Nitrogen

Review

Optimizing the Nitrogen Use Efficiency in Vegetable Crops

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Abstract: Nitrogen (N) is the most limiting nutrient for the production of vegetable crops, but anthropogenic sources pose risks due to its transformation into several reactive forms and movement throughout the environment. The bulk of the N research to date to improve Nitrogen Use Efficiency (NUE) has followed a reductionist factorial approach focused on synthetic N application rates and crop growth response, under monocultures. The increased adoption of diversified cropping systems, organic N sources, and alternative management practices makes it more challenging to unravel N form transformation, movement, and crop uptake dynamics, in time and space. Here, based on a selected review of the recent literature, we propose a holistic approach of nutrient management to highlight key management and production variables as well as multilevel cropping system, genetic, environmental, ecological, and socioeconomic interactions to improve the N cycle and NUE. The best management strategies to improve NUE include both organic and inorganic N rate calibration studies, germplasm selection, crop rotations, identification of nutrient x nutrient interactions, and pest and water management. Agroecological practices that may improve NUE include vegetational diversification in time and space, integrated crop–livestock systems, conservation tillage, organic amendment inputs, legume-based cropping systems, as well as a landscape approach to nutrient management.

Keywords: agroecology; nitrogen; nitrogen cycle; Nitrogen Use Efficiency; greenhouse gas emissions; organic matter; vegetable crops

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1. Introduction

While N is an essential nutrient for plant growth, and life on earth, surplus application rates, beyond the amounts needed by the crop, pose considerable health and environmental risks, at a local and global scale [1–4]. Because of its varied reactive forms, and complex movement dynamics in the soil, aquatic habitats, and atmosphere [5], as affected by management, biological, and environmental conditions, research on the N biogeochemical cycle, and its use efficiency, continues to be an active field of research [6–8]. The complexity of the N cycle at the farm level increases markedly in highly diversified subsistence agriculture and in capital intensive diversified production systems that include the use of crop rotations, a diversity of crop species in time and space, alternative production and soil management practices, the use of organic amendments, cover crops, and the particular socioeconomic conditions of the farm.

Nitrogen plays an integral role in plant nutrition, is involved in plant photosynthesis, and in the production of photosynthetic assimilating area to maximize light interception, and is a key constituent of proteins, amino acids, nucleic acids, enzymes, hormones, and chlorophyll [9,10]. Nitrogen regulates root growth, flower formation, canopy development and life-span, and fruit set, and it improves quality [11,12]. A N deficiency reduces transpiration rates and stomatal conductance, as well as carotenoid, chlorophyll, and soluble sugar levels; and it reduces the activity of photosynthetic enzymes and of PSII [10]. N-containing molecules, such as amino acids, polyamines, and nitric oxide (NO), play physiological and signaling pathway roles that contribute to plant defense and stress response mechanisms [13–15]. Nitrate in the soil may also serve as a signal molecule increasing the formation of lateral roots to reach areas of less mobile nutrients. In the plant, nitrate also functions as a signaling substance that regulates gene transcription, affecting seed germination, root growth, and stomatal activity [16–18]. On the other hand, the overuse of anthropogenic N has resulted in adverse environmental impacts including atmospheric reactive N deposition and pollution of aquatic habitats, contributing to global warming, reduced biodiversity, and disruption of ecosystem functions [7].

Globally, about 120 million tons of N fertilizer are applied every year, representing about 60% of all the applied NPK fertilizers [19]. As high-value crops, vegetables represent a unique case, because fertilizer input costs represent a relatively smaller percentage of the total production costs, often 5–10% [20–22]. Thus, as an insurance to minimize risk, vegetable growers have traditionally over-applied fertilizers to ensure adequate yields [23,24], when compared to the rates applied on staple crops such as cereals or root crops, that have a lower per hectare cost of production value. The relatively greater fertilizer application rates applied to vegetable crops may partly explain the relatively low nutrient use efficiency observed globally for the production of vegetables, as compared to lower-valued crops [25].

One of the most challenging aspects to better understand the N cycle and to improve its use efficiency (NUE) is to dissect and predict the effect of the myriad ecophysiological system x N interactions that are observed on the farm. The degree of multiple-level interactions, which occur both in time and space, and which may vary from farm to farm, makes it a challenge to better understand N cycle dynamics, its impacts on N uptake, and to identify management practices to improve its use efficiency [26]. An improved NUE helps to reduce production costs, the incidence of nutrient imbalances, and environmental N losses [27]. Despite improved genetics and the adoption of improved production practices, N_2O emissions have increased by 64% over the past five decades, with agriculture accounting for 78% of the increased emissions [28], highlighting the importance to improve the NUE in agricultural systems.

Despite the wide diversity in production systems and socioeconomic background, at a global scale, vegetable farmers may be divided into two major groups. A prominent group of vegetable farmers, those responsible for most of the international trade and for the consumption of vegetables by the middle class, represent those that rely on high chemical N inputs under both field or protected agriculture. The second group of vegetable farmers includes small-scale subsistence farmers, who feed about half of the global population, and who rely more on locally available resources than on external N inputs [29]. Thus, the different groups of farmers will require distinct approaches to either improve NUE or to improve the fertility of the soil to meet the crop uptake N demand and to minimize environmental losses. Here, building on earlier reviews [24,29–36], we present key management variables and system interactions that should be considered to improve the NUE in vegetable crops.

2. NUE in Vegetable Crops Production

2.1. Background on NUE in Vegetable Crops

Nitrogen Use Efficiency (NUE) is defined as the percent of the applied fertilizer N that is recovered by the current crop (Table 1). The global average NUE for crops ranges from about 50 to 80%, with values varying from region to region, primarily based on socioeconomic conditions [23,27,37]. For example, in China, where high N application rates are 3.3 times the global average for the production of maize, the observed NUE for maize was 25% compared to a 42% global average, and to 68% in North America [38]. Conversely, in Africa, where relatively low N rates are applied, NUE reaches 80% [27]. The global pooled crop NUE average is estimated to be about 55%, meaning that about 45% of the applied N may be lost to the environment, if soil N levels have already reached a steady state [2,39].

Table 1. Some of the terminology used in the literature to determine Nitrogen Use Efficiency, and as components of N management strategies.

Term	Definition	Sources
Nitrogen Use Efficiency (NUE)	Proportion of applied fertilizer N that is recovered by the current crop; A product of N uptake and utilization efficiency.	[32,40,41]
N recovery efficiency (RE_N)	N harvested in marketable product (dry weight) as a proportion of external N inputs.	[19,40,42]
Percent Apparent N recovery	Total above-ground N uptake at maturity at a given N fertilizer rate minus uptake at zero N-rate, divided by the amount of N applied.	[19,32,43]
Ndff	Nitrogen derived from fertilizer.	[19,44]
NFUE	N fertilizer use efficiency = (N derived from fertilizer/applied N rate) × 100	[44,45]
Agronomic NUE	Harvestable biomass production divided by unit of available N (soils and fertilizers); Provides an economic benefit/cost ratio of added rates of N fertilizer.	[12,41,46]
N utilization efficiency (NUtE)	Amount of marketable product per unit taken up by the crop and utilized via remobilization and assimilation.	[12,41,47]
N uptake efficiency (NUpE)	Unit of N taken by the plant divided by unit of N available in the soil.	[41,46,47]
N harvest index (NHI)	Ratio of N in harvestable product divided by the total crop N.	[46,48]
N balance	Term used to determine the amount of fertilizer N (N_{fert}) to apply, calculated as $N_{fert} = N_{outputs} - N_{inputs}$.	[26]
N budget	Assessment of the major N inputs and outputs on a farm.	[49]

In Europe, by following improved nutrient management practices for the production of cereal crops, NUE was increased over two decades from 42% to over 60%, serving as a model to improve NUE in other cropping systems and regions. Cereal yields, over that time span, were increased considerably in Europe, while chemical N applications were reduced by 25% [50]. In Nebraska, USA, when following recommended nutrient management practices, the NUE ranged from 60 to 70%, as compared to 40% obtained in plots receiving the highest N application rate [51].

To assess the N crop recovery rate from chemical N fertilizers, a multi-year experiment was conducted in the tropics on 13 different locations, in 8 countries, by evaluating the fate of initial ^{15}N chemical N and separate ^{15}N crop residue applications over a five-year crop rotation. During the first year of the study an average of 21% of the applied chemical N fertilizer was recovered by the crop, and 79% was derived from the soil N. After the 5-year period, on average, 18% of the chemical N was recovered by the crop, compared to 40% recovered from the ^{15}N-labeled crop residues [52]. Recent ^{15}N rainfed field studies conducted with maize in central Illinois, USA, showed that most of the crop N uptake (up to 89%) was provided by the soil N rather than the applied chemical fertilizers [53]. Similarly, ^{15}N studies showed that about 20% of the applied chemical N was recovered in sugarcane at maturity [54], again highlighting the importance of soil and crop residue mineralization, as a source of N.

