound and commercially optimal agricultural system [29]. It makes use of all available sources of organic, inorganic, and biological components and optimizes the nutrient cycle, including N, P, K, and other macro- and micronutrient inputs and outputs, while minimizing the losses due to leaching, runoff, volatilization, emissions, and immobilization [9]. Some of the key steps involved in the INM strategy are listed in Table 1.

Table 1. Complete set of INM strategies from assessing the plant and soil nutrient deficiencies to selecting the techniques for eradicating these problems and eventually evaluating the effects of those techniques in addition to the key steps involved in the application.

No.	Focus Points of INM Strategy	Methods	Detailed Strategies
1	Assessing plant nutritional deficiency and soil nutrient availability	Sampling and laboratory analysis	Soil sampling and post-harvest plant tissue sampling are conducted apart from the visual observation of nutrient deficiencies in plants. Usually, the results are compared with a reference healthy plant considered as the standard
2	Evaluating the potential and limitations of soil fertility management	Monitoring the relationship between the INM strategy and nutrient diagnosis	Inspection related to overuse or underuse of nitrogen fertilizers
3	Investigating the techniques and technologies to balance nutrients	Nutrient intake and output differential inspection and computing the soil nutrient budget	Choosing an appropriate INM after analyzing the variables
4	Evaluating the productivity and sustainability of INM activities	The use of locally relevant technology	Active participation of farmers in testing and analysis

The above-discussed INM strategy is centered on the timing and rate optimization of fertilizer applications, where it assists in prescribing a basal fertilizer dose in terms of N, P, and K requirements based on the soil's capacity and its potential to supply overall nutrients [9]. Based on INM strategies, the INM principles can be divided into three. The first principle describes maximizing the intake by utilizing nutrients from all available sources. A significant amount of N for crop growth is supplied by irrigation water and atmospheric N deposition, where some of it is due to lightning. Lightning can create nitrogen oxides ($NO_x \equiv NO + NO_2$) in the atmosphere [33]. The estimated annual emission of atmospheric nitrogen by lightning falls within a range of 2 to 8 Tg N yr^{-1}, which is several times less than that from present-day anthropogenic and biomass burning sources (~26 Tg N year^{-1}) [34]. Excessive nitrate (N) aggregation in the soil profile is like a massive "N resource" that has the potential to build up but will ultimately be released into the environment through leaching or denitrification [35]. Thus, irrigation water and atmospheric N deposition can be regarded as sources of important nutrient inputs for the INM strategy. The second main principle involves coordinating the regional and temporal distributions of crop demand and soil nutrient delivery. To achieve a high nutrient use efficiency in crops, there is a need to coordinate the timing of application with the crop nutrient requirements. This principally involves the frequent application of N fertilizers but in low quantities, which leads to improved crop quality and potentially reduce N losses [36]. In contrast, some non-traditional rice farmers apply 80% of the total N fertilizer as a basal dressing prior to transplanting, and the remaining portion within 10–20 days following the transplant; this has led to both poor crop production and N losses [37]. This strategy leads us to the third major INM principle, which asserts that the agricultural yield can be increased by reducing N losses. Moreover, N application should proceed in a controlled way to eradicate or minimize the deleterious environmental effects. Numerous variables, including the N application pattern, crop characteristics, soil qualities, climatic circumstances, and management techniques, affect the fate of nitrogen. Because of this, INM, for instance, supports the deep placement of urea or ammonium bicarbonate, which can greatly improve the N use efficiency while reducing nitrate leaching and NH_3 volatilization [38]. Since N_2O emissions usually occur during the nitrification processes following fertilizer N application [39] and irrigation [40], applying nitrification inhibitors can minimize N_2O emissions. In addition to nitrification inhibitors, the soil quality and ultimately yield can be improved by using organic manure together with crop residues and conservation tillage practices [41]. Numerous studies have been performed over time on the application of INM, to observe the improvements in the agronomic as well as the morpho-physiological attributes of crops.

3. Progress of INM Technology in Fruits, Vegetables, and Crops

3.1. Biostimulants

For the last two decades, applying biostimulants has presented a very useful and sustainable option for encouraging positive plant growth under optimal or stressful conditions. Regardless of their nutrient composition, they are known to improve nutrient availability, nutrient uptake efficiency, productivity, flowering, fruit development, and plant growth and tolerance of biotic and abiotic stress [42]. These biostimulants consist of a range of different microorganisms and components that stimulate plant growth and development and help in reducing the need for fertilizers. Various applications and impacts of biostimulants on different stages of crop growth are presented in Figure 4. Overall, biostimulants exhibit good activity at low concentrations, help in enhancing the grain protein content, nutritional value, and shelf life, and improve the nutritional quality and resilience of crops to abiotic stress [43].

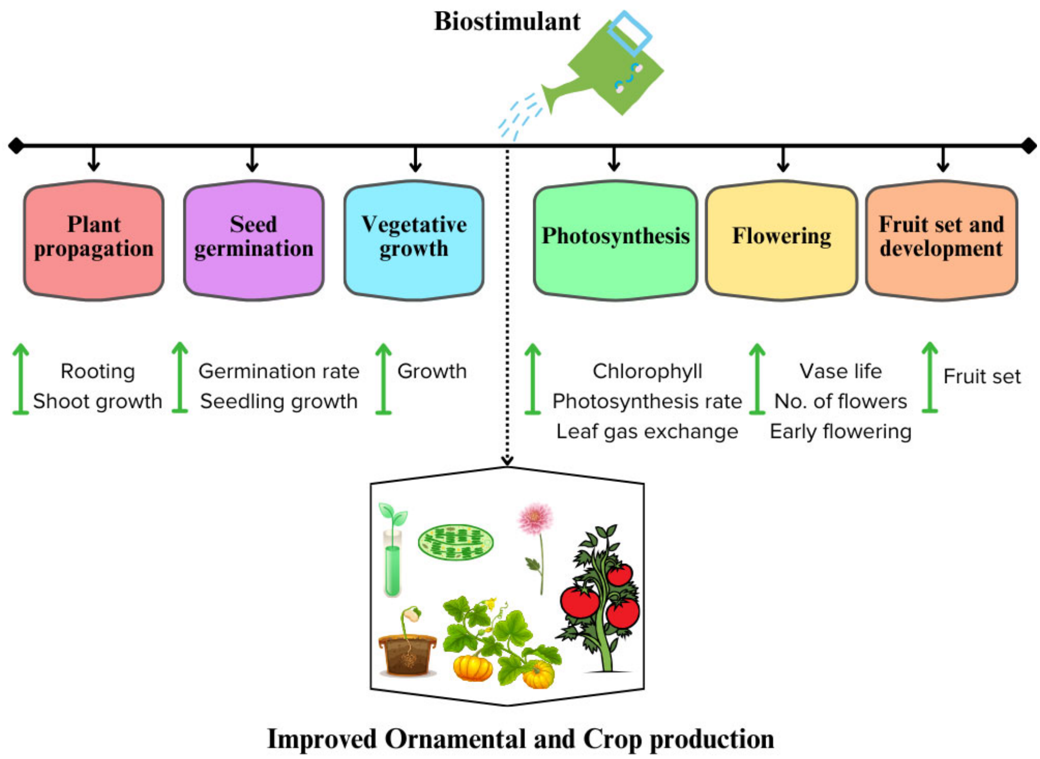

Figure 4. Biostimulants and their applications and impacts on different stages of ornamentals, fruits, vegetables, and field crops.

Enhancements of root development and nutrient availability lead to an indirect increase in the plant nutrient uptake efficiency [44]. For example, in maize, under a controlled environment, the biostimulant betaine resulted in a better plant growth and water use efficiency [45]. In another study, a biostimulant containing plant growth-promoting rhizobacteria (PGPR) increased the yield and growth of maize when paired with a lower fertilizer dosage [46]. Investigations into specific direct processes showed enhanced expression levels of genes encoding several nutrient transporters, primarily N and P, to meet the ideal plant need. The productivity of plants increases when bacterial biostimulants boost the efficiency of nutrient uptake, leading to an overall increase in plant growth. Several biostimulants and their effects on crops in terms of propagation, vegetative growth performance, photosynthesis, and fruit quality are represented in Table 2.

Table 2. Biostimulants and their effects on plant propagation, vegetative growth, photosynthesis, and leaf gas exchange.

	Biostimulants	Crops	Effect of Biostimulants	References
Plant propagation	Algamino plant	White dogwood (*Cornus alba* L.)	Improved rooting speed in cuttings	[47]
	Arbuscular mycorrhizal fungi	Olive (*Olea europaea* L.)	Enhanced rooting and seeding quality	[48]
	Microalgae *Chlorella vulgaris* and *Messastrum gracile*	Crimson cattleya (*Cattleya labiate*)	An alternative to plant growth regulators for in vitro propagation	[49]
	Root Nectar (willow bark extract and Nutrifield's biostimulant complex)	Chrysanthemum, lavender (*Lavandula angustifolia*)	Improved development of root branching and adventitious roots	[50]
	Microbial metabolites	Pear (*Pyrus communis* L.)	Enhanced auxin production that enabled efficient rooting	[51]
Vegetative growth	Moringa leaf extracts	Kale, broccoli (*Brassica oleracea*)	60% increased nitrate levels in broccoli, while 70% reduced in kale	[52]
	Moringa leaf extract	Quinoa (*Chenopodium quinoa*)	Improved grain yield and overall growth	[53]
	Seaweed-based extracts	Cucumber (*Cucumis sativus*)	Improved growth and fruit yield	[54]
	True-Algae-Max (seaweed liquid extract)	Hot peppers (*Capsicum annuum*)	Improved fruit composition and plant growth	[55]
Photosynthesis and leaf gas exchange	*Ascophyllum nodosum* (seaweed extract)	Broccoli (*Brassica oleracea*), spinach (*Spinacia oleracea*)	Reduction in stomatal closure, improved water stress tolerance and gas exchange	[56]
	FOLIAR (amino acid based)	Perennial ryegrass (*Lolium perenne*)	95% increased photochemical efficiency (Fv/Fm)	[57]
	PE Auxym (tropical plant extract)	Nalta jute (*Corchorus olitorius*)	SPAD index and photosynthesis improved	[58]
	Moringa leaf extract	Quinoa (*Chenopodium quinoa*)	Improved photosynthesis and leaf gaseous exchange	[53]

Microbial biostimulants, like arbuscular mycorrhizal fungi (AMF) and PGPB, have become more common in recent years as a sustainable way to increase both the quantity and quality of the product [59]. Seeds treated with biostimulants are one of the most creative and promising methods for enhancing seed germination, early radicle protrusion, emergence, and seedling establishment under both normal and abiotic-stressed conditions [60]. Additionally, bio-based biostimulants as seed coatings have been developed using different sources of liquid and powder forms of vermicompost and soy flour [61]. The plants' biometric parameters and the nitrogen uptake per plant were significantly higher with a biostimulant seed coating than in the control [62]. When using broccoli as a modeling system, biostimulant seed coating formulations through soy flour have shown lower germination percentages than in control plants; however, 10-day-old seedlings from these seeds showed better root and shoot growth [63]. Moreover, coating red clover (*Trifolium pratense* L.) and perennial ryegrass (*Lolium perenne* L.) seeds with different combinations of soy flour, diatomaceous earth, micronized vermicompost, and concentrated vermicompost extract led to different germination percentages. In red clover, coated treatments significantly improved the germination rate and uniformity, with no reduction in the germination percentage, while in perennial ryegrass, a delayed germination rate and reduced germination percentage were recorded compared to the non-treated seeds [64]. It has also been demonstrated that biostimulants encourage flowering. A significant field of research is the use of biostimulants at preharvest to extend the shelf life of cut flowers, which are extremely valuable economically. Also, this is a sustainable and successful method to enhance the fruit set, development, and quality of final produce [65], especially in terms of soluble solids, phenols, and ascorbic acid [66]. Moreover, a previous study has explored how a Bacillus-based microbial biostimulant promotes maize growth and drought tolerance by influencing gene expression and metabolic pathways [67]. Table 3 summarizes the effect of biostimulants on different plant developmental stages.

Table 3. Plant developmental stages: seed germination, flowering, and fruit setting in response to the biostimulants.

Plant Developmental Stages	Biostimulants	Crops	Effects of Biostimulants	References
Seed germination	Polysaccharide-enriched extracts (PEEs) obtained from Moroccan seaweed	Cherry tomato (*Solanum lycopersicum*)	0.002 mg/mL of PEEs resulted in an increased seed germination percentage and speed	[68]
	Seaweed leaf extracts (*Laurencia obtusa*, *Ulva fasciata*, and *Cystoseira compressa*)	Maize (*Zea mays*) and cowpea (*Vigna unguiculata*)	Improved seed germination and enhanced seedling growth	[69]
	KIEM (lignin derivatives, plant-derived amino acids, molybdenum)	Cucumber (*Cucumis sativus*)	Improved heat stress tolerance of cucumber seeds	[70]
	Bacillus sp. MGW9	Maize (*Zea mays*)	Stimulated salt tolerance mechanism during seed germination	[60]
	Micro-algae strains	Spinach (*Spinacia oleracea*)	Better seed germination results	[71]
Flowering	Borage leaf-extract-based biostimulant	Gladiolus cut flower	Better osmotic balance and reduced oxidative stress resulted in an improved vase life	[72]
	Moringa leaf extract	Gladiolus (white prosperity cultivar)	Improved performance of cut spikes	[73]
	Protein hydrolysates (both animal and plant origins)	Chrysanthemum	Improvement in the vase life	[74]
	Hydroxyquinoline sulfate (8-HQS)	Cut rose (*Rosa hybrida* L.)	Improvement in visual quality and better vase life	[75]
	Moringa leaf and seed extract	Cut flower (*Rosa hybrida* cv. "Upper class")	Extended vase life, proline accumulation, and reduction in stomatal aperture	[54]
Fruit set and quality	Seaweed extract	Eggplant (*Solanum melongena*)	Improved antioxidant activity, TSSs, anthocyanins, and total polyphenols	[76]
	Protein hydrolysates	Annurca apples (*Malus domestica*)	Improved total polyphenol profile	[77]
	Seaweed extract, mycorrhiza, and *Trichoderma*	Strawberries (*Fragaria* × *ananassa*)	Enhanced anthocyanins, TSSs, and total polyphenols	[78]
	CycloFlow (mixture of yeast and sugarcane molasses)	Tomatoes (*Solanum lycopersicum*)	Increased vitamin C content	[79]
	Seaweed extract and fulvic acid based	Guava (*Psidium guavaja* L.)	Increased TSS, fruit size, and fruit weight	[80]

3.2. Nutrient Management and Soilless Cultivation Systems

Soilless culturing can be defined as "any technique for cultivating plants that does not include the use of soil as a rooting medium and uses irrigation water to provide the inorganic nutrients for the roots to absorb" [81]. In this method, fertilizers containing nutrients in appropriate concentrations are dissolved in irrigation water, and the resultant solution is referred to as the "nutrient solution" [82]. This method of cultivation is heavily employed to maintain control over the growth environment and prevent fluctuations in the soil's nutrient and water levels [83].

