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# Nitrogen Management for High-Yield and High-Capsaicin Chili Production

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**Abstract** Chili pepper (*Capsicum* spp.) is an important economic crop, and its yield and capsaicin content are directly related to product quality and industrial value. Nitrogen is a key nutrient affecting chili growth, development, and secondary metabolism. Its application rate and form not only determine yield level, but also play a crucial role in regulating capsaicin synthesis. This paper systematically reviews the dynamics of nitrogen in chili cultivation systems, its uptake mechanisms, and its effects on plant growth, yield formation, and nitrogen use efficiency. It focuses on the metabolic pathways, key enzyme activities, and gene expression mechanisms involved in nitrogen-regulated capsaicin biosynthesis. Studies show that an appropriate nitrogen supply and a reasonable $NH_4^+$:$NO_3^-$ ratio can promote plant growth and increase yield while enhancing the accumulation of capsaicin and related metabolites. In contrast, both excessive and insufficient nitrogen disrupt the balance between yield and quality. In addition, practices such as integrated water–fertilizer management, controlled-release fertilizers, split application, and multi-nutrient coordinated management can improve nitrogen use efficiency and reduce environmental risks. In the future, combining precision agriculture technologies with genetic improvement strategies will help achieve coordinated development of high yield, high quality, and ecological sustainability in chili production.

**Keywords** Chili pepper; Nitrogen management; Capsaicin; Yield; Nitrogen use efficiency

## 1 Introduction

Chili pepper (*Capsicum* spp.) is an important vegetable and spice crop widely cultivated around the world. Its main characteristics include pungency, color, flavor, and health-promoting functions (Duranova et al., 2022). In addition to its traditional food value, chili has become a key raw material in multiple industries such as food, nutraceuticals, pharmaceuticals, and cosmetics. The demand for high yield and stable pungency is increasing.

Chili fruits are rich in various vitamins (A, C, E, B6, and K), minerals, carotenoids, flavonoids, polyphenols, and capsaicinoids, which give them high nutritional value and functional properties (Bal et al., 2022; Ali et al., 2025). Capsaicin, as the main capsaicinoid compound, is the primary source of pungency in chili and has a wide range of biological activities, including antioxidant, anti-inflammatory, analgesic, anti-obesity, antimicrobial, and anticancer effects. It also has positive effects on cardiovascular and metabolic health (Hernández-Pérez et al., 2020; Faisal and Mustafa, 2025).

In chili production, nitrogen supply level and its form affect leaf chlorophyll content, photosynthetic capacity, biomass accumulation, and fruit yield. However, excessive nitrogen may delay maturity, reduce pungency, lower quality, and increase the risk of environmental pollution. Optimizing nitrogen application has been shown to improve nitrogen use efficiency while maintaining or increasing yield and reducing resource waste (Zamljen et al., 2023). In addition to its effects on primary growth, nitrogen also regulates secondary metabolism. Nitrogen application rate and nitrogen form (ratio of ammonium to nitrate) can influence the content of capsaicin and dihydrocapsaicin, the activity of related enzymes (such as PAL and capsaicin synthase), and the expression of genes involved in capsaicinoid biosynthesis.

This study evaluates nitrogen management strategies for achieving both high yield and high capsaicin content in chili production. It focuses on the effects of nitrogen rate and nitrogen form on plant growth, yield, and capsaicinoid accumulation. The study explores how different nitrogen supply levels and nitrogen sources affect plant performance, capsaicin and related compounds, and key metabolic indicators. The objective is to provide practical agronomic recommendations to improve fertilizer use efficiency, support environmental sustainability, and meet the quality requirements of the chili food and pharmaceutical industries.

## 2 Nitrogen Dynamics in Chili Cultivation Systems

### 2.1 Forms of plant-available nitrogen ($NH_4^+$ and $NO_3^-$)

In chili cultivation, plant-available nitrogen mainly exists in the forms of ammonium nitrogen ($NH_4^+$) and nitrate nitrogen ($NO_3^-$). Both forms can support plant growth, but $NO_3^-$ is usually the main form absorbed by chili roots, especially in drip irrigation or fertigation systems where nitrification is active. Under these conditions, nitrate nitrogen has high mobility in the soil solution. In contrast, ammonium nitrogen has lower mobility and a shorter residence time; it can act as a direct nitrogen source and also as a substrate for nitrification (Ferrón-Carrillo et al., 2021).