For vegetable crops, the NUE during the 1970s in California, USA, was reported to be less than 50%. During the 1980s, a ^{15}N study with lettuce showed an NUE of 12% with a single pre-plant application of 180 Kg N Ha^{-1}, and a 25% NUE when receiving 60 Kg N Ha^{-1} in two split applications [55]. Globally, the estimated NUE efficiency for fruits and vegetables is estimated to be 14%, compared to 46% for maize, and 40% for both rice and wheat [56]. Improvement in NUE for vegetable crop species is attributed to either physiological or morphological plant traits [46,48,57]. Under best management practices in intensive production systems, the NUE for vegetable crops may reach 70% [58].

NUE is dependent on the physiological capacity of vegetable species to uptake, metabolize, and redistribute the necessary amount of N, during the appropriate stage of crop growth, to optimize yields. Three key components that determine the NUE of crops include the N uptake efficiency (NUpE), N utilization efficiency (NUtE), and N harvest index (NHI) [46,47] (Table 1). These components are affected by the form of N uptake, either NO_3^- or NH_4^+, N translocation within the plant, the reduction of NO_3^-, and the assimilation of reduced N into organic compounds [57].

The ability of crops to uptake N is dependent on a number of interrelated variables such as soil fertility, cultivar, soil moisture, temperature, time of the year, N uptake pattern, the incidence of pests and diseases, farmer expertise, and farm socioeconomic conditions, among other variables. In turn, physiological mechanisms that affect NUE include root growth, architecture and N uptake patterns, leaf duration and growth, and N remobilization within the plant [46]. A field study with tomato conducted in California, USA, on an unfertilized field, and previously fallowed for two years, showed a relatively low, 3% root N uptake as a percentage of the total inorganic N available in the sampled soil profile (60 cm $\times$ 50 cm $\times$ 120 cm), attributed to a generally low root density. These relatively low root uptake rates indicate a relatively low NUE and the potential for leaching of inorganic N, below the root zone [59].

Total N uptake values reported in the literature (Kg N Ha^{-1}) [23,60], and uptake patterns during the growing season, need to be updated on a periodical basis to develop realistic budgets and fertilizer management recommendations, as new cultivars are introduced [49]. There are also relatively few studies with respect to nutrient uptake patterns and budgets under organic farming systems. It is thus critical that N uptake and NUE efficiency information be developed under low-input or chemical-free farming conditions [8,12,46,61].

For leafy crops, N uptake patterns correspond to the periods of biomass accumulation. In the case of head lettuce, 70–80% of the N uptake demand occurs between heading and harvest [46]. In the case of onion, 9% of the N uptake occurred during the first half of the growth cycle, and 68% of the uptake occurred from the period of bulbing to harvest [62]. The crop uptake pattern of fruit vegetables, such as peppers, follows a Mitscherlich-type curve response, which describes the law of diminishing returns in response to greater fertilizer application rates. The response curve includes a lag phase during crop establishment, a vegetative or log phase of rapid nutrient uptake (20–30 days after transplanting), a leveling rate, a peak of maximum nutrient uptake (30–60 days), and a reproductive or senescence stage, with the highest nutrient uptake occurring during the last three phases [24,63,64]. During the last stages of crop growth and maturity, both rates of crop N uptake and of N remobilization within the plant should be considered to determine their combined effects on NUE and crop yields [40]. Greater rates of remobilization are observed in crops with a reproductive phase. For instance, almost 50% of the N uptake in pepper is partitioned to the fruits [64,65]. When comparing treatment effects, agronomic nutrient indices are more accurate, with respect to use efficiency, when the soil is in a relatively steady state with respect to nutrient content [66].

As observed in several studies, in general, higher N application rates, especially at above optimum levels, results in a lower NUE [43,51,67,68]. Farmers, in general, tend to apply N fertilizers above the recommended rates, to ensure adequate yields, and as an insurance against possible losses [23]. For instance, maize farmers in Northeast China apply an average of 350 Kg N Ha^{-1}, with a range of 210–490 Kg N Ha^{-1}, which is well above the recommended rates of 190 Kg N Ha^{-1} [69]. Similarly, vegetable growers in Spain and Florida tend to make N applications at above the recommended rates, under greenhouse and field conditions, resulting in N environmental contamination [70–72]. However, not only is NUE reduced [70,73], but some vegetable species experience a yield depression at application rates above the recommended levels [74], as well as reduced quality and delayed maturity [75,76]. The reported value of NUE for some staple and representative vegetable crops is presented in Table 2.

Table 2. Representative Nitrogen Use Efficiency (NUE) values reported for some vegetable and reference agronomic or staple crops.

Crop	NUE (%)	Region	Sources
Cereals (maize, rice, wheat)	26–35	China, commercial production, under high N application rates	[38,77]
Maize, *Zea mays*	36–46	Global; USA; reported range values	[30,37,56,78]
Rice, *Oryza sativa*	29–42	Global; reported range values	[37,56]
Wheat, *Triticum aestivum*; Rice	38–42	Global; reported range values	[37,56]
Cabbage, head, *Brassica oleracea* var. capitata	27–55	Average 40%, Florida	[79]
Cucumber, *Cucumis sativus*; bell pepper, *Capsicum annuum*; tomato, *Solanum lycopersicon*	54–61	Greenhouse fertigation, The Netherlands	[80]
Onion, *Allium cepa*	30–40; 10–26	The Netherlands; Colorado, Idaho, USA, varied by timing and method of application	[44,81]
Peppers, bell, *Capsicum annuum*	30–50	Florida	[82]
Potato, *Solanum tuberosum*	40–77; 27–37; 40–60	Range for Low N vs. high N rates; The Netherlands; Florida; Minnesota	[12,68,83]
Tomato, *Solanum lycopersicon*	15.4 (12 spring; 32 fall)	Sandy soils, Florida, ^{15}N study	[19,84]
Lettuce, *Lactuca sativa*	12–25	For high (180) and low (60 kg Ha^{-1}) N application rates	[55]

2.2. Soil Quality and NUE

Improvements in soil management and fertility impact soil N levels, N soil mineralization rates, crop N uptake, and NUE [85]. The interactions between soil management and soil moisture also affects microbial and fauna activity, the N cycle, and NUE. The soil organic matter (OM) contains over 90% of the top 25 cm of soil N, which may represent 1700 to 1800 Kg N Ha^{-1}, of which 1–3% may be mineralized on an annual basis [23]. The soil OM level and its replenishment with amendments or crop residues will thus impact the long-term soil N stocks, and mineralization rates. With some crops the soil OM may provide 60–90% of the total crop N uptake, even in fields receiving high N chemical fertilizer inputs [86]. Adequate levels of soil OM also contribute to reduce soil erosion, by helping to stabilize soil structure, with a reported 20–30% reduced erosion with a 1–3% increase in OM levels [87]. The corresponding increase in soil OM levels also contributes to increased yields [88], with a study in a temperate region showing a 12% yield increase for every 1% increase in soil OM [87].

Long-term fertilization with urea or sources of ammonium acidify the soil which may require periodic lime applications to maintain the proper soil pH and soil nutrient balance [89]. A 28-year field experiment conducted in Hunan Province, China, showed that unlimed NPK fertilized fields, with urea as the N source, resulted in 15–16% lower levels of pH, OM content, NO_3^-, and total N, as well as lower NUE, as compared to the limed treatments, indicating the impact of low pH levels on soil quality and NUE [85]. In addition, soil management practices that result in soil compaction may restrict root growth, water content, N mineralization rates, and nutrient uptake, and alter the dynamics of microbial activity, resulting in potential adverse impact on NUE [90–92].

Organic, low-input, and subsistence farmers depend less on external N inputs and instead rely on enhancing the soil organic matter content and fertility of the soil to meet long-term crop N uptake requirements. Ecologically based management practices are prescribed to improve the long-term soil fertility, organic matter content, and NUE on the farm (see Section 4) [8,29].

2.3. Effect of N Form on Crop Growth and NUE

Plants uptake N as NO_3^-or NH_4^+, and in soils, NO_3^- is generally the predominant N form for plant uptake. Crops normally uptake more NO_3^- than NH_4^+. Through the process of mineralization, the N found in organic compounds is converted to NO_3^- or NH_4^+. The bacterial led process of nitrification converts NH_4^+ into NO_3^-, especially under warm and well-drained soil conditions. Thus under cooler soil conditions the NH_4^+/NO_3^- ratio may be greater than during warmer months. Ammonium may also be dominant under acidic and aerobic conditions [93], and at high levels may cause toxicity on plants [23]. Similarly, applied urea in the soil hydrolyses into NH_4^+, which may be uptaken by plants, or is converted via nitrification into NO_3^-.

For many crops, a combination of NO_3^- and NH_4^+ improves crop growth and quality [23,93], and the particular optimal ratio will vary by crop species and growing conditions, impacting its NUE, as described in Table 3. To minimize leaching, especially on sandy soils, it is recommended that nitrate represents 25–50% of the applied fertilizer [68]. The NO_3^-/NH_4^+ ratio has an effect on the uptake of other mineral nutrients. Increased ratios of NH_4^+ may reduce the uptake of mineral cations and increase the uptake of mineral anions. A higher ratio of NH_4^+ may reduce the uptake of calcium, which may cause some physiological disorders such as blossom-end rot in tomato and pepper [94,95].