3.2.1. Hydroponics

"Hydroponics" was derived from the Greek word for agriculture, *Geoponics* (*geo* for earth and *ponos* for work). Hence, hydroponics pairs *Hydro* for water and *ponos* for work or labor. Soil serves as a substrate for plants to meet certain needs of theirs; however, it can be substituted with an artificial support and supply of sufficient macro- and micronutrients, which are necessary for plant growth and development and can be replaced by water or an inert solid medium. This technique is termed hydroponics [82]. Table 4 shows several popular growing media types that have been employed over time for various fruit and vegetable production modes and have adequate porosity and water-holding capacity. For example, Coco coir, derived from coconut husk, has good aeration and a good ability to retain moisture. Because of its porous structure, hydroton, an expanded clay product, is good at absorbing nutrients and water. Heat is employed to create perlite, which gives it a high ability to hold water. Similarly, peat moss is a dark brown, fibrous organic substance, while vermiculite is a naturally occurring mineral. Sawdust is an environmentally friendly byproduct of cutting wood; its shelf life is limited but it is 100% organic, contrary to rockwool, which is an inorganic soilless growing medium. Apart from the above-mentioned options, soil particles of sizes 0.5–1 mm also serve the purpose of holding plants and retaining water. Moreover, gravels with pea seed sizes are another choice for the soilless growing medium, as they enhance drainage.

Table 4. Various hydroponic media, and their types and techniques, employed over time in the production of different fruits, vegetables, and crops.

Media	Types		Crops	References
Solid Inert Medium	Coco coir		Arugula (*Eruca sativa*), basil (*Ocimum basilicum*), sunflower (*Helianthus annuus*)	[84]
	Hydroton		Red lettuce (*Lactuca sativa*)	[85]
	Perlite		Tomato (*Solanum lycopersicum*)	[86]
	Vermiculite		Arugula (*Eruca sativa*)	[87]
	Peat moss		Kale (*Brassica oleracea*), Swiss chard (*Beta vulgaris*), arugula (*Eruca sativa*)	[88]
	Sawdust		Rice (*Oryza sativa)* dust, wheat (*Triticum aestivum*) dust, Pak choi (*Brasica rapa*), arugula (*Eruca sativa*), kale (*Brassica oleracea*)	[88,89]
	Rockwool		Microgreens, soybean	[90–92]
	Coarse sand		Ethiopian kale (*Brassica carinata*)	[93]
	Pea gravel		Spinach (*Spinacia oleracea* L.)	[94]
Water Medium Culture	Circulating methods (closed systems)	Nutrient film technique (NFT)	Red and green lettuce (*Lactuca sativa*), microgreens	[95–97]
		Deep flow technique (DFT)	Coriander (*Coriandrum sativum*), wheat microgreen (*Triticum aestivum*)	[98]
	Non-circulating methods (open systems)	Root-dipping technique	Lettuce (*Lactuca sativa*), microgreens	[99]
		Floating technique	Pak choi (*Brasica rapa*)	[100]
		Capillary action technique	Pak choi (*Brasica rapa*)	[101]
		Ebb and flow system	Basil (*Ocimum basilicum*), kale (*Brassica oleracea*), cherry tomato (*Solanum lycopersicum*), pepper (*Capsicum annuum*)	[102]

The provision and choice of the nutrient solution are very important for this kind of cultivation method because they determine the supply of essential mineral elements, oxygen, and water to the roots of the plants [32]. The inorganic ions found in nutrient solutions are often soluble salts of vital elements that the plant needs [103]. For plant growth, the essential elements are as follows:

- Macronutrients: Carbon (C), hydrogen (H), and oxygen (O) are available in nature/the atmosphere. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) are required in large quantities.
- Micronutrients: Manganese (Mg), boron (B), iron (Fe), copper (Cu), zinc (Zn), molybdenum (Mo), chlorine (Cl), nickel (Ni), cobalt (Co), sodium (Na), and silicon (Si) are required in very small quantities.

Four factors—pH, temperature, nutrient composition, and electrical conductivity (EC)—should be taken into consideration while optimizing a hydroponic nutrient solution. The ideal pH range for crop growth is 5.5 to 6.5 in hydroponic systems [104]. Therefore, pH monitoring and adjustment are important to prevent the depletion of nutrients from the solution and nutrient imbalance. A few of the hydroponically grown crops are shown in Table 5 with their pH and electrical conductivity requirements. Temperatures can affect the reaction rate of nutrients, the movement of nutrients through the medium, the physiological aspects of ion uptake, and the activity of soil microbes. Plant metabolic activity can be positively or negatively impacted by temperatures that are either below or above optimum ranges [105]. This can involve the build-up of phenolic compounds, the production of reactive oxygen species (ROS), the intake of nutrients, the creation of chlorophyll pigment, photosynthesis, and ultimately, the growth and development of the plant [106].

Table 5. Common hydroponically grown crops and their optimum electrical conductivities (EC mS/cm) and pH ranges.

Crops	pH	EC (mS/cm)
Pak choi (*Brassica rapa* L.)	7.0	1.5 to 2.0
Asparagus (*Asparagus officinalis* L.)	6.0–7.0	6.0–6.8
Basil (*Ocimum basilicum* L.)	5.5–6.0	1.0–1.6
Broccoli (*Brassica oleracea* L. var. *italica*)	6.0 to 6.8	2.8 to 3.5
Cucumber (*Cucumis sativus* L.)	5.0 to 5.5	1.7 to 2.0
Eggplant (*Solanum melongena* L.)	6.0	2.5 to 3.5
Cabbage (*Brassica oleracea* L.)	6.5 to 7.0	2.5 to 3.0
Lettuce (*Lactuca sativa* L.)	6.0 to 7.0	1.2 to 1.8
Tomato (*Solanum lycopersicum* L.)	6.0 to 6.5	2.0 to 4.0
Strawberry (*Fragaria ananassa* L.)	6.0	1.8 to 2.2
Zucchini (*Cucurbita pepo* L.)	6.0	1.8 to 2.4

The benefits that this technique offers are a yield increase, better space and energy utilization, protection against soil-borne pathogens and pesticides, and safety against climate change due to its controlled condition. Moreover, cultivation in space or under the oceans is also feasible using these techniques, in plant-growing portable shipping containers [96].

3.2.2. Aeroponics

Aeroponics is a popular soilless crop production system that combines ecological control, plant physiology, and nutrition; it benefits from minimal maintenance requirements, superior growth processes, automatic monitoring, protected cultivation, and high yields [107]. This method involves suspending the roots, separating them from one another, and keeping them in the dark while providing the necessary nutrient solution through fogging or misting. Sufficient oxygen is supplied to the plant roots because they need oxygen for cellular respiration. The energy (ATP) produced by this mechanism supports nutrient intake, root growth, and other essential processes. Otherwise, a situation without such energy will result in reduced nutrient absorption, slowed root growth, and higher vulnerability to pathogens responsible for root diseases [108].

Aeroponics have been successfully used in the production of various fruits/vegetables such as tomato [109], cucumber [110], sweet pepper [111], strawberry [112], potato [113], and leafy vegetables such as arugula [114] and lettuce [115]. Reduced nutrient and water requirements, minimal cost, and a decrease in damage and disease are some of the potential advantages of this strategy.

3.2.3. Aquaponics

Aquaponics, which combine hydroponics and aquaculture, allows for a symbiotic relationship between fish and plants in addition to providing benefits in terms of fruit/vegetable and fish production that are not achievable with either method alone [116]. In this symbiotic relationship, plants act as a biofilter and recycle water to ponds or containers containing fish, where fish produce ammonia, which is later converted into nitrate and provides necessary nutrients to plants [117]. A few of the analyzed fish and plant species in aquaponics are presented in Table 6. The disparity in nutrient requirements between hydroponics and aquaculture is one of the main obstacles in conventional aquaponics. The aquaponic system, which only uses fish feed as a source of nutrients for the plants, is lacking in some nutrients, such as K, Fe, and Ca, which are necessary for plant growth [118]. The reduction in these nutrients is directly proportional to the decrease in the yield of the fruits/vegetables, where the pH also influences the nutrient uptake in plants due to differences in the pH requirements of plants (5–6 approx.) and fishes' preferred pH values (7–9 approx.) [119,120]. Therefore, to prevent deficiency and maximize plant production in the aquaponic system, nutrient supplementation is necessary via foliar application [121], into the culture water/fertigation [122], or through supplementation in the fish diet [123]. A basic illustration of soilless farming is shown in Figure 5.

Table 6. An overview of plant and fish species in the aquaponic system.

Plant Species	Fish Species	References
Spinach (*Spinacia oleracea*)	Shark catfish (*Pangasianodon hypophthalmus*)	[124]
Basil *(Ocimum basilicum)*	African Catfish (*Clarias gariepinus*)	[125]
Lettuce (*Lactuca sativa*)	Tilapia (Oreochromis niloticus)	[126]
Lemon grass (*Cymbopogon citratus*)	Rohu (*Labeo rohita*)	[127]
Swiss chard (*Beta vulgaris*)	Tilapia (*Oreochromis niloticus*)	[128]
Lettuce (Lactuca sativa), Pak choi (*Brassica campestris*), Chinese cabbage (*Brassica rapa*), kale (*Brassica oleracea*), collards, Swiss chard (*Beta vulgaris*)	Tilapia (*Oreochromis niloticus*)	[129]
Tomato (*Solanum lycopersicum*)	Pearlspot (*Etroplus suratensis*)	[130]

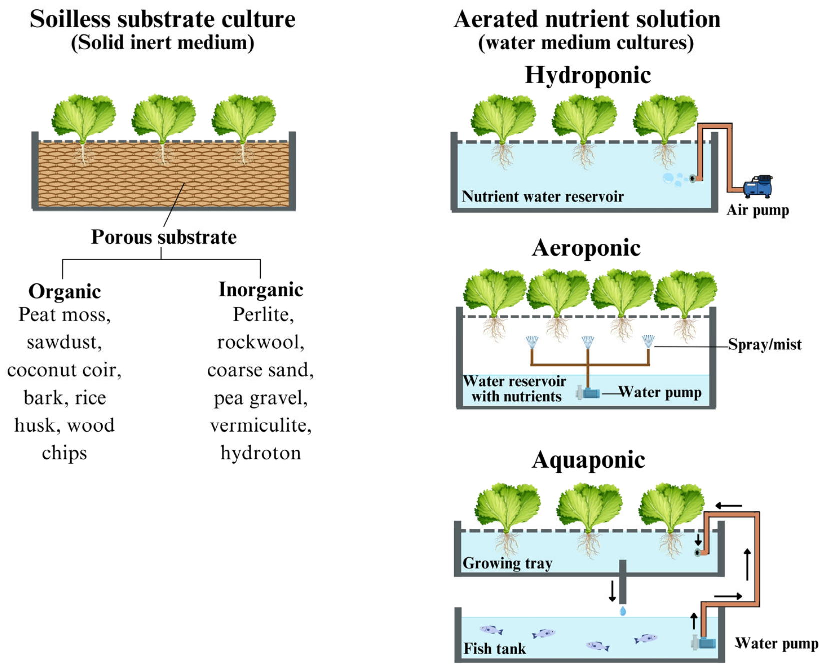

Figure 5. A sketch of soilless cultivation systems.

3.3. INM Effects on the Performance of Fruits and Vegetables

Fruits and vegetables are rich in nutrients and offer a balanced diet that includes dietary fiber, proteins, fats, carbohydrates, vitamins, and minerals [131]. Since they are the least expensive source of food, they regarded as the finest supplement to ensure nutritional security. Also, they provide numerous health advantages for our body, including being diuretic, laxative, and anti-diabetic and aiding in heart health, in addition to providing a blend of bioflavonoids and antioxidants that scavenge free radicals and reduce the risk of cancer [132]. Considering the above-mentioned benefits, fruit and vegetable production is crucial and needs serious attention from growers. Although the use of high-input technology, such as chemical pesticides, herbicides, and fertilizers, increases productivity, there are rising concerns about the harmful impacts of chemical use on soil productivity, human health, and environmental quality. Therefore, to solve problems like a low yield and output, low nutritional value, and poor quality of fruits and vegetables, INM is crucial for fruit/vegetable crops, and over time, several fruits and vegetables have come to be known to benefit from the INM practices [133]. Table 7 summarizes the use of various INM techniques, which assist in the production of different fruits and vegetables and affect the overall morphological, physiological, and biochemical parameters while minimizing the environmentally harmful effects.

Table 7. Effects of integrated nutrient management on the performance of different fruits and vegetables.