The relative proportion of $NH_4^+$ and $NO_3^-$ in the rhizosphere is strongly influenced by several factors, including fertilizer type (such as urea, nitrate fertilizers, and ammonium fertilizers), application rate, soil adsorption properties, and irrigation method (Bharati et al., 2023). Compared with supplying nitrate alone, an appropriate $NH_4^+$:$NO_3^-$ ratio can promote root development, nitrogen accumulation, and improvement in fruit quality, including increased capsaicin content (Zhang et al., 2019).

### 2.2 Soil nitrogen transformation processes (mineralization, nitrification, denitrification)

Nitrogen transformation processes in soil determine the supply of $NH_4^+$ and $NO_3^-$ over time. Organic nitrogen from organic fertilizers, crop residues, and soil organic matter is converted into $NH_4^+$ through mineralization, which enriches the pool of plant-available nitrogen and supports a stable nitrogen supply under organic or integrated nutrient management systems (Horel et al., 2019; Mancinelli et al., 2019).

After that, $NH_4^+$ is oxidized into $NO_3^-$ through nitrification. This process is mediated by microorganisms and is most active under good aeration, suitable moisture, and near-neutral pH conditions. In chili systems, this explains why $NO_3^-$-N is dominant in the root zone and closely related to yield.

Under waterlogged or anaerobic conditions, $NO_3^-$ can be reduced to gaseous nitrogen forms ($N_2O$ and $N_2$) through denitrification, leading to nitrogen loss and reduced fertilizer efficiency (Das et al., 2024). Excessive nitrogen application and poor irrigation management can result in high accumulation of mineral nitrogen in soil, low plant uptake efficiency (about 10% of applied nitrogen), serious nitrate leaching, and large nitrogen losses from the soil–plant system.

### 2.3 Nitrogen uptake mechanisms in *Capsicum* species

Nitrogen uptake in *Capsicum* species depends on the coordination between root physiological functions and transport systems. Roots absorb $NH_4^+$ and $NO_3^-$ from the rhizosphere and redistribute nitrogen to aboveground parts and fruits. Root systems adjust their length, surface area, and branching according to nitrogen availability. Aerated drip irrigation can significantly increase root length and activity, thereby enhancing nitrogen uptake capacity, and this is positively correlated with chili yield.

Chili plants show clear patterns of nitrogen distribution, with total nitrogen mainly allocated to leaves, seeds, and reproductive organs. This provides a basis for capsaicin biosynthesis, which relies on amino acid precursors. Nitrogen uptake efficiency and internal utilization efficiency vary among cultivars and under different water–fertilizer combinations.

Studies using $^{15}N$ isotopes show that, with suitable cultivar and management matching, nitrogen use efficiency can remain relatively high even under low nitrogen or deficit irrigation conditions (Zamljen et al., 2022). Appropriate nitrogen levels and balanced $NH_4^+$:$NO_3^-$ ratios can increase total nitrogen accumulation in roots, stems, leaves, and fruits. They also enhance the activity of key enzymes such as glutamine synthetase (GS) and glutamate synthase (GOGAT), as well as the expression of nitrogen metabolism-related genes, which together promote yield formation and the synthesis of secondary metabolites.

### 2.4 Environmental factors affecting nitrogen availability

Environmental conditions and management practices play an important role in regulating nitrogen availability in chili fields. Soil pH, temperature, moisture, and electrical conductivity (EC) all influence microbial mineralization and nitrification processes, as well as the balance between $NH_4^+$ and $NO_3^-$ and nitrogen loss pathways (Abd-Hamid et al., 2023).

In organic curly chili production systems, mulching methods and weather factors significantly affect soil nitrogen content. Non-mulched and organic bamboo mulch treatments can maintain higher soil nitrogen levels, while plastic mulch tends to result in lower levels. At the same time, EC is a strong positive predictor of soil nitrogen, while lower pH and higher temperatures tend to reduce nitrogen availability (Wulan et al., 2025).

Irrigation methods influence nitrogen use by affecting soil aeration and nitrogen distribution. For example, aerated drip irrigation can improve the spatial uniformity of $NO_3^-$-N, enhance root activity, and increase nitrogen uptake. Compared with conventional drip irrigation, it significantly improves yield and fruit quality (Lei et al., 2024).