Most N form studies have been conducted under greenhouse conditions and with particular crop varieties, and thus, further field-based studies are required to confirm results observed under protected conditions. The results on the effect of N form conducted under protected conditions do not necessarily correspond to those obtained in the field [96]. However, the evaluation of N form under field conditions is challenging due to the inherent dynamic nature of the soil NH_4^+/NO_3^- ratios as they are affected by differential crop uptake, microbial transformations, and NO_3^- movement in the soil profile [59,96]. An unfertilized field study conducted with tomato in California, using several methodologies to assess N soil dynamics, found that NO_3^- levels were 10–20 times higher than for NH_4^+ in the top 15 cm soil layer, with the available NH_4^+ being quickly nitrified into NO_3^-. The available NH_4^+ pool appeared to be mostly utilized by microbes rather than for crop uptake. Because of the relatively high levels of NO_3^- in the soil profile, the authors predicted that considerable N losses would be likely to occur due to leaching below the root-zone [59]. Recent ^{15}N field studies conducted in Illinois, USA, with different N sources determined that NUE was greater for NO_3^- than for NH_4^+ and urea fertilizer sources. The greater environmental losses observed for urea, resulting in the lower NUE, was attributed to greater NH_3 volatilization than for the NH_4^+ N sources [53].

Plants may also uptake organic sources of N, such as amino acids or proteins, and the levels of soluble organic N may contribute a portion of the overall N budget [8,86,97]. The predominant available N form under organic systems may vary depending on the production system. For instance, under aged manure or pig slurry fertilizer programs, the proportion of NH_4^+ in the amendments may reach 75–80%, with the balance of the total N supply for crop uptake complemented depending on the soil properties, crop rotation or field history, and management system [98].

Table 3. The effect of N form, and NO_3^-/NH_4^+ ratios, on the growth of some representative vegetable crop species.

Crop Species	N Form	References
Cucumber, *Cucumis sativus*; Cucurbits	NO_3^- improves growth while NH_4^+ depresses growth (likely due to a lower pH in the root zone).	[99,100]
Flowering Chinese Cabbage, *Brassica campestris* L. ssp. *chinensis* var. *utilis* Tsen et Lee	Improved yields with a combination of NO_3^-/NH_4^+ ratio; Improved yield at 10:0 and 9:1 ratios; Improved NUE at 9:1 ratio. An earlier study found the best growth at 1:1 ratios and marked growth reduction at 1:9 ratios.	[93,101]
Chinese Kale, *Brassica alboglabra* L. H. Bailey	Improved growth at NO_3^-/NH_4^+ ratio of 3:1 and 9:1; Improved NUE at 3:1 ratio; Inhibited growth at high NH_4^+ ratios.	[102]
Lettuce, leafy, *Lactuca sativa*	Head fresh weight higher with NO_3^-/NH_4^+ ratios of 1:1 or 1:0; Greatest NUE at 1:0 or 1:1 ratios.	[103]
Onion, *Allium cepa*	No consensus on the effect of N form on yield. An earlier study found that NO_3^- alone or in combination with NH_4^+ improved plant growth; bulb weight highest with NO_3^-/NH_4^+ ratio of 3:1 to 1:3.	[81,104]
Pepper, *Capsicum annuum*	Yields highest when NO_3^- is the predominant N form, and with an increased NO_3^-/NH_4^+ ratio.	[105,106]
Strawberry, *Fragaria* × *ananassa*	Fruit yield greatest at NO_3^-/NH_4^+ ratio of 3:1 to 1:1.	[107]
Taro, *Colocasia esculenta*	Improved growth with 75:25 or 100:0 NO_3^-/NH_4^+ ratios.	[108]
Tomato, *Solanum lycopersicon*	Trend to improved yield (but not significant) with 1:4 NO_3^-/NH_4^+ ratio; Improved fruit quality with organic N source or with 1:4 NO_3^-/NH_4^+ ratio.	[16,109]

2.4. Crop Improvement for NUE

Given its global economic importance, with a trade value of over USD 59 billion [110], maize is among the most extensively researched crop species in terms of the impact of breeding, management, and fertilizer practices on crop yields. The five-fold improvement in maize yields over the past century are attributed to be about 60% due to genetic improvement, and 40% to improved management practices [111]. While early yield increases in maize were achieved by increasing fertilizer rates, application rates have remained static over the past four decades in the USA, reflecting an improved NUE [47]. However, NUE improvements were not a goal in maize breeding programs, but rather occurred through the adoption of improved management practices such high planting densities, or selection for an increased harvest index, resulting in increased N partitioning to the ears [46,47]. Similar improvements in NUE were reported from long-term breeding programs in wheat, perhaps due to an increased N harvest index, and improved management practices [112]. An evaluation of the available germplasm indicates the potential for increasing the NUE in cereal crops, through targeted crop improvement [112,113].

It has been well recognized that germplasm diversity exists within vegetable species with respect to nutrient rates and NUE [57] with respect to crops such as okra, pumpkin, and tomato (Table 4) [114]. However, breeding for NUE has not been a component of improvement programs for most crops, likely because it is a complex genetic trait, controlled by multiple genes, and because of the difficulty in managing the many environmental variables that affect N form, movement, and cycles in the farm [46]. In many cases, the potential to select for improved NUE among modern cultivars has been diminished as the desirable traits have been bred out, after many years of selecting for yield response to high N application rates, which may prescribe the inclusion of a wider genetic pool, such as wild relatives and landraces, in the selection process [46,115–119]. While most research to date has focused on increasing NUE under conditions of high N fertility, future breeding work may include characterization and selection for high NUE under limited N availability [57,116], as is often the case under low-input or in organic production systems [8,120,121].

Table 4. Profile of breeding and germplasm selection on representative vegetable crops, with respect to Nitrogen Use Efficiency.

Crop	Notes	References
Cabbage, head, *Brassica oleracea* var. capitata	Evaluation of N harvest index, and selection criteria of growth parameters	[46]
Cassava, *Manihot esculenta*	Genotype with improved N uptake was identified among 25 accessions, under low N conditions; Molecular analysis identified mechanisms for possible improved N uptake in efficient lines	[18,122]
Eggplant, *Solanum melongena*	NUE efficient genotypes identified from germplasm collections and crosses	[116,123]
Lettuce, *Lactuca sativa*	Evaluation of wild species, plasticity in response to environmental variables	[46]
Onion, *Allium cepa*	NUE evaluation of landraces	[118]
Potato, *Solanum tuberosum*	Identification of growth traits associated with NUE among a range of potato cultivars; Differential cultivar responses to N rates; cultivar selection and N efficiency under organic systems	[12,46,83,124]
Spinach, *Spinacea oleracea*	Identification of QTLs for NUE	[46]
Tomato, *Solanum lycopersicon*	High-NUE genotype identified among 14 landrace varieties; wild relative genotype identified with increased NUE under low N rates; Genotypes with improved NUE with potential use as rootstocks; greater N uptake in drought-tolerant cultivars	[115,119,125,126]

3. Strategies to Improve NUE in Vegetable Crops

3.1. Development of Fertilizer N Recommendations for Vegetable Crops

The results of research over the past few decades indicate that the adoption of best nutrient management practices improves the NUE for individual crop species, and at a regional level [50,51,58]. Soil N tests are often unreliable to determine N rate recommendations, because of its rapid chemical transformations, such as denitrification, immobilization, mineralization, and volatilization, especially in warm climates [19]. Nitrogen fertilizer rate recommendations are thus developed based on yield response curves, or calibration studies, based on a range of N application rates [8,19].

N application recommendations are based on an understanding of the N cycle at the farm and landscape level [8,127], on nutrient budgets, and on calibration studies to determine crop response curves to a range of N application rates (Table 5). Data required to develop adequate nutrient budgets and calibration curves include total N uptake amount over the growing season (Table 6); patterns of N uptake, based on crop phenological stage; tissue N levels during particular periods of crop growth; and N residual levels or mineralization rates for representative soils in the region.

Table 5. Approaches that are followed to develop N rate recommendations, to improve yields and Nitrogen Use Efficiency (NUE).

Research Protocol	**Notes**	**References**
Studies on N cycle at a farm and landscape level	China; long-term rotation, Europe; Organic systems, California, USA; Canada	[127–130]
Nutrient budget or balance studies	Oregon; Balance (organic systems); Europe; Canada; Florida	[26,49,64,131–133]
Timing of application (uptake patterns)	Oregon; Montana	[64,134]
Calibration (growth N response curves)	At experiment station or on-farm trials; Oregon	[64,135,136]
Soil and tissue analysis	Includes soil nitrate testing, Oregon; Brazil; Florida; plant monitoring, e.g., chlorophyll meters, petiole ${NO_3}^{-1}$ sap analysis, canopy sensors	[26,64,137–139]
Placement of fertilizers	Montana; Europe	[24,134]
N fertigation guides	Greenhouse; Europe; India	[23,24,74,80,140]
Modeling, crop models, decision support systems (DSSs)	Onions, Brazil; Europe; Florida; Organic rotations and N budget, UK	[24,26,138,141,142]
Use of optical sensors	Maine	[143]
Adoption of integrated or best management practices (BMPs)	Oregon; Europe; Florida	[19,24,26,50,64,82]

Table 6. Reported Nitrogen uptake rates for representative vegetable and staple crops (marketable product), as reported in the literature.