Fruits and Vegetables	Impact of Integrated Nutrient Management	References
Tomato (*Solanum lycopersicum* L.)	50% recommended dose of fertilizer (RDF) in combination with 5 t/ha ARV (Agro Residue Vermicompost) resulted in an increased plant height, root length, dry weight, chlorophyll content, leaf area index, number of flowers per plant, and fruits per plant, which ultimately increased crop yield.	[134]
Pepper (*Capsicum annuum* L.)	Higher maximum plant height, increased leaf area index, improved chlorophyll content, and an improvement in number of branches per plant were observed after the treatment with 75% fertilizers and poultry manure at the rate of 5 t/ha, in addition to biofertilizers and 2% magnesium sulfate ($MgSO_4$).	[135]
Eggplant (*Solanum melongena* L.)	100% NPK in combination with 25% N through Vermicompost yielded an enhanced number of fruits per plant. The length as well as diameter, weight, and yield of fruit per hectare improved.	[136]
Potato (*Solanum tuberosum*)	Integrated use of Tata Geo Green at 3.75 t/ha soil treatment along with 75% NPK fertilizer (150:60:100) are optimal to produce greater plant growth, net returns, and B:C ratios.	[137]
Bottle gourd (*Lagenaria siceraria*)	Inhibition of red pumpkin beetle and powdery mildew with an increment in B:C and total soluble solids (TSSs) by using 50% NPK, 25% vermicompost, and 25% compost.	[138]
Cucumber (*Cucumis sativus* L.)	Increased yield by using RDF + vermicompost at the rate of 5 t/ha in addition to Azotobacter at the rate of 5 Kg/ha and adding phosphate-solubilizing bacteria (PSBs) at the rate of 5 kg/ha.	[139]
Bitter gourd (*Momordica charantia*)	Increased total soluble solids, protein content, ascorbic acid, shelf life, and total fruit yield were achieved using 100% RDF of NPK in addition to FYM 5 t/ha and biofertilizers at 4 kg/ha (Azotobacter and PSBs).	[140]
Ridge gourd (*Luffa acutangular*)	Use of 25% recommended dose of nutrients (RDN) in combination with 50% RDF from Azotobacter + Bio-compost (2.5 L/ha + PSB 2.5 L/ha) was found to be optimal for ridge gourd growth and yield metrics.	[141]
Cauliflower (*Brassica oleracea* var. *botrytis*)	100% RDF in combination with Azospirillium (5 L/ha), PSBs (5 L/ha), and potash-mobilizing bacteria (KMBs) (5 L/ha) enhanced morphological and quality attributes.	[142]
Broccoli (*Brassica oleracea* L. var. *italica*)	Gibberellic acid (GA_3) application at 50 ppm in combination with Azotobacter at 5 kg/ha enhanced the maximum head yield per plant, head yield per plot, and total head yield.	[143]
Cabbage (*Brassica oleracea* L. var. *capitata*)	Application of farmyard manure (FYM) 50% with Azotobacter 50% to the soil improved plant spread, leaves per plant, stalk length, leaf area, and leaf length and width, along with minimizing the days to maturity.	[144]
Chinese cabbage (*Brassica rapa*)	Mineral potassium 100% with the addition of potassium biofertilizer yielded the maximum head diameter, height, and yield.	[145]

Table 7. *Cont.*

Fruits and Vegetables	Impact of Integrated Nutrient Management	References
Onion (*Allium cepa*)	Combination of FYM at 20 tons, vermicompost at 5 tons, poultry manure at 2 tons, and 100% recommended NPK enhanced the bulb weight, neck thickness, plant height, and number of leaves.	[146]
Garlic (*Allium sativum*)	100% NPK in combination with 50 kg sulfur (S)/ha and 5% Jeevamrit (Jv) at the rate of 1 L/m^2 yielded an increased plant height, number of leaves per plant, and bulb weight and diameter, ultimately positively affecting the overall bulb yield.	[147]
Carrot (*Daucus carota*)	Carrot growth and yield increased after the combined treatment of organic manures and inorganic fertilizers (5 t/ha cow dung (CD) + 5 t/ha poultry manure (PM)).	[148]
Radish (*Raphanus sativus*)	90% recommended fertilizer dose in combination with 10% Spent Mushroom Compost (SMC), apart from FYM, *Azotobacter*, and PSB, resulted in a higher leaf number and size, root size, weight, and yield.	[149]

INM Effects on the Performance of Tomato

One of the most widely grown fruit crops is the tomato (*Lycopersicum esculentum* Mill.), which has high levels of starch (0.6–1.2%), total sugar (2.5–4.5%), and minerals (potassium, calcium, sodium, magnesium, phosphorus, boron, manganese, zinc, copper, iron, etc.). In addition to these, fresh tomato fruit includes organic acids that are known as health acids, such as citric, malic, and acetic acids [150]. Nutrient stress in crops such as tomato can result from either excessive element concentrations or inadequate element availability [151]. Soil nutrition is one of the key elements influencing plant productivity, and the availability of nutrients is susceptible to climate change impacts [152]. Since carbon, nitrogen, and phosphorus are necessary nutrients for plant growth and development, their availability has a significant effect on plants [153]. Among fruits, tomato is the most studied for integrated nutrient management. The application of both inorganic and organic nutrient sources simultaneously can potentially improve the tomato growth, yield, and quality in addition to a noticeable yield increase and disease reduction in tomatoes [150]. Consequently, it is essential to look at how tomato production and quality are affected by the direct or combined application of organic manure, inorganic fertilizer, and biofertilizers, with a possible inorganic fertilizer decrease. Therefore, in Table 8, we summarize some of the studies that have accounted for morpho-physiological, yield, yield attribute, nutrient uptake, and physio-chemical improvements in tomato fruits and other plants under diverse INM approaches.

Table 8. Effects of integrated nutrient management on tomato performance.

Tomato Parameter	Modes of INM	Impact of Integrated Nutrient Management	References
Morphological parameters	50% RDN in combination with 25% N through VC and 25% N through FYM treatment	All growth parameters for tomato improved	[154]
	NPK (120:60:80 kg/ha) application in combination with FYM 10 t/ha, S at 25 kg/ha, Azotobacter, and mixed micronutrients	Increased tomato plant height and leaf length	[155]
	Combination of 75% N through urea, muriate of potash (MOP), single superphosphate (SSP), 25% through vermicompost, B, Zn, Azotobacter + PSB	Plant spread and height improved	[156]
	50% RDF in combination with 50% N from FYM and Bio NPK	Improved crop growth rate, relative crop growth rate, and increased number of primary branches and plant height	[157]

Table 8. *Cont.*

Tomato Parameter	Modes of INM	Impact of Integrated Nutrient Management	References
Yield and yield attributes	75% N through urea, MOP, SSP, 25% through vermicompost, B, Zn, Azotobacter + PSB	Enhanced yield and maximum B:C ratio	[156]
	50% RDF + 50% N from vermicompost + Bio NPK	Maximum number of fruits per plant, fruit yield per plot, and maximum fruit yield per hectare and better B:C ratio	[157]
	75% RDF + 25% organic (FYM + VC + PM)	Maximum fruit yield	[158]
	Integrated crop nitrogen management compared to traditional management	Improved tomato yield by 32.1%	[159]
Nutrient contents and nutrient uptake	50% RDN in combination with 25% N through VC and 25% N through FYM	Increased uptake of N, P, and K	[154]
	50% RDN, 25% N through VC and FYM	39.7% increase in the N uptake	[159]
Physio-chemical properties	75% RDF and 50% vermicompost	Maximum TSS, titratable acidity (TA), pH, and ascorbic acid content	[160]
	Combined treatment of NPK and FYM	Elevated ascorbic acid contents	[161]
	Chicken manure and inorganic N fertilizer	Increases in soluble protein and TA by 124% and 118%	[162]

3.4. INM Effects on the Performance of Field Crops

3.4.1. INM Effects on the Performance of Rice

One of the important cereal crops that can be grown in lowlands, uplands, and deep-water conditions is rice (*Oryza sativa* L.). The most common cropping method used in rice production is the rice–rice cropping sequence, which has a major negative effect on the soil structure and ultimately depletes water and minerals from the soil [163]. Furthermore, because of the high nutrient requirements, a decrease in net yield per unit area may result due to the high cost of fertilizer, which is most of the time unaffordable for local farmers [164]. Nutrient shortages during rice cultivation are generally caused by the leaching of nutrients, particularly cations like potassium (K), calcium (Ca), and magnesium (Mg); however, the use of chemical fertilizers without adding organic manure or micronutrients also contributes to soil nutrient deficits [165]. The food and nutritional security of farmers is directly impacted by these unbalanced nutrient levels, which also lower the crop and soil quality. Thus, in light of the discussion above, various INM applications are known to contribute to soil quality, a better yield, and a greater net return in rice production, as shown in Table 9.

Table 9. Effects of integrated nutrient management on rice performance.

Rice Parameters	Modes of INM	Impact of Integrated Nutrient Management	References
Growth parameters	100% RDF + $S_{40}Zn_5B_{1.5}$ kg ha^{-1}	Accumulation of dry matter and plant height	[166]
	75% NPK + 25% FYM	Plant maximum height	[167]
	75% RDN + 25% N	Maximum plant height recorded at 90 days after treatment (DAT)	[168]
	125% RDF + 25% vermicompost	Dry matter accumulation	[169]
	75% RDN + 25% poultry manure	Dry matter accumulation	[170]
Yield and yield attributes	Integrated effect of fertilizer and FYM	Increase in grain yield	[171]
	Application of poultry manure as soil and panchakavya as foliar application	Increase in grain yield	[172]
	Application of 100% RDF in combination with 5 t ha^{-1} FYM	Highest number of panicles, increased panicle length and test weight, and higher grain and straw yields	[173]

Table 9. *Cont.*

Rice Parameters	Modes of INM	Impact of Integrated Nutrient Management	References
Yield and yield attributes	50% recommended NPK + 50% N as FYM in addition to 5 kg zinc ha^{-1}	All yield attributes influenced through INM such as number of effective tillers, length of panicle, grains per panicle, filled and unfilled grains per panicle, and test weight	[174]
	2.5 t poultry manure ha^{-1} along with 75 kg N + 16.5 kg P and 31.3 kg K ha^{-1}	Higher crop growth and improved grain yield	[175]
Nutrient contents and nutrient uptakes	75% RDN and 25% N through vermicompost	Increased N contents of both grain and straw	[168]
	100% RDF through inorganic fertilizer + 25% RDN through Neem Cake	Increased uptake of nutrient contents (%) of grain and straw	[176]
	Synchronized treatment of organic manure and chemical fertilizer	Significant uptake of N, P, and K	[175]
Physio-chemical properties	Combination of organic manure and fertilizer	Improved various physio-chemical properties, improved uptake, and raised nutrient absorption	[176]
	Increased compost concentration along with fertilizer	Reduced pH and sodium absorption ratio	[177]
	Addition of inorganic fertilizers with organic manures	Improved mineralization	[175]

3.4.2. INM Effects on the Performance of Wheat

Nitrogen use efficiency (NUE) is a crucial factor used to evaluate a crop production system and improve the yield while maintaining environmental sustainability [178]. By providing crops with the best possible nutrition and minimizing nitrogen losses from the field, thus increasing the NUE, agricultural productivity can be increased. The INM approach, which aims to substitute some organic nutrient sources for chemical fertilizers without negatively impacting production, is considered a sustainable choice for wheat cultivation [179]. For example, the continuous use of organic materials like crop residues, green manures, and farmyard manures decisively affects N dynamics in the soil–plant system [180]. Extensive research has been conducted on wheat crops regarding the use of INM and its beneficial attributes. Table 10 shows that, in addition to better physiological and biochemical traits, INM applications increased the growth parameters of wheat as well as its nutrient levels, efficient nutrient uptake, yield, and yield attributes.

Table 10. Effects of integrated nutrient management on wheat performance.

Wheat Parameters	Modes of INM	Impact of Integrated Nutrient Management	References
Growth parameters	-	Increased plant height and accumulation of dry matter	[181]
	Combined application of 4 t/ha vermicompost and Azotobacter chroococcum inoculation at the rate of 5 mL/kg seed and 100% RDN	Accumulation of dry matter and increased plant height	[182]
	100% RDF and 25% N through vermicompost + $ZnSO_4$ at 25 kg/ha	Improved plant height (92.25 cm) and dry matter accumulation (274.65 g m^{-2}) were achieved	[183]
	Application of 100% NPK + 5 t/ha FYM + 5 t/ha vermicompost	Higher leaf area, dry matter, and plant height	[184]
	RDF 100% in combination with Azotobacter + PSB	Significantly improved wheat plant height	[185]

Table 10. *Cont.*

Wheat Parameters	Modes of INM	Impact of Integrated Nutrient Management	References
Yield and yield attributes	Application of 150% RDF together with 10 tons of FYM + 25 kg $ZnSO_4$/ha	Maximum grain yield of 3.8–3.9 t/ha was achieved	[186]
	-	Increased length of spike, number of grains per spike, grain weight per spike, and 1000-seed weight	[181]
	Application of inorganic fertilizer in combination with higher/lower dose of FYM, biofertilizer, and sulfur	Improved spike length and number of grains per spike	[187]
	75% RDF + vermicompost at the rate of 1 t/ha^{-1} + PSB	Higher yield attributes and ultimately yield of wheat, which led to higher uptake of NPK by the crop	[188]
	100% RDN + 25% N through vermicompost	Higher number of effective tillers (94%), longer spike length (34%), higher grain yield (165%), and greater straw yield (157%) of wheat over control	[189]
Nutrient contents and nutrient uptakes	RDF 100% + vermicompost (2 t/ha) in addition to PSB	Significant nutrient uptake was registered	[190]
	75% RDF, in addition to vermicompost at 1 t/ha and PSB	Enhanced NPK availability in soil for the wheat crop compared to control	[188]
	75% RDF and 25% N through FYM	Efficient nutrient supply system for wheat variety Malviya 234 was achieved	[191]
Physio-chemical properties	Combine application of FYM and 75% RDN	Sustained soil quality and ultimately wheat productivity can be achieved	[192]
	-	Increased protein content	[181]
	Applied potassium at the rate of 100 kg K_2O/ha	Under Mediterranean rain-fed conditions (Algeria), durum wheats' physiological indices improved	[193]

3.4.3. INM Effects on the Performance of Different Crops

Even though wheat and rice are the most studied crops for INM over time, INM has been employed to test and evaluate several other crops, including cotton, millet, sorghum, sugarcane, and chickpea, as shown in Table 11. INM stands out as a critical method for striking a harmonious balance between productivity and sustainability in modern farming, which is vital as global agriculture faces the challenge of feeding a growing population while minimizing the environmental effect [194]. In modern agriculture, INM presents a comprehensive and sustainable method for satisfying the capacity for crops to meet dietary needs, standing as not merely a strategy, but a paradigm shift [195]. As the benchmark in innovation, INM integrates many sources of nutrients to create a dynamic and balanced supply for crops at every stage of growth [196].