There is also an interaction between salinity and nitrogen application. A moderate increase in nitrogen can partly reduce the effects of salt stress, but excessive nitrogen application can increase soil salinity, which suppresses early plant growth and reduces yield (Yasuor et al., 2017).

## 3 Effects of Nitrogen on Chili Growth and Yield Formation

### 3.1 Effects on vegetative growth and biomass accumulation

Nitrogen significantly promotes the vegetative growth and dry matter accumulation of chili (*Capsicum*). With increasing nitrogen application, plant height, leaf number, branch number, leaf area, and aboveground biomass generally increase until reaching an optimal level. Beyond this level, excessive nitrogen may inhibit growth or cause toxicity symptoms (Da Silva et al., 2020; Mahmud et al., 2020; Nisa et al., 2024). Chili biomass assimilation is sensitive to nitrogen fertilization, and nitrogen supply affects total dry matter of shoots and fruits by regulating leaf area development. Integrated nutrient management and the use of organic fertilizers (such as farmyard manure, vermicompost, and poultry manure) combined with mineral nitrogen can further enhance vigorous vegetative growth. In contrast, insufficient or deficient nitrogen supply limits chlorophyll formation and canopy expansion (Biratu et al., 2021).

### 3.2 Effects on flowering, fruit set, and fruit development

Nitrogen supply plays an important role in reproductive development by regulating flowering intensity, fruit set, and fruit growth. Adequate nitrogen promotes early flower bud differentiation and increases the number of flowers, leading to higher fruit number per plant, greater fruit length, higher single fruit weight, and increased total yield. In chili and 'Anaheim' sweet pepper, higher nitrogen levels can promote early flower bud formation, but excessive or frequent nitrogen application reduces mature fruit yield and may even lead to early termination of the fruiting period (Payero et al., 1990). Excess nitrogen often stimulates excessive vegetative growth, suppresses assimilate allocation to reproductive growth, and results in lower fruit set and reduced yield, although plants appear vigorous. Appropriate nitrogen levels (e.g., 100~225 $kg{\cdot}N{\cdot}ha^{-1}$, depending on the cultivation system) improve fruit length, fruit number, and marketable yield, whereas nitrogen deficiency reduces flower number and fruit size (Timilsina and Khanal, 2024).

### 3.3 Nitrogen Use Efficiency (NUE) in chili production systems

Under conventional high nitrogen fertilization or fertigation conditions, nitrogen use efficiency (NUE) in chili is usually low. A large amount of nitrate nitrogen remains in the soil or substrate, while only a limited proportion is absorbed by plants and converted into biomass and fruits. In substrate cultivation and drip irrigation systems for sweet pepper, yield increases within a certain range as nitrogen application increases. However, when nitrogen input exceeds crop demand, NUE declines continuously and nitrate accumulation increases (Chemweno et al., 2025). Moderate nitrogen application combined with slight water deficit can improve NUE and water use efficiency without significantly reducing yield. Field experiments on processing chili and studies based on critical nitrogen dilution curves show that when the initial soil nitrogen level is high, a relatively low nitrogen rate (about

120 kg N ha⁻¹) is sufficient to maintain yield. This indicates that fertilizer input and nitrate leaching can be reduced while maintaining productivity (Tang et al., 2023) (Figure 1).