Crop	**N Uptake (Kg Ha^{-1})**	**Notes**	**References**
Broccoli, *Brassica oleracea* var. Italica group	50–90	Oregon, USA	[64]
Brussel sprouts, *Brassica oleracea* var. Gemmifera	170	Organic, Europe	[61]
Cabbage, head, *Brassica oleracea* var. capitata	130–230	Europe	[46]
Cassava, *Manihot esculenta*	124 (55–62 roots, 202 entire plant)	Tropics	[88]
Lettuce, *Lactuca sativa*	105; 100–110	Organic, Europe; California	[46,61]
Onion, *Allium cepa*	60–120, 160	Oregon, California, USA; Brazil	[62,64,144]
Potato, *Solanum tuberosum*	130; 80–130; 220	Organic, Europe; Oregon, USA; California, USA	[46,61,64]
Spinach, *Spinacea oleracea*	20–90	Leafy baby and processing, California, USA	[46]
Tomato, *Solanum lycopersicon*	3.9–4.4 (fruit) 51.8–72.2 (whole plant)	Florida, USA	[19]

A challenge to develop appropriate N fertilizer recommendations for vegetable crops is that calibration data or N response curves are location- [136,138], crop species-, cultivar-, and production system-specific (such as plasticulture vs. bare-ground culture, or conventional vs. organic). Calibration research should also be revisited periodically, as new cultivars are continually introduced, as production practices are adjusted, and as new technology is adopted to improve production efficiency. Fertilizer calibration data are lacking for most production areas, especially in the tropics. When available, calibration data are often only available for a few selected crops of major economic importance, or are outdated, based on field research that may be years to decades old. When local calibration studies are unavailable, extensionists and crop advisors often rely on studies conducted in other regions or countries. In practice, in most instances and locations, decisions on the rates and timing of N applications are based to some degree on calibration studies conducted elsewhere, and largely on the experience of local growers, consultants, and extension advisors (Table 7) [26]. As a consequence, it is likely that the lack of currently available calibration data, for specific crops and production areas, results in farmers over-applying N on their farms, resulting in lower rates of NUE and in respective economic and environmental losses.

Table 7. Recommended N application rates for representative vegetable crops.

Crop	Application Rate (Kg Ha^{-1})	Comments	References
Cabbage, head, *Brassica oleracea* var. capitata	220–350	Europe	[46]
Carrot, *Daucus carota*	120; 100–150	California, 110–116-day season; California (Oxnard); Florida, sandy soils	[145,146]
Celery, *Apium graveolens*	200–400	California	[147,148]
Cucurbits	60–100; 90–170 (summer squash); 150	Wisconsin; California; Florida	[149–151]
Lettuce, *Lactuca sativa*	120–220	Europe	[46]
Onion, *Allium cepa*	170–200; 200;	Pennsylvania and Utah; Washington State	[118,152–154]
Pepper, *Capsicum annuum*	150–200; 200–240; 300	Georgia; Florida, higher rates with extended season; Puerto Rico	[63,82,155]
Potato, *Solanum tuberosum*	120–180; 150–250; 200–250; 250–300	California; Florida	[12,46,68,147]
Spinach, *Spinacea oleracea*	140–290	Europe	[46]
Tomato, *Solanum lycopersicon*	110–225 (plus weekly maintenance applications of 10 kg for staked tomatoes); 160–200	California, fresh market; Florida and Eastern USA	[19,156–158]

3.2. Best Management Practices to Improve NUE

Research on NUE indicates that environmental losses may be reduced by 15–30% by adopting improved management practices [41]. A global meta-analysis estimates that NUE may be increased by improving nutrient (by 27%), crop (6.6%), and soil (0.6%) management practices. The analysis estimates that NUE may be improved globally by 30% by adopting improved production practices [27]. These values and improvements would vary by cropping system and region, but point out the potentials for improving crop NUE, by adopting best management practices (BMPs). Recommended practices to improve NUE under intensive commercial vegetable production systems include following what are considered to be BMPs such as adopting the right source, rate, timing, and placement of N fertilizers, along with management practices such as tissue testing and fertigation-based plasticulture systems [19,27,159–161]. Conversely, production factors that may decrease NUE include poor seed-bed preparation, unadapted cultivars, poor seed quality and stand establishment, and improper irrigation or drainage, as well as pest and weed infestations [162].

An initial step to estimate N application rates for a specific crop with realistic yields is to develop a nutrient budget by subtracting the total amount needed by the crop by the estimated residual levels already available in the soil [71]. A management program is designed to synchronize the levels of available or applied N with the estimated demand of the crop during the different phenological stages of development. Tissue analyses may be conducted during the growing season to monitor the crop's nutritional status to further fine-tune the N management program [24]. The ultimate level of NUE reached in particular locations will vary depending on farmer expertise and on field conditions. However, when particular management practices are adopted uniformly by all farmers, NUE tends to increase area-wide. Experience indicates that with many crops, it is possible to increase NUE by 30–50% with the adoption of recommended management practices [66].

While soil N tests are normally unreliable to estimate soil N levels [59], some locations, especially in temperate areas, have adopted the use of pre-side dress Nitrate-N tests, to estimate available N soil levels, prior to planting. Multiple field trials conducted in California, USA, with cool season vegetables, determined that at NO_3^- soil levels above 20 ppm, initial side-dress N applications could be delayed without affecting crop growth [26,163]. In addition, system-wide management practices may be adopted, such as alternative soil management or tillage, alternative cropping systems such as double cropping or intercropping, the integration of livestock and crop production, and alternative water management, as well as agroecological systems that may help to improve internal N cycles and use efficiency [8,164]. A profile of several recommended management practices to improve NUE is presented in Table 8.

Table 8. Profile of representative management practices to improve Nitrogen Use Efficiency in vegetable cropping systems.

Production Practice	Notes	References
Optimize N application rates based on crop demand	Improved NUE	[27,82,164]
Selection of adapted crop varieties	Potato and lettuce germplasm; Selection for roots systems with improved N uptake	[124,165,166]
Controlled- or slow-release fertilizers	Utilizing nitrification inhibitors, which is not cost-effective in some systems	[24,68,81,167,168]
Combined use of organic and chemical fertilizers	Improved NUE, soil fertility, and use of local resources	[27,169]
Placement of fertilizers	Field placement including subsurface drip fertigation	[24,81,164,170,171]
Planting density, spacing	Spacing x N response interaction, onions, tomato	[172–175]
Plasticulture systems and fertigation	Improved NUE	[65,158,170,176,177]
Timing of application to synchronize with crop uptake demand	Tomato, onion, including split applications	[19,23,45,58]
Precision farming	Assessment of yield variations across a field; N status monitoring systems; may not be cost-effective in some systems or for small-scale production	[159,178,179]
Grafting	Improved NUE, melons, tomato	[26,125,180]

3.3. Crop Rotations Effects on NUE

Crop rotations have historically been used to manage soil fertility, to manage pest and weed infestations, and to diversify the farming operation [181]. By incorporating species with complementary nutrient use patterns, root traits, and microbial rhizosphere assemblage, crop rotations help to improve the N cycle within the farm; improve the soil structure; increase organic matter, nutrient, and water contents; improve NUE; reduce residual N losses; and improve yields [8,24,181,182]. A ^{15}N field study conducted in Nebraska, USA, showed that a combination of low N application rates and complex rotation schemes improved internal organic N cycling while maintaining similar N mineralization rates as those obtained under high-N-rate treatments, showing the potential of complex rotations to reduce N losses and to improve NUE [183].

While residual N levels may remain from the previous crop in fertilized fields, the ultimate management goal, especially on sandy soils, aims to minimize N residual levels by fine-tuning chemical N applications to the actual needs of each crop in the rotation [184]. Rotation ^{15}N studies in sandy soils have found negligible levels of N recovery from the chemical N rates applied on the first crop; with the second crop in the rotation recovering about 2% of the initial ^{15}N application, to <1% recovery for further subsequent crops in the rotation [19]. In a double-crop tomato experiment conducted in northern Florida, USA, in which a ^{15}N-labeled fertilizer was applied only for the first crop, the ^{15}N fertilizer recovery efficiency for both seasons ranged from 10.7 to 15.4%, and thus, the levels of unrecovered N ranged from about 85–90%. At the highest N application rate in the experiment, about 90% resulted in environmental losses, attributed to leaching or volatilization [19]. With such potential chemical N losses, given that farmers tend to over-fertilize their crops, alternative management practices may be adopted, such as changing the fertilizer input, and including cover crops or catch crops in the rotation, to make better use of residual N levels and to improve soil tilth and NUE [24,120,181,185,186]. For example, a two-year legume-based rotation field and modeling study conducted in northern Florida, USA, showed that N application rates could be reduced by 26% and that N leaching was reduced by 37%, without sacrificing yields, under the rotation and irrigation scheduling program [187].

The fertility of the soil, residual N availability, and NUE may also be improved when legumes are incorporated into a rotation [24,120]. A six-year rotation on farm experiments conducted in Malawi showed improvements in several soil fertility variables when pigeon peas (*Cajanus cajan*) and peanuts (*Arachis hypogaea* L.) were included in the rotation, including greater levels of mineralizable and microaggregate carbon [121], indicating the potential of legume-based rotations to improve NUE and long-term productivity.