Table 11. Effects of integrated nutrient management on different crop performance indicators.

Crops	Impacts of Integrated Nutrient Management	References
Cotton (*Gossypium arboreum*)	Soil fertility status improved using cotton stalks, less dependency of FYM, and reduced costs of inorganic nutrients by 20–25 USD/h	[197]
Pearl millet (*Pennisetum glaucum*)	Economically viable and environmentally friendly recommended dose of inorganic fertilizer (25%) with the combination of Azospirillum biofertilizers, PSB, and 2% foliar application of urea is suitable for increasing pearl millet yield	[198]
Chickpea (*Cicer arietinum* L.)	75% RDF with vermicompost and *Rhizobium* resulted in an increased growth and yield of the crop	[199]
Fenugreek (*Trigonella foenum*-graecum)	Growing finger millet with the residual soil fertility of the previous leguminous crop can result in adequate development and output of this less nutrient-demanding crop	[200]

Table 11. *Cont.*

Crops	Impacts of Integrated Nutrient Management	References
Finger millet (*Eleusine coracana*)	Increased nutritional quality of the grains, nutrient uptake, and nitrogen use efficiency indices were achieved through INM	[201]
French bean (*Phaseolus vulgaris*)	75% RDF in addition to 1 t vermicompost was responsible for an increased ascorbic acid content and dry matter content of green pods	[202]
Sunflower (*Helianthus annuus*)	In addition to increasing the head diameter, the biological yields of the 25 cultivars of Shams, Ghasem, and Haysan sunflowers were enhanced by 39.2%, 31.5%, and 34.5%, respectively, when treated with humic acid plus chemical fertilizer	[203]
Sorghum (*Sorghum bicolor*)	If manure and mineral fertilizer are combined, sorghum yields can be increase by 500–5000 kg/ha depending on the type of soil and amount of rainfall in the area	[204]
Sweet potato (*Ipomoea batatas*)	Incorporation of organic manures plus chemical fertilizers enriched the crop yield and enhanced the water use efficiency and economic return to farmers	[205]

4. Potential Constraints in INM

The key factors causing considerable damage to sustainable agriculture and irreversible productivity reductions are soil erosion, nutrient mining, structural deterioration, and fertility loss [206]. Restoring soil productivity and preserving soil health are essential to addressing and avoiding poor soil health. Accordingly, considerable initiative should be taken to encourage the efficient application of INM. For example, biostimulants are known to improve the crop output if the overall growth and productivity suffer from stress [24]. In this context, biostimulant use must be subjected to various economical studies, to monitor the viability of their applications. The need to control biostimulant costs is another issue that prevents less experienced farmers from using these techniques. The increased cost of a soilless cultivation system, lack of skilled manpower, and potential risks related to humidity and disease onset are a few of the constraints on adopting this modern approach. Also, energy costs are concerning in CEA, which uses a lot of energy for its automated operations, such as the use of artificial lights [207,208] and pumps. On the one hand, these create a source of GHGs if the energy used is from non-renewable sources, and on the other hand, they are not cost friendly. Research suggests that the carbon footprint of soilless cultivation is complex. Some studies show that it can be lower than in traditional methods, particularly when considering factors like reduced transportation needs, water use efficiency, and a precise nutrient supply, as soilless farms reduce the carbon footprint associated with long-distance transportation of produce, often use significantly less water than traditional agriculture, and allow for the controlled delivery of nutrients directly to the plant roots, potentially minimizing fertilizer waste and runoff [209]. However, it is also true that electricity use for the pumps can affect the carbon footprint, but the use here of renewable energy sources like solar power can significantly reduce the carbon footprint of soilless cultivation [210].

Furthermore, determining the nutrient balance in the soil while considering the nutrients consumed by the present crop, as well as those needed for the next one, requires careful consideration [211]. Given the anticipated rapid soil organic matter loss and the loss of soil fertility, it is necessary to continuously examine the fertility of the soil, to determine the amounts of nutrients lost through crop absorption, erosion, and leaching [212]. Additionally, the high initial cost, intense monitoring, electricity dependence, low root oxygenation, reduced technical expertise, and possibility of water-based microorganism infestations are a few of the limitations of hydroponic agriculture. Likewise, difficult maintenance on a large scale, clogged misting nozzles, and inadequacy and difficulty in knowledge transfer to regular farmers are a few of the constraints in aeroponics [213].

Similarly, due to the challenges of obtaining FYM and biofertilizers, as well as a lack of expertise, inadequate advising services, and limitations in recycling organic wastes to produce high-quality compost, certain low-income farmers find it difficult to gather organic manure [214]. A few other constraints for INM include biotic or abiotic stresses [215], inadequate tillage, and a shortage of necessary equipment. Moreover, a failure to provide adequate extension services to support farmers and educate them about the value of INM, and the absence of non-governmental organizations (which could offer support in maintaining soil properties and the soil nutrient balance, reducing environmental impacts, and boosting profitability), present further constraints on the use of INM [180].

5. Conclusions and Future Perspectives on INM

The utilization of nutrient inputs from organic fertilizers bears essential significance for plant development and sustainability, since the ongoing misuse of chemical fertilizers is linked to low resource use efficiency and substantial environmental contamination. In terms of better fertilizer use efficiency, greater soil health, decreased environmental pollution, and increased nutritional quality, INM has come to light as a potential method for producing crops, fruits, and vegetables, both indoors as well as outdoors. However, an ongoing search for better approaches, models, and their successful integration is necessary, which may allow for INM with higher yields and a more sustainable and food-secure world. In INM techniques, soil and plant nutrient management should be encouraged as a crucial component of a successful agricultural system. Consequently, the productive potential of the soil resources should be given the main emphasis in INM methods. Moreover, a certain amount of mechanization is necessary for the broader adoption of INM techniques, because these systems frequently need more labor inputs compared to those that only use inorganic fertilizers and basic management techniques. Maintaining the existing nutritional supplies is less expensive and easier than restoring and rebuilding degraded ones. Here, no-till, strip-till, ridge-till, and mulch-till are a few of the conservation techniques that must be considered, as they assist in reducing the loss of water and nutrients from agro-ecosystems due to decreased surface water flows and soil erosion. Elsewhere, recycling residues or animal dung into organic fertilizer can improve the efficiency with which readily lost nutrients, such as nitrogen, can be easily utilized, offering a sustainable farming technique for environmental conservation.

Also, research on specific local plants that will generate the highest yields is necessary in addition to the analysis of when to apply various treatments while considering reasonable economic and environmental constraints. Extension personnel ought to take into consideration both farmer expertise and relevant research findings when interpreting research data for practical applications. Precision farming, sensor innovations, geographic information systems (GIS), crop models, several software programs, the geographic positioning system (GPS), machine learning, and the Internet of Things (IoT) are a few examples of the technological advancements that have contributed to INM, both in the soil as well soilless agricultural operations. The physiological effects of biostimulants are well known. In many cases, they act by regulating the activity of genes. Knowledge of such effects is of interest in regard to producing genetically modified/genetically engineered plant varieties/hybrids. More research on the transcriptome and proteomic effects of biostimulants is needed, which will clarify the mechanisms with which they enhance nutrient uptake and/or utilization by the plant. The findings will uncover how biostimulants help mitigate reductions in plant growth under abiotic stress and will generally explain the mechanisms behind stress tolerance responses. In addition to technology, which is continually developing, behavioral adaptations are also necessary to eradicate negative environmental effects and increase crop productivity. In the end, providing incentives might be a major factor in encouraging smallholder farmers to implement INM. There should be an intensification of the dialogues between growers and policymakers, ensuring devoted cells are established at local-level institutions for the further spread of INM. Finally, to encourage the use of organic fertilizers and biostimulants and limit inorganic N and P fertilizers' usage, nutrient management regulations or nutrient input taxes should be taken into consideration.

Author Contributions: Conceptualization, A.A., G.C. and G.N.; writing—original draft preparation, A.A.; writing—review and editing, G.N., G.C., J.M. and A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This article received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the efforts of Noramon Tantashutikun for designing the figures.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ghosh, A.; Kumar, A.; Biswas, G. Exponential population growth and global food security: Challenges and alternatives. In *Bioremediation of Emerging Contaminants from Soils*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 1–20. [CrossRef]
2. Aryal, J.P.; Manchanda, N.; Sonobe, T. Expectations for household food security in the coming decades: A global scenario. In *Future Foods*; Academic Press: Cambridge, MA, USA, 2022; pp. 107–131.
3. Wheller, T.; Braun, J. Climate change impacts global food security. *Science* **2013**, *341*, 508–513. [CrossRef] [PubMed]
4. Lal, R. Soils and sustainable agriculture: A review. *Agron. Sustain. Dev.* **2008**, *28*, 57–64. [CrossRef]
5. Erisman, J.W.; Sutton, M.A.; Galloway, J.; Klimont, Z.; Winiwarter, W. How a century of ammonia synthesis changed the world. *Nat. Geosci.* **2008**, *1*, 636–639. [CrossRef]
6. Chen, X.; Ma, L.; Ma, W.; Wu, Z.; Cui, Z.; Hou, Y.; Zhang, F. What has caused the use of fertilizers to skyrocket in China. *Nutr. Cycl. Agroecosyst.* **2018**, *110*, 241–255. [CrossRef]
7. Zhang, C.; Ju, X.; Powlson, D.; Oenema, O.; Smith, P. Nitrogen surplus benchmarks for controlling N pollution in the main cropping systems of China. *Environ. Sci. Technol.* **2019**, *53*, 6678–6687. [CrossRef] [PubMed]
8. NBS. National Bureau of Statistics (China). 2020. Available online: http://www.stats.gov.cn (accessed on 7 June 2024).
9. Wu, W.; Ma, B. Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: A review. *Sci. Total Environ.* **2015**, *512*, 415–427. [CrossRef] [PubMed]
10. Davidson, E.; Galloway, J.; Millar, N.; Leach, A. N-related greenhouse gases in North America: Innovations for a sustainable future. *Curr. Opin. Environ. Sustain.* **2014**, *9–10*, 1–8. [CrossRef]
11. Sutton, M.A.; Howard, C.M.; Erisman, J.W.; Billen, G.; Bleeker, A.; Grennfelt, P.; Van Grinsven, H.; Grizzetti, B. *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives*; Cambridge University Press: Cambridge, MA, USA, 2011.
12. European Commission. Council Directive 91/676/EEC of 12 December 1991 Concerning the Protection of Waters against Pollution Caused by Nitrates from Agricultural Sources. *Off. J.* **1991**, *L 375*, 0001–0008. Available online: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31991L0676:EN:HTML (accessed on 10 June 2024).
13. European Commission. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (OJ L 327 22.12.2000 p. 1). In *Documents in European Community Environmental Law*; European Commission: Brussels, Belgium, 2006; pp. 879–969. [CrossRef]
14. Velthof, G.L.; Lesschen, J.P.; Webb, J.; Pietrzak, S.; Miatkowski, Z.; Pinto, M.; Kros, J.; Oenema, O. The impact of the nitrates directive on nitrogen emissions from agriculture in the EU-27 during 2000–2008. *Sci. Total Environ.* **2014**, *468–469*, 1225–1233. [CrossRef]
15. Food and Agriculture Organization of the United Nations (FAO). *FAO Database: Agriculture Production and Agri-Environmental Indicators*; FAO: Rome, Italy, 2019.
16. Yang, L.; Wang, L.; Chu, J.; Zhao, H.; Zhao, J.; Zang, H.; Zeng, Z. Improving soil quality and wheat yield through diversified crop rotations in the North China Plain. *Soil Tillage Res.* **2024**, *244*, 106231. [CrossRef]
17. Yang, X.; Steenhuis, T.S.; Davis, K.F.; Van der Werf, W.; Ritsema, C.J.; Pacenka, S.; Du, T. Diversified crop rotations enhance groundwater and economic sustainability of food production. *Food Energy Sec.* **2021**, *10*, e311. [CrossRef]
18. Liang, Z.; Xu, Z.; Cheng, J.; Ma, B.; Cong, W.F.; Zhang, C.; Groot, J.C. Designing diversified crop rotations to advance sustainability: A method and an application. *Sustain. Prod. Cons.* **2023**, *40*, 532–544. [CrossRef]
19. Gou, X.; Reich, P.B.; Qiu, L.; Shao, M.; Wei, G.; Wang, J.; Wei, X. Leguminous plants significantly increase soil nitrogen cycling across global climates and ecosystem types. *Glob. Chang. Biol.* **2023**, *29*, 4028–4043. [CrossRef] [PubMed]
20. Xu, H.; Detto, M.; Fang, S.; Chazdon, R.L.; Li, Y.; Hau, B.C.; Yao, T.L. Soil nitrogen concentration mediates the relationship between leguminous trees and neighbor diversity in tropical forests. *Commun. Biol.* **2020**, *3*, 317. [CrossRef] [PubMed]
21. Bhupenchandra, I.; Chongtham, S.K.; Devi, E.L.; Choudhary, A.K.; Salam, M.D.; Sahoo, M.R.; Khaba, C.I. Role of biostimulants in mitigating the effects of climate change on crop performance. *Front. Plant Sci.* **2022**, *13*, 967665. [CrossRef] [PubMed]
22. European Biostimulants Industry Council. What Are Biostimulants? 2012. Available online: https://biostimulants.eu/ (accessed on 10 June 2024).
23. Biostimulant Coalition. What Are Biostimulants? 2013. Available online: http://www.biostimulantcoalition.org/about/ (accessed on 10 June 2024).
24. Zulfiqar, F.; Moosa, A.; Ali, H.M.; Bermejo, N.F.; Munné-Bosch, S. Biostimulants: A sufficiently effective tool for sustainable agriculture in the era of climate change? *Plant Phys. Biochem.* **2024**, *211*, 108699. [CrossRef]