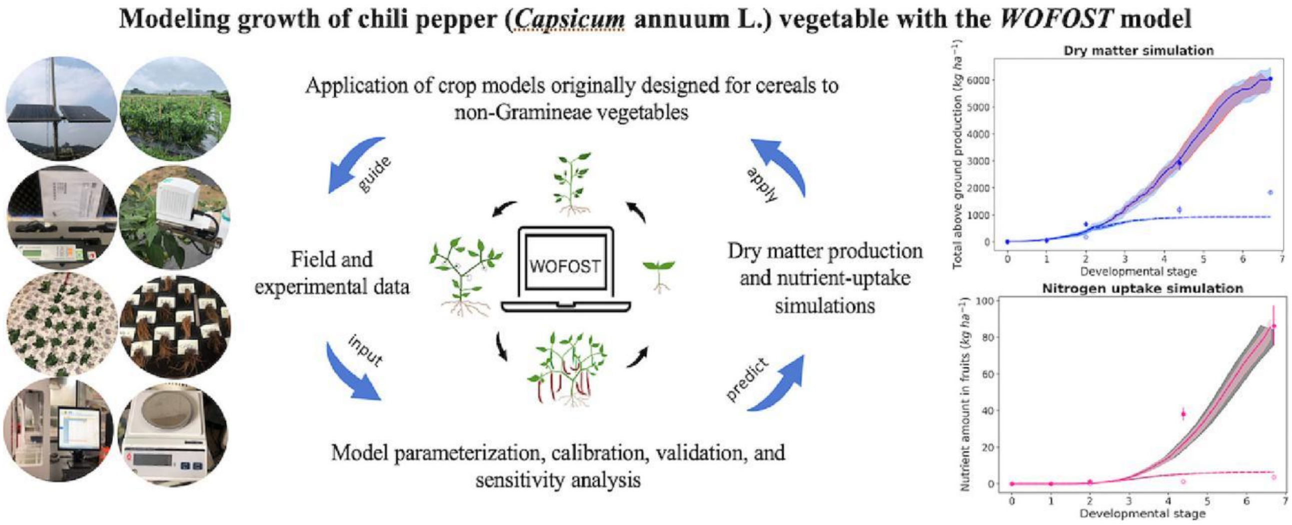

Figure 1 Growth simulation of chili pepper (*Capsicum annuum* L.) based on the WOFOST model and dynamic analysis of dry matter accumulation and nitrogen uptake (Adapted from Tang et al., 2023)

### 3.4 Yield response under different nitrogen application levels

The yield response of chili and sweet pepper to nitrogen typically follows a curvilinear pattern. As nitrogen application increases from zero to an optimal range, yield gradually increases; beyond this range, yield stabilizes or even declines. Field and pot experiments show that maximum or near-maximum yields can be achieved at 100~230 kg•N•ha⁻¹ for chili, 150~225 kg•N•ha⁻¹ for greenhouse sweet pepper, and about 120 kg•N•ha⁻¹ for open-field processing chili. Further increases in nitrogen application do not result in additional yield gains (Han et al., 2021; Subedi et al., 2023). Excessive nitrogen application (>230~300 kg•N•ha⁻¹ or high-concentration nutrient solutions) can reduce yield, shorten the fruiting period, or cause leaf toxicity, indicating that excess nitrogen is not only agronomically inefficient but also environmentally harmful. Results based on the WOFOST-Chili model and multi-objective optimization of water and nitrogen show that extremely high nitrogen levels cannot simultaneously achieve maximum yield, highest NUE, and optimal environmental benefits. Instead, moderate nitrogen application represents the best compromise for high-yield chili production (Vadillo et al., 2024).

## 4 Regulation of Capsaicin Biosynthesis by Nitrogen

### 4.1 Overview of capsaicin biosynthetic pathways

Capsaicin biosynthesis originates from the convergence of two metabolic pathways. One is the phenylpropanoid pathway, which provides the aromatic structural unit vanillylamine derived from phenylalanine. The other is the branched-chain fatty acid pathway, which supplies the C9 acyl group from valine or leucine.

In the phenylpropanoid pathway, phenylalanine is first deaminated to form cinnamic acid, which is further converted into ferulic acid derivatives, and then into vanillin and vanillylamine. At the same time, branched-chain amino acids are converted into fatty acid CoA thioesters. The final step is an acylation reaction, in which an acyltransferase links vanillylamine with fatty acyl-CoA to form capsaicin and related capsaicinoids. This process mainly occurs in the placenta tissue of the fruit.

### 4.2 Key enzymes and genes involved in capsaicin synthesis

During capsaicin biosynthesis, the key enzymes include phenylalanine ammonia-lyase (PAL), cinnamate 4-hydroxylase (C4H), 4-coumarate CoA ligase (4CL), hydroxycinnamoyl transferase (HCT), and caffeoyl-CoA O-methyltransferase (COMT) in the phenylpropanoid branch, as well as branched-chain amino acid aminotransferase (BCAT), ketoacyl synthase (KAS), and acyl-CoA ligase (ACL) in the fatty acid branch (Kabita et al., 2019).

The BAHD family acyltransferase encoded by Pun1/AT3 catalyzes the final condensation reaction and is a key factor in pungency formation. Loss-of-function alleles of this gene result in the absence of capsaicin production (Egan et al., 2019). The putative aminotransferase pAMT is responsible for providing vanillylamine and shows strong developmental stage and tissue-specific regulation.