4. Agroecological Practices to Improve NUE

4.1. Organic and Low-Input Farming Practices Effect on NUE

Nitrogen is among the most limiting production factors in organic farming with a modeling study on potatoes showing that 48% of the yield variability could be explained by the N availability [12]. Ecologically-based management strategies on farms that rely on little or no chemical N inputs, revolve around improving the long-term fertility of the soil. Suggested ecological soil management principles include building the soil organic matter content and nutrient reserves; increasing vegetational diversity in time and space to build synergistic and multifunctional interactions; minimizing soluble N pools that may be susceptible to environmental loss; and developing mass N balance budgets at the farm and landscape level to better understand and improve nutrient flows in time and space [8,29].

The synchronization of soil and organic amendment N mineralization levels with the timing of crop uptake is a major challenge for organic production [8,131,188]. Variables that affect the improved synchronization of available soil N and crop uptake include the soil fertility, root growth and architecture, and the selection of crop species adapted to lower N soil conditions. Plant traits that may improve adaptation to low N soils include a higher root-to-shoot ratio, slower growth rates, and effective microbial associations. In turn, organically managed soils have in general lower mineral N levels, but have a greater mineralization potential due to a greater organic matter content [120].

A three-year organic rotation study with several vegetable crops, conducted in Portugal, concluded that split applications of fast N release nutrient sources, and increasing the legume/cereal ratio of cover crops to improve N mineralization rates, improved N uptake and NUE [131]. A survey of organic and conventional farms in Germany found lower surplus N levels, subject to environmental losses, and a greater NUE in the organic farms. Overall, the highest NUE and lowest surplus N levels were observed on the integrated crop–livestock organic farms [132]. A ^{15}N experiment that compared organic and conventionally managed soils in Switzerland found a greater NUE in the organically amended soils (93%) compared to the conventional ones (55%), attributed in part to the slower rate of N mineralization from the organic amendments. Soil fertility attributes that linked the organic soils to a greater NUE included microbial activity, organic matter content, and aggregate size [189]. Conversely, soils with a reduced microbial activity resulted in a 20% reduced N crop uptake, increased leaching (by 65%) and emission losses (94%) [190], which highlights the importance of soil fertility and microbial activity on the N cycle and NUE in organic farms. The importance of long-term soil ecological management under organic legume-based cover crop rotations as the sole N source, was also observed in a recent study, showing a near balance of N inputs and outputs, and improved soil N mineralization rates, likely a result of improved N cycling and NUE [191].

Organic residues and amendments can provide a considerable source of N, contribute to build up the soil organic matter, and may improve the system NUE [192]. The selection of the type of amendment used on the farm depends in part on the N mineralization rates meeting the crop uptake demand during the different growth stages. N mineralization rates in temperate areas, during the first month after application, range from 60% for specialty organic sources such as feather meal to 20–40% for legume residues and poultry manure, and to less than 5% for composts. By one year after application, N mineralization rates range from 100% for specialty soluble organic sources to 50% for legume residues and poultry manure, and to 5–10% for composts [64]. Alternative organic amendments, such as seaweed, may be used as N sources, which may also contain growth-promoting or biostimulant properties [193–195]. Examples of other amendments, as effective sources of N on vegetable crops include composts and vermicompost; commercial manure sources such as chicken pellets; soybean meal in combination with effective microorganisms; and commercial fertilizer mixes, such as a combination of feather, meat, and blood meal [144,196,197]. A combination of readily soluble N sources with organic amendments may help to better synchronize N availability with crop uptake by immobilizing N during the early growth stages and by mineralizing N during the later stages of high N uptake demand, minimizing environmental losses, as observed in a ^{15}N experiment with Chinese cabbage [198]. A description of some organic and agroecological management practices that may be adopted to increase NUE is presented in Table 9.

Table 9. Profile of selected agroecological management practices that may help to improve Nitrogen Use Efficiency.

Production Practice	Notes	Source
Organic systems	Lower surplus N levels in organic systems, improved NUE	[132,189]
Legume-based rotations	A more balanced N budget, improved N cycles	[29,191]
Organic amendments	Locally available, a source of N, and improve soil organic matter; serve as a slow-release source of N	[8,24]
Cover crops	Soil fertility and improved N cycles	[24,199,200]
Intercropping systems	Improved N cycling, NUE, soil microbial interactions	[24,201–204]
Integrated crop–livestock/aquaculture systems	Improved nutrient cycling, economic diversification, resilient systems	[29,205]
Agroforestry/alley cropping	Improved nutrient cycling, reduced N losses	[206–208]

4.2. System Diversification to Improve NUE

Vegetational diversification can help to improve N cycles and NUE at the farm and landscape level. Diversification consists of introducing species, in time and space, that are complementary in terms of resource use with respect to space, light, water, and nutrients [209,210]. The complementary nature of the species results in a synergistic resource and nutrient use efficiency, through niche complementarity, imparting a greater level of productivity and resilience to the agroecosystem [211].

Cover crops represent an efficient and practical way to incorporate crop diversification within a farming operation, as part of a rotation program [24]. Cover crops may help to improve soil organic matter content and fertility, resulting in improved N cycles, NUE, and yields [27,121,200,212]. Cover crops may consist of legumes that contribute N via biological N fixation; grasses or other non-leguminous species that help to break disease or weed cycles and to serve as 'catch crops' of residual N; and legume–non-legume combinations, to obtain the partial benefit of both types of cover crops [8]. In addition, cover crops provide many other ecological services to the agroecosystem [200,213,214]. As is the case with the use of organic amendments, the rate and timing of N mineralization from cover crop residues is important to meet the N demand of the following crop, as well as to better synchronize the N residue mineralization rates with the demand during the different growth stages of the cash crop [215]. The C/N ratio of the cover crop residues determines their rate of mineralization. Legume residues in general have C/N ratios between 12 and 25 which promote mineralization, while cereal C/N ratios above 80 lead to immobilization [120].

In lettuce, an improved NUE was observed when following a cover crop mixture of rye and hairy vetch, as compared to single species cover crops, and this was accompanied by apparently improved microbial activity, as indicated by greater microbial β-glucosidase enzyme activity, which likely regulated the mineralized N pool from the crop residues [216]. In an eight-year experiment conducted in Salinas, California, consisting of organic vegetable rotations, a rye–legume cover crop combination also resulted in improved NUE. However, because of the relatively high levels of external inputs, the legume cover crops increased the surplus of N in the system, which may result in environmental losses, while rye was more effective as a cover crop, to minimize N surplus levels from the system [217]. Based on multi-year cover crop evaluations conducted in Japan, including ^{15}N studies, a combined 2:1 hairy vetch/rye planting ratio was also found to improve the mineralization and synchronization of N release by the individual species, with the N uptake demand of tomato, along with an increase in the overall soil N pool and N cycling [218].

A ^{15}N isotopic crop residue 4-year field study conducted in Washington State, USA, determined the level of N contribution from *Brassica hirta* mustard cover crops to a following potato crop. Overall, the Brassica cover crops recovered 34 to 51% of the 56 Kg Ha^{-1} of ^{15}N applied. About 30% of the N in the Brassica cover crops was released for the following potato crop, representing a contribution of 30–40 Kg Ha^{-1} of N [219], indicating the potential on non-legume cover crops to serve as catch crops of N for the following crop in the rotation [220]. A two-year field experiment conducted in Massachusetts, USA, also showed that adequate yields could be reached with potatoes with reduced N application rates of 75 kg N Ha^{-1} when following a legume and of 150 Kg M Ha^{-1} when following a forage radish cover crop, showing an improved NUE with these cover crops, compared to the standard rates of 225 Kg N Ha^{-1} required to reach the same yields without a cover crop in the rotation [221].

Additional strategies to increase vegetational diversification in vegetable agroecosystems, in time and space, with the goal of improving system resilience, soil fertility, N cycles, and NUE include intercropping [24,209], alley cropping [206], agroforestry [207], as well as integrated crop–livestock systems [8] (Table 9). Diversified systems of production are more often found in small-scale conventional or organic farms as well as in subsistence farms of the tropics, but are increasingly being adopted in some temperate regions with the goal of establishing more resilient systems that may be able to better cope with the environmental challenges and fluctuations posed by climate change.

Well-designed intercropping systems may result in improved N cycling and NUE by incorporating crop species with complementary growth habits and nutrient uptake demands, such as by interplanting deep-rooted with shallow-rooted crops [24,202,222]. Effective intercropping systems may maintain productivity under a lower N soil status or application rates, through an increased NUE [223]. The species composition and design of the intercropping system, such as the planting patterns, will determine whether the complementary resource use between the species is dominated by above or below-ground interactions [224].

Intercropping systems showed an improved NUE with cabbage and faba bean (*Vicia faba* L.) intercrops [203] and an improved land equivalent ratio for NUE (LER_{NUE}) in a tomato and corn intercropping system [225]; and reduced N applications maintained yields in an organic cauliflower and grass–legume mix system, minimizing the risks of leaching [201]; however, an organic strip intercropping system of faba bean and tomato did not provide consistent positive effects on tomato N uptake, as the N mineralization rates from the companion faba bean intercrop fluctuated throughout the experimental period [226].