25. Palm, C.A.; Gachengo, C.N.; Delve, R.J.; Cadisch, G.; Giller, K.E. Organic inputs for soil fertility management in tropical agroecosystems: Application of an organic resource database. *Agric. Ecosys. Environ.* **2001**, *83*, 27–42. [CrossRef]
26. Hindoriya, P.S.; Kumar, R.; Meena, R.K.; Ram, H.; Kumar, A.; Kashyap, S.; Bhattacharjee, S. The Impact of Integrated Nutrient Management on Trifolium alexandrinum Varietal Performance in the Indo-Gangetic Plains: A Comparative Yield and Economic Analysis. *Agronomy* **2024**, *14*, 339. [CrossRef]
27. Sharma, A.; Sharma, J.C.; Shukla, Y.R.; Verma, M.L.; Singh, U.; Spehia, R.S.; Kumar, A. Nutrient Management Influences Root Characteristics and Nitrogen Use Efficiency in the Vegetable-Based Agroecosystem in the Northwestern Himalayas. *Sustainability* **2023**, *15*, 10593. [CrossRef]
28. Ali, A.; Hussain, T.; Tantashutikun, N.; Hussain, N.; Cocetta, G. Application of smart techniques, internet of things and data mining for resource use efficient and sustainable crop production. *Agriculture* **2023**, *13*, 397. [CrossRef]
29. Hahn, L.; Kurtz, C.; De Paula, B.V.; Feltrim, A.L.; Higashikawa, F.S.; Moreira, C.; Parent, L.É. Feature-specific nutrient management of onion (*Allium cepa*) using machine learning and compositional methods. *Sci. Rep.* **2024**, *14*, 6034. [CrossRef]
30. Suleiman, M.K.; Shahid, S.A. Prospective of Agricultural Farming in Kuwait and Energy-Food-Water-Climate Nexus. In *Terrestrial Environment and Ecosystems of Kuwait: Assessment and Restoration*; Springer Nature: Cham, Switzerland, 2024; pp. 363–391. [CrossRef]
31. Chamuah, S.; Amin, M.A.; Sultana, N.; Hansda, N.N.; BM, H.; Noopur, K. Protected Vegetable Crop Production for Long-term Sustainable Food Security. *J. Sci. Res. Rep.* **2024**, *30*, 660–669. [CrossRef]
32. Jan, S.; Rashid, Z.; Ahngar, T.A.; Iqbal, S.; Naikoo, M.A.; Majeed, S.; Nazir, I. Hydroponics—A review. *Int. J. Curr. Microbiol. App. Sci.* **2020**, *9*, 1779–1787. [CrossRef]
33. Arndt, J.A.; Aulinger, A.; Matthias, V. Quantification of lightning-induced nitrogen oxide emissions over Europe. *Atmos. Environ.* **2019**, *202*, 128–141. [CrossRef]
34. Murray, L.T. Lightning NO x and impacts on air quality. *Curr. Poll. Rep.* **2016**, *2*, 115–133. [CrossRef]
35. Ju, X.; Xing, G.; Chen, X.; Zhang, S.; Zhang, L.; Liu, X.; Cui, Z.; Yin, B.; Christie, P.; Zhu, Z.; et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 3041–3046. [CrossRef] [PubMed]
36. Witt, C.; Dobermann, A. Toward a decision support system for site-specific nutrient management. In *Increasing the Productivity of Intensive Rice Systems Through Site-Specific Nutrient Management*; Dobermann, A., Witt, C., Dawe, D., Eds.; Science Publishers, Inc.: Enfield, NH, USA; International Rice Research Institute (IRRI): Los Baños, Philippines, 2004; pp. 359–395.
37. Chen, X.; Cui, Z.; Vitousek, P.; Cassman, K.; Matson, P.; Bai, J.; Meng, Q.; Hou, P.; Yue, S.; Römheld, V.; et al. Integrated soil—Crop system management for food security. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 6399–6404. [CrossRef] [PubMed]
38. Jambert, C.; Serca, D.; Delmas, R. Quantification of N-losses as NH_3, NO, and N_2O and N_2 from fertilized maize fields in southwestern France. *Nutr. Cycl. Agroecosyst.* **1997**, *48*, 91–104. [CrossRef]
39. Ma, B.L.; Wu, T.Y.; Tremblay, N.; Deen, W.; McLaughlin, N.B.; Morrison, M.J.; Gregorich, E.G.; Stewart, G. Nitrous oxide fluxes from corn fields: On-farm assessment of the amount and timing of nitrogen fertilizer. *Glob. Chang. Biol.* **2010**, *16*, 156–170. [CrossRef]
40. Ju, X.; Lu, X.; Gao, Z.; Chen, X.; Su, F.; Kogge, M.; Römheld, V.; Christie, P.; Zhang, F. Processes and factors controlling N_2O production in an intensively managed low carbon calcareous soil under sub-humid monsoon conditions. *Environ. Pollut.* **2011**, *159*, 1007–1016. [CrossRef] [PubMed]
41. Huang, Y.; Sun, W. Changes in topsoil organic carbon of croplands in mainland China over the last two decades. *Chin. Sci. Bull.* **2006**, *51*, 1785–1803. [CrossRef]
42. Gupta, S.; Bhattacharyya, P.; Kulkarni, M.G.; Doležal, K. Growth regulators and biostimulants: Upcoming opportunities. *Fro. Plant Sci.* **2023**, *14*, 1209499. [CrossRef]
43. Bulgari, R.; Franzoni, G.; Ferrante, A. Biostimulants application in horticultural crops under abiotic stress conditions. *Agronomy.* **2019**, *9*, 306. [CrossRef]
44. Rakkammal, K.; Maharajan, T.; Ceasar, S.A.; Ramesh, M. Biostimulants and their role in improving plant growth under drought and salinity. *Cereal Res. Comm.* **2023**, *51*, 61–74. [CrossRef]
45. Lin, K.H.; Lin, F.W.; Wu, C.W.; Chang, Y.S. Biostimulation of maize (*Zea mays*) and irrigation management improved crop growth and water use under controlled environment. *Agronomy* **2019**, *9*, 559. [CrossRef]
46. Adoko, M.Y.; Noumavo, A.D.P.; Agbodjato, N.A.; Amogou, O.; Salami, H.A.; Aguégué, R.M.; Baba-Moussa, L. Effect of the application or coating of PGPR-based biostimulant on the growth, yield and nutritional status of maize in Benin. *Front. Plant Sci.* **2022**, *13*, 1064710. [CrossRef]
47. Pacholczak, A.; Szydło, W.; Jacygrad, E.; Federowicz, M. Effect of auxins and the biostimulator AlgaminoPlant on rhizogenesis in stem cuttings of two dogwood cultivars (Cornus alba 'Aurea'and 'Elegantissima'). *Acta Sci. Polo. Hort. Cul.* **2012**, *11*, 93–103.
48. Ritter, G.; Villa, F.; Da Silva, D.F.; Alberton, O.; Menegusso, F.J.; Eberling, T.; Dória, J. Microbiological biostimulant promotes rooting of olive cuttings. *Int. J. Agric. Biol. Eng.* **2021**, *14*, 207–212. [CrossRef]
49. Corbellini, J.R.; Ribas, L.L.F.; De Maia, F.R.; Corrêa, D.D.O.; Noseda, M.D.; Suzuki, R.M.; Amano, É. Effect of microalgae *Messastrum gracile* and *Chlorella vulgaris* on the in vitro propagation of orchid *Cattleya labiata*. *J. Appl. Phycol.* **2020**, *32*, 4013–4027. [CrossRef]
50. Wise, K.; Gill, H.; Selby-Pham, J. Willow bark extract and the biostimulant complex Root Nectar® increase propagation efficiency in chrysanthemum and lavender cuttings. *Sci. Hortic.* **2020**, *263*, 109108. [CrossRef]

51. Luziatelli, F.; Gatti, L.; Ficca, A.G.; Medori, G.; Silvestri, C.; Melini, F.; Ruzzi, M. Metabolites secreted by a plant-growth-promoting *Pantoea agglomerans* strain improved rooting of *Pyrus communis* L. cv Dar Gazi cuttings. *Front. Microbiol.* **2020**, *11*, 539359. [CrossRef]
52. Toscano, S.; Ferrante, A.; Branca, F.; Romano, D. Enhancing the quality of two species of baby leaves sprayed with Moringa leaf extract as biostimulant. *Agronomy* **2021**, *11*, 1399. [CrossRef]
53. Rashid, N.; Wahid, A.; Ibrar, D.; Irshad, S.; Hasnain, Z.; Al-Hashimi, A.; Khan, S. Application of natural and synthetic growth promoters improves the productivity and quality of quinoa crop through enhanced photosynthetic and antioxidant activities. *Plant Phys. Biochem.* **2022**, *182*, 1–10. [CrossRef] [PubMed]
54. Hassan, F.A.S.; Mazrou, R.; Gaber, A.; Hassan, M.M. Moringa extract preserved the vase life of cut roses through maintaining water relations and enhancing antioxidant machinery. *Postharvest Biol. Technol.* **2020**, *164*, 111156. [CrossRef]
55. Ashour, M.; Hassan, S.M.; Elshobary, M.E.; Ammar, G.A.; Gaber, A.; Alsanie, W.F.; El-Shenody, R. Impact of commercial seaweed liquid extract (TAM®) biostimulant and its bioactive molecules on growth and antioxidant activities of hot pepper (*Capsicum annuum*). *Plants* **2021**, *10*, 1045. [CrossRef] [PubMed]
56. Lola-Luz, T.; Hennequart, F.; Gaffney, M. Effect on yield, total phenolic, total flavonoid and total isothiocyanate content of two broccoli cultivars (*Brassica oleraceae* var italica) following the application of a commercial brown seaweed extract (*Ascophyllum nodosum*). *Agric. Food Sci.* **2014**, *23*, 28–37. [CrossRef]
57. Kauffman, G.L.; Kneivel, D.P.; Watschke, T.L. Effects of a biostimulant on the heat tolerance associated with photosynthetic capacity, membrane thermostability, and polyphenol production of perennial ryegrass. *Crop Sci.* **2007**, *47*, 261–267. [CrossRef]
58. Carillo, P.; Colla, G.; El-Nakhel, C.; Bonini, P.; D'Amelia, L.; Dell'Aversana, E.; Rouphael, Y. Biostimulant application with a tropical plant extract enhances *Corchorus olitorius* adaptation to sub-optimal nutrient regimens by improving physiological parameters. *Agronomy* **2019**, *9*, 249. [CrossRef]
59. Fusco, G.M.; Nicastro, R.; Rouphael, Y.; Carillo, P. The effects of the microbial biostimulants approved by EU regulation 2019/1009 on yield and quality of vegetable crops. *Foods* **2021**, *11*, 2656. [CrossRef]
60. Li, H.; Yue, H.; Li, L.; Liu, Y.; Zhang, H.; Wang, J.; Jiang, X. Seed biostimulant *Bacillus* sp. MGW9 improves the salt tolerance of maize during seed germination. *AMB Exp.* **2021**, *11*, 74. [CrossRef]
61. Gupta, S.; Doležal, K.; Kulkarni, M.G.; Balázs, E.; Van Staden, J. Role of non-microbial biostimulants in regulation of seed germination and seedling establishment. *Plant Growth Reg.* **2022**, *97*, 271–313. [CrossRef]
62. Amirkhani, M.; Mayton, H.S.; Netravali, A.N.; Taylor, A.G. A seed coating delivery system for bio-based biostimulants to enhance plant growth. *Sustainability* **2019**, *11*, 5304. [CrossRef]
63. Amirkhani, M.; Netravali, A.N.; Huang, W.; Taylor, A.G. Investigation of soy protein–based biostimulant seed coating for broccoli seedling and plant growth enhancement. *HortScience* **2016**, *51*, 1121–1126. [CrossRef]
64. Qiu, Y.; Amirkhani, M.; Mayton, H.; Chen, Z.; Taylor, A.G. Biostimulant seed coating treatments to improve cover crop germination and seedling growth. *Agronomy* **2020**, *10*, 154. [CrossRef]
65. Cocetta, G.; Ertani, A.; Bulgari, R.; Franzoni, G.; Nicola, S.; Ferrante, A. Biostimulants and Plant Response under Adverse Environmental Conditions: A Functional Interplay. In *Plant Performance under Environmental Stress*; Husen, A., Ed.; Springer: Cham, Switzerland, 2021; pp. 417–436. [CrossRef]
66. Paradiso, R.; Di Mola, I.; Ottaiano, L.; Cozzolino, E.; Pelosi, M.E.; Rippa, M.; Mori, M. Integrating Smart Greenhouse Cover, Reduced Nitrogen Dose and Biostimulant Application as a Strategy for Sustainable Cultivation of Cherry Tomato. *Plants* **2024**, *13*, 440. [CrossRef]
67. Lephatsi, M.; Nephali, L.; Meyer, V.; Piater, L.A.; Buthelezi, N.; Dubery, I.A.; Tugizimana, F. Molecular mechanisms associated with microbial biostimulant-mediated growth enhancement, priming and drought stress tolerance in maize plants. *Sci. Rep.* **2022**, *12*, 10450. [CrossRef]
68. Mzibra, A.; Aasfar, A.; Benhima, R.; Khouloud, M.; Boulif, R.; Douira, A.; Meftah Kadmiri, I. Biostimulants derived from Moroccan seaweeds: Seed germination metabolomics and growth promotion of tomato plant. *J. Plant Growth Regul.* **2021**, *40*, 353–370. [CrossRef]
69. Hussein, M.H.; Eltanahy, E.; Al Bakry, A.F.; Elsafty, N.; Elshamy, M.M. Seaweed extracts as prospective plant growth bio-stimulant and salinity stress alleviator for *Vigna sinensis* and *Zea mays*. *J. Appl. Phycol.* **2021**, *33*, 1273–1291. [CrossRef]
70. Campobenedetto, C.; Mannino, G.; Agliassa, C.; Acquadro, A.; Contartese, V.; Garabello, C.; Bertea, C.M. Transcriptome analyses and antioxidant activity profiling reveal the role of a lignin-derived biostimulant seed treatment in enhancing heat stress tolerance in soybean. *Plants* **2020**, *9*, 1308. [CrossRef]
71. Rupawalla, Z.; Shaw, L.; Ross, I.L.; Schmidt, S.; Hankamer, B.; Wolf, J. Germination screen for microalgae-generated plant growth biostimulants. *Algal Res.* **2022**, *66*, 102784. [CrossRef]
72. Zulfiqar, F.; Moosa, A.; Ferrante, A.; Darras, A.; Sheteiwy, M.S.; Ali, B.; El Sabagh, A. Borage leaf extract improves the vase life of cut gladiolus flowers by delaying the senescence process and reducing water stress. *Posth. Biol. Technol.* **2024**, *210*, 112766. [CrossRef]
73. Younis, A.; Akhtar, M.S.; Riaz, A.; Zulfiqar, F.; Qasim, M.; Farooq, A.; Bhatti, Z.M. Improved cut flower and corm production by exogenous moringa leaf extract application on gladiolus cultivars. *Acta Sci. Pol. Hortorum Cultus* **2018**, *17*, 25–38. [CrossRef]
74. Carillo, P.; Pannico, A.; Cirillo, C.; Ciriello, M.; Colla, G.; Cardarelli, M.; Rouphael, Y. Protein hydrolysates from animal or vegetal sources affect morpho-physiological traits, ornamental quality, mineral composition, and shelf-life of Chrysanthemum in a distinctive manner. *Plants* **2022**, *11*, 2321. [CrossRef]