In extremely pungent cultivars, genes such as Pun1, pAMT, KAS, and BCAT are upregulated in both placenta and pericarp tissues, significantly increasing capsaicin content in the whole fruit. The transcription factor MYB31 (Cap1/Pun3) acts as a master regulator that activates genes involved in capsaicin biosynthesis and is an important genetic basis for extreme pungency in C. chinense (Zhu et al., 2019).

### 4.3 Effects of nitrogen levels on capsaicin accumulation

Nitrogen supply influences the capsaicin biosynthetic pathway by regulating precursor availability, enzyme activity, and gene expression. Moderate nitrogen application can increase total phenolic compounds (precursors), enhance the activity of PAL and capsaicin synthase, and upregulate the expression of genes such as PAL, AT3 (Pun1), 4CL, C4H, COMT, pAMT, and HCT, thereby achieving the highest capsaicin content.

In contrast, both low and excessive nitrogen levels reduce PAL activity, precursor content, and related gene expression, while increasing the activity of competing phenolic pathways and degradation enzymes such as peroxidase (POD) and polyphenol oxidase (PPO).

Similar results have been observed in hydroponically grown C. frutescens. As the nutrient solution (nitrogen) concentration increases, capsaicin content first rises to an optimal range but decreases beyond this point, indicating that excessive nitrogen may cause toxicity or shift metabolism toward basic growth processes (Rahim et al., 2024).

In habanero pepper, capsaicin content is highest under nitrogen stress, decreases significantly after a small nitrogen supply, and increases again at higher nitrogen levels, suggesting a complex nonlinear response to nitrogen (Medina-Lara et al., 2008). Proper NPK or organic nitrogen management can simultaneously improve yield and capsaicin/dihydrocapsaicin content, although the effects depend on cultivar differences (Hammam et al., 2020; Stan et al., 2021) (Table 1).

### 4.4 Trade-off between yield and capsaicin content

Nitrogen creates a trade-off relationship among vegetative growth, yield, and capsaicin accumulation, rather than a simple opposition. Moderate nitrogen application usually promotes fruit size, placenta development, and yield, while maintaining relatively high capsaicin levels. For example, applying 562.5 kg/ha urea or using a moderate EC level of AB fertilizer can achieve this balance (Rahim et al., 2024).

Excessive nitrogen tends to stimulate vegetative growth and fruit development, but may reduce capsaicin content due to dilution effects, decreased PAL and capsaicin synthase activity, or increased allocation of metabolites to competing phenolic and lignin pathways.

On the other hand, severe nitrogen limitation can induce higher capsaicin accumulation in some genotypes, but this is usually accompanied by reduced yield. By optimizing nitrogen application rates and maintaining balanced nutrient management (including moderate deficit fertilization in some highly pungent cultivars), it is possible to maintain or even increase capsaicin content without significant yield loss.

## 5 Nitrogen Management Strategies for Optimizing Yield and Quality

### 5.1 Optimal nitrogen application rate and timing

Chili yield and capsaicinoid content show a curvilinear response to nitrogen (N) application, with the optimal level clearly lower than the excessive rates commonly used in practice. In open-field sweet pepper production, the highest yield was obtained at 153~230 kg•N•ha$^{-1}$. In coastal regions of Bangladesh, 116 kg•N•ha$^{-1}$ was identified as the optimal rate, and no further yield increase was observed at 145 kg•N•ha$^{-1}$ (Nahida et al., 2024).

Table 1 Interaction between cultivar and fertilization on capsaicinoid content and Scoville scale (Adopted from Stan et al., 2021)