Integrated crop–livestock systems have been an integral part of many traditional cropping systems around the world for thousands of years, improving the cycling and use of nutrients at the farm or landscape level [29,159,205,227]. For example, an early analysis of nutrient flow in traditional integrated systems followed in Jiangsu Province, China, showed that fish waste, from seven different species, provided over 25% of the crop N inputs, while pig waste supplied an additional 13% of the N input for crops and forage production, in addition to contributing to the soil organic matter content [227]. Aquaponic systems utilizing fish effluent as a nutrient source have been shown to improve crop growth and NUE, compared to other nutrient sources [228]. However, research in Alabama, USA, showed a greater NUE with the conventional fertilizer treatment, attributed to possible greater nitrification rates from the fish effluent, which indicated a need to better fine-tune their system [137]. Table 9 provides an overview of alternative diversification strategies and their effects on the N cycle [8].

5. Nitrogen x System Interactions That Affect NUE

The uptake, use efficiency and N cycle, is affected by myriad multi-level production, environmental, genetic, and ecophysiological interactions. The N uptake and use efficiency may be affected by variables such as the incident light level and shade adaptation [229], soil type and fertility, planting distance, crop variety, timing of application, cropping schemes, and management practices. The bulk of the research on N applications over the past 70 years focused on yield maximization based on vegetationally simplified agricultural systems, following a reductionist research approach. By focusing on a few variables and nutrient flows, the reductionist research approach highly simplified the analysis of the N cycle at the farm level. A challenge for future N cycle research following a holistic approach will be the incorporation of the many interaction effects into the model, especially when analyzing the N system flow under alternative and highly diversified production systems [8]. As such, new directions for research aim to better understand the ecophysiological basis of nutrient x cropping system x environmental interactions, often under diversified and chemical-free production systems. The goals of a more inclusive and comprehensive analysis of the N cycle on vegetable farms include minimizing environmental losses, improved NUE, and to establish more resilient systems that will be better adapted to the environmental fluctuations and extremes posed by the specter of climate change [8,29,230].

5.1. Water Use x N Interactions

Because of its solubility, transformation, and mobility of the various reactive N forms in the environment, water x N interactions are among the most important determinants of potential environmental losses and of its synchronization with crop uptake in the improvement of NUE. Crop N uptake is strongly affected by the soil water supply [43]. In general, as observed with potato, increased irrigation rates and N applications result in decreased water and NUE [231]. Excessive N application rates early in the growing season may result in considerable leaching losses from rainfall or surplus irrigation [69]; anaerobic conditions after heavy irrigation may lead to denitrification losses; and deficit soil moisture from droughts or uneven irrigation may restrict N uptake, resulting in lower crop yields or quality. Farmer education and management guidelines to improve both water use efficiency (WUE) and NUE are important, because as with the use of fertilizers, farmers tend to over-irrigate their crops, resulting in potential excess N losses [24,232]. Furthermore, improvements in WUE and NUE are often correlated variables that tend to result in high yields, as water mobilizes nitrate in the soil, making it available for crop uptake via mass flow and diffusion via transpiration [74,233].

To maintain crop productivity while minimizing losses, current research efforts aim to improve both water and N use efficiency [74]. The type of irrigation affects several production variables and N uptake dynamics. In potato, sprinkler irrigation improved marketable tuber quality by reducing water stress, lower soil temperatures, and improved N management, as compared to furrow irrigation [231]. Irrigation can also be employed in some cases to reduce ammonia N volatilization, such as when irrigating a field after an application urea, reducing losses by 65–95%, depending on the urea formulation [234].

^{15}N studies showed that crop NUE may be improved with the integrated timing and rates of both the irrigation supply and N applications, resulting in improved yields and lower N losses [77]. Tillage and organic amendment use practices may also have a positive impact on water use and NUE. A four-year experiment under rainfed agriculture showed that the combined practice of no-tillage and the application of organic amendments improved soil moisture conservation, resulting in equal or improved yields, and with increased water and NUE, as compared to conventional tillage and the use of chemical fertilizers [235]. Other management practices on the farm, related to the available soil moisture content, also affect the crop response to N applications. For example, under rainfed systems, the NUE is increased when basal N applications are made after the start of the rainy season has begun [236].

The determination of the appropriate irrigation and N application rates is an active field of research, such as for the production of high-value specialty crops, with the use of organic N sources, and under protected cultivation [237]. The more precise and timing application of N may increase its use efficiency [238], but the particular rates and practices may be cultivar and location specific [231]. Research in Ghana showed that weekly drip fertigation, as compared to sprinkler irrigation or two fertigation events, improved the NUE in okra [171]. To fine-tune a tomato fertigation program, research in Florida, USA, determined that a pre-plant basal N application representing 25% of the total application rates improved yields compared to a full fertigation program. Also, a partial deficit irrigation treatment, consisting of limited watering rates during the first 4 weeks of growth after transplanting, resulted in similar yields to those obtained under standard irrigation rates [239]. Research conducted with cucumber and tomatoes in Beijing, China, showed that limiting the irrigation rate by calibrating its application with the soil matric potential did not affect yields and improved the NUE when compared to the traditional and greater irrigation rates [240]. Conversely optimal yields with field-grown cucumbers grown in Egypt were obtained with a high irrigation rate, at 1.0 of crop evapotranspiration (ET), compared to lower ET levels, and with a combination of chemical and organic amendments at high N rates of 315 Kg Ha^{-1} [241].

Plastic and organic mulches may be used effectively to improve both water and NUE, along with other benefits to the production system, such as weed control [43,69]. An analysis on the effect of mulches on cereal crops showed that mulches overall increase WUE, especially under conditions of adequate fertilization [43]. A similar review of the cereal literature found that mulching increased NUE from 4–18%, compared to non-mulching treatments, especially in arid and semi-arid regions [43]. A study conducted in a rainfed arid region of central Mozambique found a differential effect in the response to organic mulch applications, depending on the soil moisture holding capacity of the soils. Crop residue applications increased the WUE and NUE in soils with a low water holding capacity, while these variables were reduced when residues with a high C/N ratio were applied on soils with a high water holding capacity, apparently fixing the available N for their microbial decomposition [242].

Vegetational diversification in time and space may be managed to improve soil water relations. Research indicates that the water use efficiency and corresponding NUE of some crops may be improved with crop rotations [243], including a reduction in nutrient losses [244]. Reflecting on the current international efforts to optimize water and N use, their interaction has been recently evaluated for broccoli [245]; cucumbers [246]; African eggplant (*Solanum aethiopicum* L.) [247]; onions [248,249]; and tomato [239] (Table 10).

Table 10. The effect of selected Nitrogen x water management interactions on Nitrogen Use Efficiency.

Interaction Variable	**Notes**	**References**
Crop responses to N x water interactions	Broccoli (tunnels), Cabbage; Greenhouse cucumbers; African eggplant (*Solanum aethiopicum* L,); Onions; tomato	[239,245–247,249,250]
Cultivar selection	Selection of early maturing cultivars during drought periods	[251]
Fertigation	Improved NUE	[24,171,238]
Irrigation system selection	Effect on moisture uniformity, WUE x N x yields	[231,249]
Irrigation rates and timing	Irrigation x N interaction	[239]
Organic Mulches	Reduced evapotranspiration and erosion; moderates soil temperature and moisture; N cycling	[43,242]
Plastic mulches	Reduced evapotranspiration and erosion; moderates soil temperature and moisture	[43,69]
Rotations	Water and NUE	[243,244]
Tillage	Moisture retention under no-till farming and NUE	[235]

5.2. Nutrients x N Interactions

Nitrogen interacts with other nutrients in a way that may impact competition for nutrient uptake, crop physiology, quality and yields, and NUE. In general, high soil N levels may have an adverse effect on the uptake of potassium (K), boron (B) and zinc (Zn), while high levels of K or magnesium (Mg) may reduce the uptake of N [252]. The type of N form has a differential effect on nutrient uptake. Under high NH_4^+ levels or NO_3^- deficiency, there is a reduced cation uptake of K, Mg, and Ca, while there is an increase in anion uptake of phosphorus (P), sulfur (S), and micronutrients, with the reverse observed under high NO_3^- levels [99,105]. While nutrient x nutrient interaction studies conducted in the greenhouse provide valuable insights, they should be treated with caution, as different responses may be observed under field conditions, and may vary to a degree by environment, soil type, and cultivar, among other possible variables.

Some crops, like cassava, require proportionately more K than N to maintain adequate yields, so low K levels often become the limiting nutrient factor to reach higher yields [88,253]. In this case, adequate levels of K will be required to optimize crop growth, yields, as well as NUE. In pepper, as observed with other Brassica and solanaceous crops, calcium uptake was reduced with incremental increases in NH_4^+ as the source of N, with yield reductions observed with NH_4^+/NO_3^- ratios greater than 50%. The lower fruit levels of Ca observed when NH_4^+ is the primary N source may also lead to a greater incidence of blossom-end rot in fruit vegetables, further reducing potential productivity and NUE [105,254]. Conversely, when supplemental Calcium was added to an NH_4^+-N source in greenhouse and field studies, NH_4^+ uptake was increased, resulting in greater top growth, root yields in radish, and NUE [255].