75. Hashemabadi, D.; Torkashvand, A.M.; Kaviani, B.; Bagherzadeh, M.; Rezaalipour, M.; Zarchini, M. Effect of Mentha pulegium extract and 8-hydroxy quinoline sulphate to extend the quality and vase life of rose (*Rosa hybrid*) cut flower. *J. Environ. Biol.* **2015**, *36*, 215.
76. Pohl, A.; Kalisz, A.; Sekara, A. Seaweed extracts' multifactorial action: Influence on physiological and biochemical status of Solanaceae plants. *Acta Agrobot.* **2019**, *72*, 1758. [CrossRef]
77. Graziani, G.; Ritieni, A.; Cirillo, A.; Cice, D.; Di Vaio, C. Effects of biostimulants on annurca fruit quality and potential nutraceutical compounds at harvest and during storage. *Plants* **2020**, *9*, 775. [CrossRef]
78. Soltaniband, V.; Brégard, A.; Gaudreau, L.; Dorais, M. Biostimulants promote plant development, crop productivity, and fruit quality of protected strawberries. *Agronomy* **2022**, *12*, 1684. [CrossRef]
79. Francesca, S.; Arena, C.; Hay Mele, B.; Schettini, C.; Ambrosino, P.; Barone, A.; Rigano, M.M. The use of a plant-based biostimulant improves plant performances and fruit quality in tomato plants grown at elevated temperatures. *Agronomy* **2020**, *10*, 363. [CrossRef]
80. Basile, B.; Brown, N.; Valdes, J.M.; Cardarelli, M.; Scognamiglio, P.; Mataffo, A.; Colla, G. Plant-based biostimulant as sustainable alternative to synthetic growth regulators in two sweet cherry cultivars. *Plants* **2021**, *10*, 619. [CrossRef]
81. Putra, P.A.; Yuliando, H. Soilless culture system to support water use efficiency and product quality: A review. *Agric. Agric. Sci. Procedia* **2015**, *3*, 283–288. [CrossRef]
82. Savvas, D.; Gianquinto, G.; Tuzel, Y.; Gruda, N. Soilless Culture. FAO Plant Production and Protection Paper No. 217: Good Agricultural Practices for Greenhouse Vegetable Crops. 2013. Available online: https://cris.unibo.it/handle/11585/173272 (accessed on 13 June 2024).
83. Caputo, S. History, techniques and technologies of soil-less cultivation. In *Small Scale Soil-Less Urban Agriculture in Europe*; Springer: Cham, Switzerland, 2022; pp. 45–86. [CrossRef]
84. Dalal, D.; Mainani, R.; Thakker, R.; Solanki, H. A Study of Selected Microgreens in Soil-Less Media. *Int. Assoc. Biol. Comput. Dig.* **2022**, *1*, 228–230. [CrossRef]
85. Rosli, N.S.M.; Abdullah, R.; Yaacob, J.S.; Razali, R.B.R. Effect of biochar as a hydroponic substrate on growth, colour and nutritional content of red lettuce (*Lactuca sativa* L.). *Bragantia* **2023**, *82*, e20220177. [CrossRef]
86. Cedeño, J.M.; Magán, J.J.; Thompson, R.B.; Fernández, M.D.; Gallardo, M. Comparison of Methods to Determine Nutrient Uptake of Tomato Grown in Free-Draining Perlite Substrate—Key Information for Optimal Fertigation Management. *Horticulturae* **2024**, *10*, 232. [CrossRef]
87. Radtke Wieth, A.; Dutra Pinheiro, W.; Da Silva Duarte, T. Commercial substrates and nutrient concentrations in the production of arugula microgreens. *Agron. Colomb.* **2021**, *39*, 5–11. [CrossRef]
88. Saleh, R.; Gunupuru, L.R.; Lada, R.; Nams, V.; Thomas, R.H.; Abbey, L. Growth and biochemical composition of microgreens grown in different formulated soilless media. *Plants* **2022**, *11*, 3546. [CrossRef] [PubMed]
89. Ritonga, S.; Vinolina, N.S. Response of wheatgrass and ricegrass growth on various types of planting media. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *977*, 012034. [CrossRef]
90. Pamungkas, P.B.; Nadia, L.S.; Amrih, D. Study of microgreens growth on various planting medium. *AIP Conf. Proc.* **2023**, *2491*, 020018. [CrossRef]
91. Sharma, A.; Hazarika, M.; Heisnam, P.; Pandey, H.; Devadas, V.S.; Wangsu, M.; Kartha, B.D. Factors affecting production, nutrient translocation mechanisms, and LED emitted light in growth of microgreen plants in soilless culture. *ACS Agric. Sci. Technol.* **2023**, *3*, 701–719. [CrossRef]
92. Paradiso, R.; Buonomo, R.; Dixon, M.A.; Barbieri, G.; De Pascale, S. Soybean cultivation for Bioregenerative Life Support Systems (BLSSs): The effect of hydroponic system and nitrogen source. *Adv. Space Res.* **2014**, *53*, 574–584. [CrossRef]
93. Maru, R.N.; Wesonga, J.; Okazawa, H.; Kavoo, A.; Neondo, J.O.; Mazibuko, D.M.; Orsini, F. Evaluation of Growth, Yield and Bioactive Compounds of Ethiopian Kale (*Brassica carinata* A. Braun) Microgreens under Different LED Light Spectra and Substrates. *Horticulturae* **2024**, *10*, 436. [CrossRef]
94. Maboko, M.M. Effect of plant density and harvesting frequency on yield components of hydroponically grown mustard spinach (*Brassica juncea*). In II All Africa Horticulture Congress. *Acta Hortic.* **2012**, *1007*, 515–521. [CrossRef]
95. Sinaga, A.N.; Zahra, A.M.; Nugroho, E.; Simatupang, H.K.; Pitaloka, N.D.; Annisa, H.N.; Pahlawan, M.F. Hydroponic NFT-Based Indoor Farming of Red and Green Lettuce Microgreens in Response to Artificial Lighting. In Proceedings of the 3rd International Conference on Smart and Innovative Agriculture (ICoSIA 2022), Yogyakarta, Indonesia, 22–23 November 2022; Atlantis Press: Amsterdam, The Netherlands, 2023; pp. 625–634. [CrossRef]
96. Singh, B. New Systems of Vegetable Production: Protected Cultivation, Hydroponics, Aeroponics, Vertical, Organic, Microgreens. In *Vegetables for Nutrition and Entrepreneurship*; Springer Nature: Singapore, 2023; pp. 31–56. [CrossRef]
97. Soufi, H.R.; Roosta, H.R.; Hamidpour, M. The plant growth, water and electricity consumption, and nutrients uptake are influenced by different light spectra and nutrition of lettuce. *Sci. Rep.* **2023**, *13*, 20766. [CrossRef]
98. Da Silva, M.G.; Soares, T.M.; Gheyi, H.R. Production of Coriander Using the Hydroponic Technique. In *Handbook of Coriander (Coriandrum sativum)*; CRC Press: Boca Raton, FL, USA, 2023; pp. 39–62.
99. Srivastava, U.; Mathur, A. Recent Advancements in Prevalent Practices for Plant Cultivation by Hydroponics. *Def. Life Sci. J.* **2023**, *8*, 255–268. [CrossRef]

100. Puspitahati, P.; Andica, F. Floating Raft Hydroponic System Using Spray Bars Pumps On Pakcoy Cultivation Growth (*Brassica rapa* L.). In Proceedings of the 3rd Sriwijaya International Conference on Environmental Issues, SRICOENV 2022, Palembang, South Sumatera, Indonesia, 5 October 2022. [CrossRef]
101. Atherton, H.R.; Li, P. Hydroponic cultivation of medicinal plants—Plant organs and hydroponic systems: Techniques and trends. *Horticulturae* **2023**, *9*, 349. [CrossRef]
102. Wortman, S.E. Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system. *Sci. Hortic.* **2015**, *194*, 34–42. [CrossRef]
103. Kim, J.; Kim, H.J.; Gang, M.S.; Kim, D.W.; Cho, W.J.; Jang, J.K. Closed hydroponic nutrient solution management using multiple water sources. *J. Biosyst. Eng.* **2023**, *48*, 215–224. [CrossRef]
104. Nalwade, R.; Mote, T. Hydroponics farming. In Proceedings of the 2017 IEEE International Conference on Trends in Electronics and Informatics (ICEI), Tirunelveli, India, 11–12 May 2017; pp. 645–650. [CrossRef]
105. Nxawe, S.; Ndakidemi, P.A.; Laubscher, C.P. Possible effects of regulating hydroponic water temperature on plant growth, accumulation of nutrients and other metabolites. *Afr. J. Biotechnol.* **2010**, *9*, 9128–9134.
106. Ali, A.; Cavallaro, V.; Santoro, P.; Mori, J.; Ferrante, A.; Cocetta, G. Quality and physiological evaluation of tomato subjected to different supplemental lighting systems. *Sci. Hortic.* **2023**, *323*, 112469. [CrossRef]
107. Rajendiran, G.; Rethnaraj, J. Smart Aeroponic Farming System: Using IoT with LCGM-Boost Regression Model for Monitoring and Predicting Lettuce Crop Yield. *Int. J. Intell. Eng. Syst.* **2023**, *16*, 251–262.
108. Ouyang, Z.; Tian, J.; Yan, X.; Yang, Z. Micro-nano oxygenated irrigation improves the yield and quality of greenhouse cucumbers under-film drip irrigation. *Sci. Rep.* **2023**, *13*, 19453. [CrossRef]
109. Farawn, K.K.; Leunov, V.I.; Tereshonkova, T.A.; Salman, A.H.; Al-Rukabi, M.N.M.; Shaaban, F. Evaluate tomato growing in the conditions of subirrigation aeroponics at Fitopiramida greenhouse. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1010*, 012034. [CrossRef]
110. Regmi, A.; Rueda-Kunz, D.; Liu, H.; Trevino, J.; Kathi, S.; Simpson, C. Comparing resource use efficiencies in hydroponic and aeroponic production systems. *Technol. Hortic.* **2024**, *4*, e005. [CrossRef]
111. Sobczak, A.; Kućko, A.; Pióro-Jabrucka, E.; Gajc-Wolska, J.; Kowalczyk, K. Effect of Salicylic Acid on the Growth and Development of Sweet Pepper (*Capsicum annum* L.) under Standard and High EC Nutrient Solution in Aeroponic Cultivation. *Agronomy* **2023**, *13*, 779. [CrossRef]
112. Cayambe, J.; Heredia-R, M.; Torres, E.; Puhl, L.; Torres, B.; Barreto, D.; Diaz-Ambrona, C.G. Evaluation of sustainability in strawberry crops production under greenhouse and open-field systems in the Andes. *Int. J. Agric. Sustain.* **2023**, *21*, 2255449. [CrossRef]
113. Buckseth, T.; Sharma, S.; Tiwari, J.K.; Kumar, V.; Sharma, A.K.; Challam, C.; Singh, R.K. Plant Sources Identify Variations in Potato Production Potential Under Aeroponics. *Potato Res.* **2023**. [CrossRef]
114. He, J. Enhancing Productivity and Improving Nutritional Quality of Subtropical and Temperate Leafy Vegetables in Tropical Greenhouses and Indoor Farming Systems. *Horticulturae* **2024**, *10*, 306. [CrossRef]
115. Tunio, M.H.; Gao, J.; Mohamed, T.M.; Ahmad, F.; Abbas, I.; Shaikh, S.A. Comparison of nutrient use efficiency, antioxidant assay, and nutritional quality of butter-head lettuce (*Lactuca sativa* L.) in five cultivation systems. *Int. J. Agric. Biol. Eng.* **2023**, *16*, 95–103. [CrossRef]
116. Verma, A.K.; Chandrakant, M.H.; John, V.C.; Peter, R.M.; John, I.E. Aquaponics as an integrated agri-aquaculture system (IAAS): Emerging trends and future prospects. *Technol. Forecast. Soc. Chang.* **2023**, *194*, 122709. [CrossRef]
117. Masabni, J.; Niu, G. Aquaponics. In *Plant Factory Basics, Applications and Advances*; Academic Press: Cambridge, MA, USA, 2022; pp. 167–180. [CrossRef]
118. Angkha, B.; Verma, A.K.; Kumar, S.H.; Prakash, C.; Thomas, R.M. Mobilization of mica by Bacillus sp. and its effect on Nile tilapia (*Oreochromis niloticus*) cum holy basil (*Ocimum tenuiflorum*)–based aquaponic system. *Aquac. Int.* **2020**, *28*, 2045–2058. [CrossRef]
119. Stathopoulou, P.; Tsoumalakou, E.; Levizou, E.; Vanikiotis, T.; Zaoutsos, S.; Berillis, P. Iron and potassium fertilization improve rocket growth without affecting tilapia growth and histomorphology characteristics in aquaponics. *Appl. Sci.* **2021**, *11*, 5681. [CrossRef]
120. Yıldız, H.Y.; Bekcan, S. Role of stocking density of tilapia (*Oreochromis aureus*) on fish growth, water quality and tomato (*Solanum lycopersicum*) plant biomass in the aquaponic system. *Int. J. Environ. Agriic. Biotechnol.* **2017**, *2*, 238971. [CrossRef]
121. Roosta, H.R. Effects of foliar spray of K on mint, radish, parsley and coriander plants in aquaponic system. *J. Plant Nut.* **2014**, *37*, 2236–2254. [CrossRef]
122. Rakocy, J.E. Aquaponics—Integrating fish and plant culture. In *Aquaculture Production Systems*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; pp. 344–386. [CrossRef]
123. Siqwepu, O.; Salie, K.; Goosen, N. Evaluation of potassium diformate and potassium chloride in the diet of the African catfish, *Clarias gariepinus* in a recirculating aquaculture system. *Aquaculture* **2020**, *526*, 735414. [CrossRef]
124. John, V.C.; Verma, A.K.; Krishnani, K.K.; Chandrakant, M.H.; Varghese, T.; Pathak, M.S. Effect of potassium supplementation on osmoregulatory and stress response of *Pangasianodon hypophthalmus* (Sauvage, 1878) with *Spinacia oleracea* L. in aquaponics. *J. Fish Biol.* **2022**, *101*, 249–261. [CrossRef]
125. Pasch, J.; Ratajczak, B.; Appelbaum, S.; Palm, H.W.; Knaus, U. Growth of basil (*Ocimum basilicum*) in DRF, raft, and grow pipes with effluents of African catfish (*Clarias gariepinus*) in decoupled aquaponics. *AgriEngineering* **2021**, *3*, 92–109. [CrossRef]
126. Ani, J.S.; Manyala, J.O.; Masese, F.O.; Fitzsimmons, K. Effect of stocking density on growth performance of monosex Nile Tilapia (*Oreochromis niloticus*) in the aquaponic system integrated with lettuce (*Lactuca sativa*). *Aquacult. Fish.* **2022**, *7*, 328–335. [CrossRef]

127. Mamatha, D.; Verma, A.K.; Tiwari, V.K.; Chandrakant, M.H.; Nayak, S.K.; Javed, H. Biointegration of rohu (*Labeo rohita*) fry and lemon grass (*Cymbopogon citratus*) in a recirculating aquaponic System. *J. Ind. Soc. Coast. Agric. Res.* **2020**, *38*.
128. Kaburagi, E.; Yamada, M.; Baba, T.; Fujiyama, H.; Murillo-Amador, B.; Yamada, S. Aquaponics using saline groundwater: Effect of adding microelements to fish wastewater on the growth of Swiss chard (*Beta vulgaris* L. spp. cicla). *Agri. Water Manag.* **2020**, *227*, 105851. [CrossRef]
129. Bailey, D.S.; Ferrarezi, R.S. Valuation of vegetable crops produced in the UVI Commercial Aquaponic System. *Aquacult. Rep.* **2017**, *7*, 77–82. [CrossRef]
130. Peter, R.M.; Verma, A.K.; Saharan, N.; Tiwari, V.K.; Chandrakant, M.H.; Thomas, R.M. Effect of hydraulic loading rate on production of tomato (*Solanum lycopersicum*) with pearlspot (*Etroplus suratensis*) in recirculating aquaponic system. *J. Agric. Eng.* **2021**, *58*, 300–308. [CrossRef]
131. Walling, I.; Kanaujia, S.P.; Changini, M. Response of broccoli (*Brassica oleracea* var, italica) to integrated nutrient management. *Ann. Plant Soil Res.* **2022**, *24*, 106–109. [CrossRef]
132. Yuan, X.; Tajima, R.; Matsumoto, M.; Fujiwara, A.; Aoyama, T.; Okada, C.; Takimoto, H. Analysing food groups and nutrient intake in adults who met and did not meet the daily recommended vegetable intake of 350 g: The 2016 National Health and Nutrition Survey in Japan. *J. Nutr. Sci.* **2024**, *13*, e12. [CrossRef]
133. Kumar, M.; Chaudhary, V.; Naresh, R.K.; Maurya, O.P.; Pal, S.L. Does integrated sources of nutrients enhance growth, yield, quality and soil fertility of vegetable crops. *Int. J. Curr. Microb. App. Sci.* **2018**, *7*, 125–155. [CrossRef]
134. Chopra, A.K.; Payum, T.; Sachin, S.; Vinod, K. Effect of integrated nutrient management on agronomical attributes of tomato under field conditions. *Arch. Agric. Environ. Sci.* **2017**, *2*, 86–91.
135. Gokul, D.; Poonkodi, P.; Angayarkanni, A. Effect of integrated nutrient management on the growth and nutrient content of chilli. *Int. J. Chem. Stud.* **2020**, *8*, 2647–2651. [CrossRef]
136. Ankit, P.; Choudhary, A.; Raj, S.; Pooja, S.; Forum, B. Effect of integrated nutrient management on yield of brinjal. *Int. J. Agric. Food Sci.* **2022**, *4*, 12–16.
137. Kumar, P.; Kumar, A.; Kumar, N.; Atik, A.; Verma, M. Effect of integrated nutrient management on productivity and nutrient availability of potato. *Int. J. Curr. Microbiol. Appl. Sci.* **2017**, *6*, 1429–1436. [CrossRef]
138. Tomar, A.; Sangeeta, M.; Asati, K.; Swati, B. Integrated nutrient management in bottle gourd variety Kashi Ganga on the plant disease, TSS and economics under Malwa condition of MP. *Int. J Curr. Sci. Res. Rev.* **2022**, *5*, 2581–8341. [CrossRef]
139. Singh, J.; Singh, M.; Kumar, M.; Gupta, A.; Singh, K. Growth, yield and quality parameters of cucumber as influence by INM applications. *Int. J Curr. Microbilol. Appl. Sci.* **2020**, *9*, 2319–7706. [CrossRef]
140. Dudhat, M.A.; Patel, K.D. Evaluation of INM on performance of quality and yield attributes of hybrid bitter gourd. *J. Pharmacogn. Phytochem.* **2020**, *9*, 1643–1645.
141. Patel, H.S.; Patel, N.B.; Sarvaiya, J.P.; Chawla, S.L. INM on growth and yield of ridge gourd cv. GARG-1. *Pharma Innov.* **2021**, *10*, 1064–1069.
142. Chaudhari, V.M.; Patel, N.K.; Barot, D.C.; Solanki, K.S. Impact of biofertilizers based nutrient management on growth and yield of cauliflower cv. Pusa Snowball KT-25. *Pharma Innov.* **2023**, *12*, 3037–3040.
143. Kumari, K.; Singh, S.K.; Mehmi, V.; Kumar, U.; Kaur, K. Influence of plant growth regulators and bio-fertilizers on growth and yield of broccoli under central region of Punjab. *J. Agriways* **2019**, *7*, 44–49.
144. Kumar, D.; Kumar, S.; Kumar, R.; Verma, S. Effect of organic and inorganic fertilizer on growth, yield and quality of cabbage. *Int. J. Pure Appl. Biosci.* **2017**, *5*, 1590–1593. [CrossRef]
145. Abou, M.M.; Zaki, M.F.; Sedera, S.A. Bio-fertilizers and foliar application of milagro biostimulants in relation to growth, head yield and quality as mineral K requirement of Chinese cabbage. *Middle East J. Agric.* **2018**, *7*, 1310–1322.
146. Kaur, B.; Boparai, A.K.; Singh, K. Effect of integrated nutrient sources on agronomic performance of onion (*Onion cepa* L.) and soil properties. *Ind. J. Ecol.* **2023**, *50*, 367–371. [CrossRef]
147. Singh, B.; Sharma, H.R. Effect of Integrated Nutrient Management on Growth, Yield and Quality in Garlic (*Allium sativum* L.). *Int. J. Plant Soil Sci.* **2023**, *35*, 648–654. [CrossRef]
148. Amartey, J.N.A.; Sarkordie-Addo, J.; Essilfie, M.E.; Dapaah, H.K. Growth and yield of carrots affected by integrated nutrient management of organic and inorganic fertilizers. *Afr. J. Agric. Res.* **2022**, *18*, 576–585. [CrossRef]
149. Shilpa, D.; Sharma, M.; Kaur, M.; Kumar Sharma, A.; Sharma, P.; Chauhan, M. Soil fertility, growth, yield and root quality of radish (*Raphanus sativus* L.) as influenced by integrated nutrient management practices. *Comm. Soil Sci. Plant Anal.* **2023**, *54*, 1316–1333. [CrossRef]
150. Dong, M.; Xin, R.; Li, Z.Y.; Li, Y.L.; Huang, X.H.; Dong, X.P.; Qin, L. Simultaneously quantification of organic acids metabolites by HPLC mass spectrometry to reveal the postharvest quality change in cherry tomato. *J. Food Comp. Anal.* **2023**, *117*, 105105. [CrossRef]
151. Miah, M.G.R.; Karim, A.S.; Islam, M.M.; Islam, M.D.; Kamal, M.Z.U. Effects of water stress and nutrient management on the performance of tomato. *Int. J. Environ. Agric. Biotechnol.* **2023**, *8*. Available online: https://i.agriculturejournals.org/index.php/ijeab/article/view/73 (accessed on 21 May 2024). [CrossRef]
152. Saroha, A.; Kotiyal, A.; Thakur, A. Climate-Resilient Fertilizer Management for Crop Production. In *Climate-Resilient Agriculture, Vol 2: Agro-Biotechnological Advancement for Crop Production*; Springer International Publishing: Cham, Switzerland, 2023; pp. 61–79. [CrossRef]

153. Elbasiouny, H.; El-Ramady, H.; Elbehiry, F.; Rajput, V.D.; Minkina, T.; Mandzhieva, S. Plant nutrition under climate change and soil carbon sequestration. *Sustainability* **2022**, *14*, 914. [CrossRef]
154. Charishma, K.V.; Chatterjee, S.; Supriya, T.; Bera, M.; Barman, S.; Datta, N. Integrated nutrient management on the growth, yield, nutrient uptake and soil nutrient status of tomato (*Solanum lycopersicum*) cv."Arka Rakshak" under north-eastern ghats region of India. *Crop Res.* **2022**, *57*, 266–274. [CrossRef]
155. Singh, D.P.; Maurya, B.K.; Kumari, M.; Singh, R.P.; Singh, D.B.; Kumar, P. Response of integrated nutrient management (INM) on growth and yield attributes in tomato (*Solanum lycopersicum* L.). *Ann. Agric. Res.* **2023**, *44*, 120–126. Available online: https://epubs.icar.org.in/index.php/AAR/article/view/134818 (accessed on 21 May 2024).
156. Singh, D.; Kushum, S. Effect of integrated nutrient management on the growth, yield and quality in tomato (*Solanum lycopersicum* L.). *Int. J. Environ. Clim. Chang.* **2022**, *12*, 2802–2811. [CrossRef]
157. Jethava, B.A.; Patel, K.M.; Rathva, V.D.; Macwan, S.J. Effect of integrated nutrient management and micronutrients on growth, yield and economics of tomato cv. GAT-5. *Pharma Innov. J.* **2023**, *12*, 4462–4466.
158. Sharma, H.L.; Tailor, S.P.; Rajawat, K.S.; Kurmi, K.P. Effect of integrated nutrient management on the growth, yield parameters and economics in tomato (*Lycopersicon esculentum* L.) under Southern Rajasthan conditions. *Pharma Innov. J.* **2023**, *12*, 321–326. [CrossRef]
159. Li, C.; Li, Y.; Cui, D.; Li, Y.; Zou, G.; Thompson, R.; Yang, J. Integrated crop-nitrogen management improves tomato yield and root architecture and minimizes soil residual N. *Agronomy* **2022**, *12*, 1617. [CrossRef]
160. Chaurasiya, P.C.; Kumar, S. Effect of integrated nutrients management on growth, yield and quality of tomato (*Solanum lycopersicum* L.) under Chhattisgarh plains. *Pharma Innov.* **2023**, *12*, 857–860.
161. Pavani, Y.; Janaki, P.; Jagadeeswaran, R.; Sankari, A.; Ramalakshmi, A.; Arthanari, P.M. Response of tomato to fertilizer nutrients integration and herbicides spray: Evaluating growth, yield, fruit quality and herbicides residue. *Plant Sci. Today* **2024**, *11*, 93–101. [CrossRef]
162. Tao, Y.; Liu, T.; Wu, J.; Wu, Z.; Liao, D.; Shah, F.; Wu, W. Effect of combined application of chicken manure and inorganic nitrogen fertilizer on yield and quality of cherry tomato. *Agronomy* **2022**, *12*, 1574. [CrossRef]
163. Seth, A.; Sarkar, D.; Datta, A.; Mandal, B.; Chowdhury, A.; Masto, R.E.; Saha, S. Suitability of complex extractants for assessment of available soil zinc for nutrition of rice (*Oryza sativa* L.) in subtropical India. *Soil Sci.* **2017**, *182*, 28–35. [CrossRef]
164. Sarkar, D.; Baishya, L.K.; Meitei, C.B.; Naorem, G.C.; Thokchom, R.C.; Singh, J.; Rahman, F.H. Can sustainability of maize-mustard cropping system be achieved through balanced nutrient management? *Field Crops Res.* **2018**, *225*, 9–21. [CrossRef]
165. Bhardwaj, A.K.; Malik, K.; Chejara, S.; Rajwar, D.; Narjary, B.; Chandra, P. Integration of organics in nutrient management for rice-wheat system improves nitrogen use efficiency via favorable soil biological and electrochemical responses. *Front. Plant Sci.* **2023**, *13*, 1075011. [CrossRef]
166. Biswas, P.; Bohra, J.S.; Kumar, N. Effect of nutrient management on quality, NPK content and uptake in rice (*Oryza sativa* L.) under rice-wheat cropping system. *J. Pharmacogn. Phytochem.* **2020**, *9*, 1254–1258.
167. Tomar, R.; Singh, N.B.; Singh, V.; Kumar, D. Effect of planting methods and integrated nutrient management on growth parameters, yield and economics of rice. *J. Pharmacaogn. Phytochem.* **2018**, *7*, 520–527.
168. Ram, M.S.; Shankar, T.; Maitra, S.; Duvvada, S.K. Effect of Integrated Nutrient Management on Growth, Yield, Nutrient Content and Economics of Summer Rice (*Oryza sativa* L.). *Int. J. Pure Appl. Biosci.* **2020**, *8*, 421–427. [CrossRef]
169. Rao, A.; Singh, N.B.; Pandey, D.; Singh, M.P. Effect of integrated nutrient management on productivity and profitability of rice under SRI. *J. Pharmacogn. Phytochem.* **2020**, *9*, 665–667.
170. Shankar, T.; Maitra, S.; Ram, M.S.; Mahapatra, R. Influence of integrated nutrient management on growth and yield attributes of summer rice (*Oryza sativa* L.). *Crop Res.* **2020**, *55*, 1–5. [CrossRef]
171. Behera, H.S.; Pany, B.K. Impact of inorganic nitrogenous fertilizers and farmyard manure combination on grain, straw, biological yield and harvest index of rice (*Oryza sativa* L.). *J. Pharmacogn. Phytochem.* **2021**, *10*, 257–260. [CrossRef]
172. Aasif, M.; Chinnamani, I.; Kumar, N.S.; Hemalatha, M.; Suresh, S. Influence of integrated nutrient management practices on yield and nutrient uptake of rice under system of rice intensification. *Int. J. Adv. Agric. Sci. Technol.* **2008**, *5*, 10–16.
173. Apon, M.; Gohain, T.; Apon, R.; Banik, M.; Mandal, A.K. Effect of integrated nutrient management on growth and yield of local rice (*Oryza sativa* L.) under rainfed upland condition of Nagaland. *Pharma Innov. J.* **2018**, *7*, 426–429.
174. Sharma, A.K.; Singh, T.; Patel, A.; Yadav, R.A. Influence of integrated nutrient management practices on scented rice (*Oryza sativa* L.) Pertaining to eastern Uttar Pradesh. *J. Pharmacogn. Phytochem.* **2018**, *7*, 1448–1453.
175. Baishya, L.K.; Rathore, S.S.; Singh, D.; Sarkar, D.; Deka, B.C. Effect of integrated nutrient management on rice productivity, profitability and soil fertility. *Ann. Plant Soil Res.* **2015**, *17*, 86–90.
176. Tiwari, H.; Singh, A.K.; Pandey, S.R.; Tiwari, A. Effect of Integrated nutrient management practices on nutrient content and uptake by rice (*Oryza sativa* L.). *J. Pharmacogn. Phytochem.* **2020**, *9*, 2131–2134.
177. Sarwar, G.; Hussain, N.; Schmeisky, H.; Suhammad, S.; Ibrahim, M.; Ahmad, S. Efficiency of Various Organic Residues for Enhancing Rice-Wheat Production under Normal Soil Conditions. *Pak. J. Bot.* **2008**, *40*, 2107–2113.
178. Ding, W.; Xu, X.; He, P.; Ullah, S.; Zhang, J.; Cui, Z.; Zhou, W. Improving yield and nitrogen use efficiency through alternative fertilization options for rice in China: A meta-analysis. *Field Crops Res.* **2018**, *227*, 11–18. [CrossRef]
179. Bhardwaj, A.K.; Rajwar, D.; Mandal, U.K.; Ahamad, S.; Kaphaliya, B.; Minhas, P.S.; Prabhakar, M.; Banyal, R.; Singh, R.; Chaudhari, S.K.; et al. Impact of carbon inputs on soil carbon fractionation, sequestration and biological responses under major nutrient management practices for rice-wheat cropping systems. *Sci. Rep.* **2019**, *9*, 9114. [CrossRef] [PubMed]