A greater response to phosphorus applications is observed when supplemental levels of N are provided, in N deficient soils [159,256,257]. Nitrogen may help to increase plant P levels by promoting root growth, improving uptake and translocation, and by increasing the soil pH to solubilize soil or P fertilizer [256]. For the production of celery transplants, an interaction was observed between N and P levels. Increased P levels of up to 125 ppm in the soil solution increased seedling growth only when N levels were above 250 ppm [258]. On a global scale, and as observed in Africa [257], an analysis of agricultural production on 113 countries found a close correlation between P use efficiency (PUE) and NUE, indicating that both nutrients, as well as the adoption of best nutrient management practices, are integral to maintain agricultural productivity [25].

Additional nutrient x N or NUE positive interactions have been observed for Selenium [259,260] and sulfur [261]. Other nutrients such as molybdenum and copper are involved in N metabolism [257], and their uptake may be affected by the soil pH, as affected by the prevailing N form in the soil [256].

5.3. Environmental Stress x N Interactions

Environmental stress has a strong impact on plant growth, photosynthetic assimilating area, shoot–root interactions, nutrient uptake, yields, and quality, and thus, it has a strong influence on NUE. Chlorophyll fluorescence has been used as a technique to evaluate the effect of environmental stress on the photosynthetic process. Because N is intricately involved in the photosynthetic process, chlorophyll fluorescence may serve as an early indicator of N x environmental stress interactions, including biotic and abiotic stress such from pests, nutrients, or water deficits [10,262,263]. For example, chlorophyll fluorescence may be used to identify germplasm with greater photosynthetic efficiency under temperature stress, which affects NUE, as heat stress disrupts nutrient uptake, leaf area duration, and both N metabolism and fixation [264].

While high ammonium levels are toxic to many plants, there is evidence indicating that at lower levels, it may allow plants to overcome periods of biotic or abiotic stress, including improved tolerance to salinity, with the production of bioactive compounds such as glucosinolates, and improved nutrient uptake via rhizosphere acidification [265]. While crop salinity adversely affects N uptake and metabolism, research indicates that modulation of N in the plant may help to overcome some of the effects of salt stress by either modifying N fertilizer practices, such as the form of N, or by selecting plants with an improved N metabolism. Some of the possible physiological mechanisms of N nutrition to ameliorate the impacts of salt stress include the up-regulation of salt stress-tolerant genes, activation of the antioxidant system, and synergistic hormonal interactions [266].

The potential effect of N nutrition to overcome periods of abiotic stress include tolerance to drought stress through an improved NUE, WUE, and osmoregulation [267,268]. Drought-tolerant tomato cultivars also have shown a greater N uptake than have drought-sensitive ones, allowing the plants to better maintain some physiological functions [126]. Nitric oxide has been found to be a mediator in the stress response to both drought and salinity stress, as a signaling molecule that enhances the activity of antioxidant defense mechanisms, moderating the plant water status and photosynthetic activity [269]. Mycorrhizal associations may also help to improve the plant's nutrient status and N uptake under stressful growing conditions, such as during exposure to ozone, or nutrient deficiency [270]. Nitrogen may also play a role in increasing the tolerance to high temperatures, as observed in cucumber. By playing a role in the regulation of the specific heat capacity and leaf water status, a higher N supply resulted in lower leaf temperatures through increased transpiration rates [271].

5.4. Pest x N Interactions

A balanced crop nutrition is considered a centerpiece of a pest management program [272]. Crop quality and yield losses caused by pests and weeds have a direct impact on NUE, resulting in direct economic losses for farmers. Nutrient management practices may be adjusted in terms of N form, rate, and timing of application to minimize the incidence and degree of losses from pest infestations or weed competition. By playing an integral role in the production of vegetative growth, in the plant's metabolism, and as a part of its defense system, the N plant status affects the plant's susceptibility or tolerance to pest infestations. Surplus N levels may trigger pest outbreaks, as pests and pathogens rely on N resources for their sustenance (e.g., amino acids), while N deficits may also make the plant more susceptible to infection by diseases or to competition from weeds [160,273] (Table 11). The common practice of over fertilizing and over watering also often results in succulent plant growth and in pest outbreaks [9]. As part of the nutrient management practices that are followed to minimize the incidence of pest outbreaks, other closely interlinked production factors need to be considered as part of the overall management strategy, such as germplasm selection, soil moisture, tillage, vegetational diversification, and landscape or area-wide design.

In general, high N rates are related with increased susceptibility to biotrophic pathogens that require live living host cells for their sustenance, and to a reduced susceptibility to necrotrophs, which feed on dead or dying cells [274]. While in general, a greater N/C ratio is more likely to result in pest outbreaks, N may also play a role in the plant's disease defense mechanism as it is a component of varied plant defense compounds, such as enzymes and proteins that are involved in the plant immune signaling cascade response mechanisms and resistance metabolic pathways [273–276].

Table 11. Effect of Nitrogen nutrition on selected plant pathogens.

Pathogen	Notes	References
Bacterial rots, *Pantonea* spp.; Bacterial blights, *Pseudomonas*	Low foliar N results in higher disease incidence, onion; celery	[152,277]
Damping-off, *Phytophthora*, *Pythium*, *Rhizoctonia* spp.	High N rates and planting density increase disease severity, eggplant, tomato; N stimulates plant defense compounds, potato	[275,278,279]
Early blight, *Alternaria solani*	N deficient tomato and potato plants are more susceptible; N stimulates plant defense compounds, potato, tomato	[272,275,280]
Foliar diseases, *Mycosphaerella*, *Diplocarpon* spp.	Increased incidence with high N during spring applications in strawberry	[281]
Fruit rots, *Botrytis*	High N spring applications increase disease incidence, strawberry	[282]
Fusarium wilt, *Fusarium* oxysporum	High N favors the disease, tomato; N stimulates plant defense compounds, tomato	[275,278]
Leaf spots, *Botrytis fabae* and rust (*Uromyces viciae-fabae*)	High N results in greater disease incidence on faba bean, *Vicia faba* L.	[283]
Soft rots, *Erwinia*, *Pseudomonas*, *Clostridium*	Excessive N may exacerbate the disease on vegetables, affecting fruits, tubers, roots, and foliage; N stimulates plant defense compounds, tomato	[275,278,284]
Storage diseases, *Aspergillus*; Bacterial soft rot, *Pseudomonas*, *Erwinia*, *Botrytis*	Increased incidence with excess N rates, onion	[81,285]
Physiological disorders	Increased incidence of sugar ends in potato with high N rates	[231]

Nitrogen fertilizer practices, especially under monoculture systems, also have an effect on arthropod population dynamics [2]. Higher population levels in response to high N fertilizer applications have been reported for important vegetable pests such as aphids, with differential effects on abundance, growth rates, timing of N applications, and abundance of natural enemy populations [150,286,287]; caterpillars [279,288]; higher numbers with high N rates, and lower tissue N levels found in leafhopper resistant okra varieties [279,289]; mites [279,290,291]; thrips, showing a greater feeding preference at higher N levels [70,152]; and increased numbers and fitness on whiteflies [292,293]. Greater pest numbers may also be observed in crops receiving chemical N sources, as compared to organic sources [294].

A number of management practices and variables affect the interaction between weed pressure, crop fertility, and NUE. Nitrogen contributes to vigorous top growth which can increase early competitiveness against weeds, reducing the length of the weed-free period required to maintain yield losses below economic injury levels [295]. Research conducted over several years on small farms in Zimbabwe showed that greater weed infestations resulted in a lower NUE, which could be improved with higher planting densities and improved weed management practices [296]. Research with peanuts conducted over two years in Egypt found an interaction between N fertilizer rates, the length of weed-free periods, and NUE. The highest N rate resulted in the greatest yields, increased weed pressure, but a lower seed oil content and a 50% lower NUE, compared to the lower N rates. Overall, increased weed pressure resulted in lower yields and a lower NUE. With respect to the weed-free periods (WFP), a lower NUE was observed with a WFP up to 6 weeks after emergence, with increasing NUE values obtained with longer weed-free periods. A higher NUE was also observed when the fields were allowed to remain weedy only up to the first 4 weeks after emergence, indicating that most of the competition for N likely occurred during the later stages of crop growth [297]. A weed-free period x N rate experiment conducted with tomatoes in Central Sulawesi, Indonesia also found a significant weed-free period x N rate interaction. The optimal N application rates to reach commercial yields decreased, as the length of the weed-free periods increased (from 0 to 8 weeks), while the greatest weed growth for each WFP was obtained with the higher N rates (of up to 150 Kg N Ha^{-1}), highlighting the importance of timely weed management to minimize the need for high N application rates [298].

Because weeds are often more competitive for N than crops, in well fertilized soils, several management strategies may be considered to improve the crop N competitiveness [299]. Management practices to reduce weed competition for N include proper placement, such as side-dressing applications vs. broadcasting; the timing of applications to better synchronize crop uptake demands; cultivar selection; and planting densities; as well as weed-management strategies such as mulching or crop rotations [299]. In organic systems where tillage is often practiced for weed control, it is important to consider the effect of tillage on potential soil N mineralization, which could result in environmental losses during periods of low N uptake demand [120]. Thus, the timing of tillage operations to reduce weed pressure below economic injury levels, and to better synchronize it with periods of higher N crop demand may minimize the potential of crop N losses from leaching or volatilization. Research conducted in Tehran, Iran, illustrates the need to recognize the important water x weed x N use interactions, when evaluating aspects of NUE, especially in semi-arid regions under irrigation. A two-year experiment with maize showed increased yield responses to N with a higher irrigation rate; greater N environmental losses with the highest N rate (450 Kg N Ha^{-1}); greater N losses under no weed pressure than in weedy plots; a greater NUE in treatments with a greater irrigation rate; a greater NUE at the lower N rates (150 Kg N Ha^{-1}) compared to the highest N rate; and a greater level of inputs in weedy plots resulted in proportionally greater yield losses, highlighting the need to use inputs moderately to optimize their use efficiency [300].

5.5. Soil Biota x N Interactions

As a driver of the N cycle, involved in the regulation of soil ecological functions, the soil biota and crop NUE are closely interlinked [8,190,204]. A diverse microbial community, involved in six distinct N transformation processes such as N mineralization, ammonification, and fixation, contribute to the N cycle and to the overall soil N pool. High chemical N fertilizer inputs, common in commercial operations, tend to decrease the soil microbial activity and diversity [43]. Current research efforts aim to identify nutrient and management practices, such as vegetational diversity, grazing, tillage, and the application of organic amendments, that reduce the reliance on chemical N inputs, reduce N losses, and improve the soil microbial activity, which has a positive impact on the system NUE [86,190,301].

Several alternative management practices may be followed to improve the soil fertility and microbial activity. A two-year greenhouse and field experiment conducted in Hokkaido, Japan, found a 47.5% increased lettuce NUE with rye (*Secale cereale*)/hairy vetch and 27% with sole hairy vetch cover crop rotations, compared to the controls. In terms of N, hairy vetch appeared to be the most valuable component of the cover crops, by increasing the concentration of soil inorganic N. Both cover crop treatments also had a greater microbial β-glucosidase enzyme (BG) activity, responsible for residues degradation, and a greater soil microbial biomass than the controls, indicating their possible role in improving N mineralization and NUE [216]. A similar stimulation of soil microbial and invertebrate activity from the use of legume–grass mixtures and non-legume cover crops on organic systems were reported from a six-year study with cool season vegetables in Salinas, California [302]. Organic mulches also help to improve microbial activity, with reported improvements of 42% in microbial biomass, compared to non-mulch treatments, resulting in improved soil quality and yields. A review of the literature indicated that in cereal crops, mulching increased NUE by 4–17% compared to non-mulched treatments, attributed primarily to an increased rhizosphere microbial activity [43]. Intercropping systems, given the differential root distribution and exudate pattern of the component intercrops, also have a positive impact on the diversity and activity of microbial activity, contributing to improved internal nutrient cycles and NUE [204].

Fungal mycorrhizae form symbiotic associations with crops, providing several benefits including overcoming periods of stress and improving nutrient uptake. Mycorrhizae may form synergistic associations with N-fixing rhizobia bacteria, resulting in increased N fixation rates [303]; N may be transported via mycorrhizal networks [304]; and N uptake and metabolism may improve during periods of stress [270,305], resulting in improved crop growth and improved N uptake, as observed under varied levels of stress with legumes, eggplant, and tomato [262,305,306].

Microbial inoculants, such as from *Bacillus*, *Pseudomonas*, *Streptomyces*, *Trichoderma*, and mycorrhizal species, are increasingly being used under commercial production, as biofertilizers or for plant growth promotion, which may have a positive effect on N uptake [307]. Plant growth-promoting bacterial inoculants that are applied in some commercial operations include from *Pseudomonads*, *Azoarcus*, *Beijerinckia*, and *Cyanobacteria* species. While research indicates that microbial inoculants, applied in consortia, may have growth-promoting effects, and may improve water use and nutrient uptake [308,309], further research is required to validate their effects under a varied set of production systems and environmental conditions [310].

Earthworms, among the most important soil invertebrates, are considered to be drivers of the global food system as soil ecological engineers, contributing to residue decomposition, soil structure, water conservation, soil microbial activity, and organic matter and nutrient cycling [311–313]. As decomposers of crop residues, earthworms help to release N for crop uptake, among other benefits, resulting in an estimated 23% increased top growth and 25% increased global crop yields, under conditions of no high external N inputs, highlighting their potential contribution to N uptake and NUE under low-input, subsistence, or organic systems [314]. A ^{15}N residue-labeled study evaluated the intricate interactions between earthworms, microbial activity, and mycorrhizae with respect to crop N uptake. Earthworms enhanced the residue decomposition by regulating soil microbial activity, and with the combined presence of *Glomus* mycorrhizae, this resulted in a synergistic effect, improving crop N uptake, from the residue-derived N mineralization [315].

6. Nitrogen Loss Management

Given the wider recognition about the environmental risks posed by reactive N forms in the environment, N fertilizer recommendations aim to maintain crop quality and productivity, while minimizing losses [36]. In commercial operations, it is estimated that farm losses represent up to 70% of the applied N fertilizer, and that these losses may be reduced by 15–30% by adopting improved management practices [41]. Studies with potato have reported total N losses of 35%, N leaching losses of 20–30%, up to 60% under excess irrigation, and <0.5% losses from volatilization [71,141]. In field-grown tomato, N losses reached almost 90% under high ^{15}N application rates, while in hydroponic tomatoes, N volatilization can reach up to 15% of the applied N [19,316]. Under chemical-free or organic farming conditions, asynchrony between the timing of N mineralization and crop uptake may result in N losses, such as in the case of early-season precipitation, as observed in sweet corn [8,188].

Mitigation strategies have been proposed to reduce N emissions, both from the manufacture of chemical fertilizers and by following best management practices that involve the proper N source, application rates, timing, and placement [4,317]. Solutions to address problems of N pollution are not only agronomic, but have a strong social component, based on the particular socioeconomic conditions of the production system. Thus, policy, economic, market, and structural barriers need to be identified to design educational and implementation programs that meet the needs of particular production regions [318,319].

Examples of management strategies to minimize losses by improving the N cycle on the farm [8] include developing a baseline crop N budget analysis [49,141]; proper irrigation rates, placement, and scheduling [232,250]; increased vegetational diversity [320]; conservation practices such as the planting of vegetative buffers [321]; slow-release fertilizers [73]; N fertigation, especially in arid regions [322]; and cover crops in the rotation, showing an average of a 63% reduction in nitrate leaching [323].

7. Conclusions

Nitrogen is the most limiting nutrient for the production of vegetable crops. Historically, farmers have applied high N rates to ensure adequate yields, resulting in significant economic and environmental losses, and possibly having adverse impacts on the long-term fertility of the soil.

Because the N cycle is affected by so many interacting system variables, an understanding of and predictions about its movement are highly location-, season-, and cropping system-specific. Thus, only broad generalizations can be currently made about its movement in the environment, based on general biophysical mechanisms and known microbial and chemical transformations. Because vegetable crops are considered specialty or minor crops that represent hundreds of species, individual species have historically received considerably less research attention compared to the major cereal staple crops, with respect to N fertilization practices. However, because vegetables are relatively high-value crops, often grown under capital and input-intensive systems, it is important to evaluate mitigation strategies to minimize potential impacts from the extensive use of N fertilizers.

The bulk of the N research conducted to date, with respect to crop production, has followed a factorial-based reductionist approach, evaluating the effect of single variables, such as N application rates, on the crop growth response to N applications. The reductionist approach to N research has revealed a partial mechanistic understanding about the N cycle such as the effect of the different chemical N forms, microbial–N interactions, and on the physiology of crop uptake. However, here we propose that a holistic perspective is required to obtain an understanding of the myriad multi-level cropping system, genetic, socioeconomic, environmental, and ecological interactions that affect the N cycle and NUE. A system-level analysis that considers all the key production variables involved is necessary to develop a holistic understanding of the underlying ecophysiological mechanisms that affects the N cycle and NUE on vegetable crops. A greater understanding of the important system level interactions that have an impact on NUE will allow for the design of improved management practices, in time and space, at both the farm and landscape level.

Steps to improve N use recommendations include developing a budget to estimate total N outputs minus inputs, based on realistic yield estimates. Diagnostic tools such as N tissue analysis are employed to fine-tune N recommendations. Best N management practices include adjustments to the total application rates, the timing, and the placement of application. Proposed agroecological practices to improve the NUE include the use of cover crops, rotations, alternative tillage, integrated crop–livestock systems, vegetational diversification, a greater reliance on organic amendments, and germplasm selection [8]. Proposed deterministic system-level interactions that may adversely impact NUE include water use x N, nutrient x nutrient, pest x N, soil biota x N, and abiotic plant stress x N interactions. The differential effect of these production interactions on NUE will be affected by the environmental, cropping system, and socioeconomic conditions.

Because vegetable crops are grown under such a wide range of cropping systems and environmental settings, the particular socioeconomic conditions should be considered to better formulate recommended practices to improve the system NUE. When considering the human-factor or local socioeconomic conditions, the level of complexity rises considerably when conducting research, outreach, or educational activities to improve the management of the N cycle on the farm, and agricultural productivity.

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