180. Chaubey, A.K.; Mishra, S.; Singh, S.K.; Chaubey, C.; Pandey, K.P. Integrated Nutrients Management for Future Production: A Review. *Int. J. Environ. Clim. Chang.* **2023**, *13*, 1770–1779. [CrossRef]
181. Akhtar, N.; Ramani, V.B.; Yunus, M.; Femi, V. Effect of different nutrient management treatments on growth, yield attributes, yield and quality of wheat (*Triticum aestivum* L.). *Int. J. Curr. Microbiol. Appl. Sci.* **2018**, *7*, 3473–3479.
182. Saini, L.H.; Saini, A.K.; Malve, S.H.; Patel, J.P.; Nand, B.; Chaudhary, H.S. Growth and yield attainment of wheat under different levels of vermicompost, biofertilizers and nitrogen. *Pharma Innov. J.* **2023**, *12*, 1245–1249.
183. Patyal, A.; Shekhar, C.; Sachan, R.; Kumar, D.; Yadav, A.; Kumar, G. Effect of integrated nutrient management (INM) on growth parameters and yield of wheat (*Triticum aestivum* L.). *Int. J. Plant Soil Sci.* **2022**, *34*, 962–967. [CrossRef]
184. Kumar, G.; Niwas, R. Effect of organic and inorganic fertilizers on growth and yield of wheat (*Triticum aestivum* L.). *Pharma Innov. J.* **2022**, *11*, 1005–1009.
185. Kumawat, H.; Singh, D.P.; Jat, G.; Choudhary, R.; Singh, P.B.; Dhayal, S.; Khardia, N. Effect of fertility levels and liquid biofertilizers on growth and yield of wheat (*Triticum aestivum* L.). *Pharma Innov. J.* **2021**, *10*, 1365–1369.
186. Pandey, I.B.; Dwivedi, D.K.; Pandey, R.K. Integrated nutrient management for sustaining wheat (*Triticum aestivum*) production under late sown condition. *Ind. J. Agric.* **2009**, *54*, 306–309.
187. Desai, H.A.; Dodia, I.N.; Desai, C.K.; Patel, M.D.; Patel, H.K. Integrated nutrient management in wheat (*Triticum aestivum* L.). *Trends Biosci.* **2015**, *8*, 472–475.
188. Devi, K.N.; Singh, M.S.; Singh, N.G.; Athokpam, H.S. Effect of integrated nutrient management on growth and yield of wheat (*Triticum aestivum* L.). *J. Crop Weed.* **2011**, *7*, 23–27.
189. Fazily, T.; Thakral, S.K.; Dhaka, A.K. Effect of integrated nutrient management on growth, yield attributes and yield of wheat. *Int. J. Adv. Agric. Sci. Technol.* **2021**, *8*, 106–118. [CrossRef]
190. Singh, G.; Kumar, S.; Singh, G.; Singh, N. Effect of integrated nutrient management on nutrient uptake and grain yield of wheat (*Triticum aestivum* L.) under irrigated conditions. *J. Pharmacogn. Phytochem.* **2019**, *8*, 1077–1080.
191. Kumar, A.; Singh, A.K.; Kumar, S.; Kumar, D.; Gopal, T.; Pandey, D.; Pandey, V.K. Effect of nutrient management and moisture regime on growth and yield of wheat (*Triticum aestivum* L.). *J. Pharmacogn. Phytochem.* **2018**, *7*, 610–613.
192. Dhaliwal, S.S.; Sharma, V.; Shukla, A.K.; Gupta, R.K.; Verma, V.; Kaur, M.; Behera, S.K.; Singh, P. Residual effect of organic and inorganic fertilizers on growth, yield and nutrient uptake in wheat under a basmati rice–wheat cropping system in North-Western India. *Agriculture* **2023**, *13*, 556. [CrossRef]
193. Messaoudi, A.; Labdelli, F.; Rebouh, N.Y.; Djerbaoui, M.; Kucher, D.E.; Hadjout, S.; Ouaret, W.; Zakharova, O.A.; Latati, M. Investigating the Potassium Fertilization Effect on Morphological and Agrophysiological Indicators of Durum Wheat under Mediterranean Rain-Fed Conditions. *Agriculture* **2023**, *13*, 1142. [CrossRef]
194. Begam, A.; Pramanick, M.; Dutta, S.; Paramanik, B.; Dutta, G.; Patra, P.S.; Biswas, A. Inter-cropping patterns and nutrient management effects on maize growth, yield and qality. *Field Crops Res.* **2024**, *310*, 109363. [CrossRef]
195. Paramesh, V.; Kumar, R.M.; Rajanna, G.A.; Gowda, S.; Nath, A.J.; Madival, Y.; Toraskar, S. Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. *Front. Sustain. Food Syst.* **2023**, *7*, 1173258. [CrossRef]
196. Li, C.; Stomph, T.J.; Makowski, D.; Li, H.; Zhang, C.; Zhang, F.; Van der Werf, W. The productive performance of intercropping. *Proc. Nat. Acad. Sci. USA* **2023**, *120*, e2201886120. [CrossRef] [PubMed]
197. Velmourougane, K.; Manikandan, A.; Blaise, D.; Vellaichamy, M. Cotton stalk compost as a substitution to farmyard manure along with mineral fertilizers and microbials enhanced Bt cotton productivity and fibre quality in rainfed vertisols. *Waste Biom. Valor.* **2022**, *13*, 2847–2860. [CrossRef]
198. Iraiyanban, A.A.A.; Manuel, R.I.; Joseph, P.A.; Kumar, P.D. Influence of Cropping System and Nutrient Management Practices on the Yield, and Economics of Pearl Millet [*Pennisetum glaucum*]. *Int. J. Environ. Clim. Chang.* **2023**, *13*, 701–709. [CrossRef]
199. Prakash, S.; Reddy, S.V.V.; Prasad, R.; Ballabh, J. Effect of Integrated Nutrient Management in Chickpea (*Cicer arietinum* L.). *J. Sur. Fish. Sci.* **2022**, *8*, 278–282.
200. Palai, J.B. Performance of Finger Millet on Residual Soil Nutrient Status of Preceding Leguminous Crops under Integrated Nutrient Management—A Review. *Indian J. Nat. Sci.* **2022**, *13*, 42631.
201. Gafoor, R.A.; Pillai, S.; Nishan, M.A. Effect on integrated nutrient management on finger millet (*Eleusine coracana* (L.) Gaertn.): A review. *J. Pharmacogn. Phytochem.* **2021**, *10*, 292–298. [CrossRef]
202. Kharsan, G.D.B.; Barman, G.D.; Shrivastava, S.; Devi, S. Integrated nutrient management studies on French bean (*Phaseolus vulgaris* L.) quality attributes in Vertisols of Chhattisgarh plain. *Pharma Innov.* **2023**, *12*, 4663–4665.
203. Arbabi, A.; Sirousmehr, A.; Ganbari, A.; Fanaei, H.R. Effect of organic, chemical and combined fertilizers on some quantitative and qualitative characteristics of three sunflower (*Heliantus annuus* L.) cultivars. *J. Agric. Sci. Sustain. Prod.* **2023**, *33*, 25–37.
204. Kugedera, A.T.; Kokerai, L.K. A review on the effects of mineral fertilizer, manure and water management in improving sorghum grain yields in semi-arid areas. *J. Plant Nut.* **2024**, *47*, 1175–1188. [CrossRef]
205. Thakur, O.; Verma, A.; Thakur, P. Response of integrated nutrient management on Sweet Potato: A review. *Int. J. Stat. Appl. Math.* **2023**, *8*, 875–879.
206. Kugedera, A.T.; Nyamadzawo, G.; Mandumbu, R.; Nyamangara, J. Potential of field edge rainwater harvesting, biomass transfer and integrated nutrient management in improving sorghum productivity in semi-arid regions: A review. *Agrofor. Syst.* **2022**, *96*, 909–924. [CrossRef]

207. Ali, A.; Santoro, P.; Ferrante, A.; Cocetta, G. Investigating pulsed LED effectiveness as an alternative to continuous LED through morpho-physiological evaluation of baby leaf lettuce (*Lactuca sativa* L. var. Acephala). *S. Afr. J. Bot.* **2023**, *160*, 560–570. [CrossRef]
208. Ali, A.; Santoro, P.; Mori, J.; Ferrante, A.; Cocetta, G. Effect of UV-B elicitation on spearmint's (*Mentha spicata* L.) morpho-physiological traits and secondary metabolites production. *Plant Growth Regul.* 2023; 1–14. [CrossRef]
209. Gonnella, M.; Renna, M. The Evolution of soilless systems towards ecological sustainability in the perspective of a circular economy. Is it really the opposite of organic agriculture? *Agronomy* **2021**, *11*, 950. [CrossRef]
210. Gebreegziher, W.G. Soilless culture technology to transform vegetable farming, reduce land pressure and degradation in drylands. *Cogent Food Agric.* **2023**, *9*, 2265106. [CrossRef]
211. Chejara, S.; Malik, K.; Rani, M.; Bhardwaj, A.K. Integrated nutrient management: Concept, constraints, and advantages for a sustainable agriculture. *J. Nat. Res. Cons. Manag.* **2021**, *2*, 85–94. [CrossRef]
212. Srinivasarao, C.; Naik, M.R.; Lakshmi, C.S.; Kumar, G.R.; Manasa, R.; Rakesh, S.; Prasad, J.V.N.S. Economic and Environmental Benefits of Integrated Nutrient Management in Indian Agriculture. 2020. Available online: http://krishi.icar.gov.in/jspui/handle/123456789/81307 (accessed on 21 May 2024).
213. Garzón, J.; Montes, L.; Garzón, J.; Lampropoulos, G. Systematic review of technology in aeroponics: Introducing the technology adoption and integration in sustainable agriculture model. *Agronomy* **2023**, *13*, 2517. [CrossRef]
214. Kumar, A.; Chandel, N.; Barkha, B. Organic Farming vs. Integrated Nutrient Management: A Comparative Review of Agricultural Productivity and Sustainability. *Int. J. Plant Soil Sci.* **2024**, *36*, 460–473. [CrossRef]
215. Francini, A.; Giro, A.; Ferrante, A. Biochemical and molecular regulation of phenylpropanoids pathway under abiotic stresses. In *Plant Signaling Molecules*; Woodhead Publishing: Sawston, UK, 2019; pp. 183–192. [CrossRef]