| Treatment | Capsaicin (C) (mg·g$^{-1}$ d.w.) | Dyhidrocapsaicin (DhC) (mg·g$^{-1}$ d.w.) | Ratio C/DhC | Capsaicinoids (mg·g$^{-1}$ d.w.) | Scoville Heat Units (SHU) |
|---|---|---|---|---|---|
| De Cayenne×Ch | 0.69 ± 0.04 b | 0.37 ± 0.01 bc | 1.86 ± 0.06 cdefgh | 1.06 ± 0.06 c | 17066 ± 886.72 c |
| De Cayenne × O + Ch | 0.39 ± 0.02 fghi | 0.28 ± 0.02 def | 1.40 ± 0.11 hi | 0.67 ± 0.02 hi | 10787 ± 245.93 hi |
| De Cayenne × O | 0.47 ± 0.03 def | 0.23 ± 0.01 fgh | 2.05 ± 0.16 cde | 0.70 ± 0.03 ghi | 11270 ± 491.86 ghi |
| De Cayenne × Ct | 0.52 ± 0.02 cd | 0.33 ± 0.01 cd | 1.58 ± 0.05 efghi | 0.85 ± 0.03 ef | 13685 ± 483.00 ef |
| Traian 2 × Ch | 0.56 ± 0.02 c | 0.41 ± 0.01 b | 1.37 ± 0.03 i | 0.97 ± 0.03 cd | 15617 ± 464.77 cd |
| Traian 2 × O + Ch | 0.34 ± 0.01 ghij | 0.16 ± 0.01 ijk | 2.13 ± 0.07 bc | 0.50 ± 0.02 jk | 8050 ± 245.93 jk |
| Traian 2 × O | 0.35 ± 0.01 ghij | 0.26 ± 0.01 efg | 1.35 ± 0.04 i | 0.61 ± 0.02 ij | 9821 ± 278.86 ij |
| Traian 2 × Ct | 0.41 ± 0.02 efgh | 0.29 ± 0.01 def | 1.42 ± 0.07 ghi | 0.7 ± 0.02 ghi | 11270 ± 245.93 ghi |
| Turkish × Ch | 0.33 ± 0.01 hij | 0.13 ± 0.01 jk | 2.55 ± 0.16 ab | 0.46 ± 0 k | 7406 ± 0.00 k |
| Turkish × O + Ch | 0.27 ± 0.01 j | 0.13 ± 0.01 jk | 2.09 ± 0.12 bcd | 0.40 ± 0.01 k | 6440 ± 92.95 k |
| Turkish × O | 0.29 ± 0.01 j | 0.11 ± 0.01 k | 2.65 ± 0.12 a | 0.40 ± 0.01 k | 6440 ± 161.00 k |
| Turkish × Ct | 0.32 ± 0.01 ij | 0.19 ± 0.01 hij | 1.69 ± 0.07 cdefghi | 0.51 ± 0.02 jk | 8211 ± 245.93 jk |
| Sigaretta × Ch | 0.31 ± 0.01 ij | 0.19 ± 0.02 hij | 1.66 ± 0.17 cdefghi | 0.50 ± 0.01 jk | 8050 ± 185.91 jk |
| Sigaretta × O + Ch | 0.42 ± 0.02 efg | 0.21 ± 0.02 ghi | 2.02 ± 0.12 cdef | 0.63 ± 0.04 i | 10143 ± 580.49 i |
| Sigaretta × O | 0.39 ± 0.01 fghi | 0.24 ± 0.01 fgh | 1.63 ± 0.07 defghi | 0.63 ± 0.02 i | 10143 ± 245.93 i |
| Sigaretta × Ct | 0.49 ± 0.01 cde | 0.26 ± 0.01 efg | 1.89 ± 0.08 cdefg | 0.75 ± 0.02 fgh | 12075 ± 245.93 fgh |
| Jovial × Ch | 0.83 ± 0.01 a | 0.53 ± 0.02 a | 1.57 ± 0.06 efghi | 1.36 ± 0.02 a | 21896 ± 371.81 a |
| Jovial × O + Ch | 0.76 ± 0.01 ab | 0.48 ± 0.02 a | 1.59 ± 0.05 efghi | 1.24 ± 0.02 b | 19964 ± 278.86 b |
| Jovial × O | 0.45 ± 0.02 def | 0.32 ± 0.01 cde | 1.41 ± 0.04 hi | 0.77 ± 0.02 fgh | 12397 ± 371.81 fgh |
| Jovial × Ct | 0.57 ± 0.01 c | 0.37 ± 0.01 bc | 1.54 ± 0.01 ghi | 0.94 ± 0.01 de | 15134 ± 185.91 de |
| Chorbadjiiski × Ch | 0.52 ± 0.01 cd | 0.33 ± 0.01 cd | 1.58 ± 0.02 efghi | 0.85 ± 0.02 ef | 13685 ± 245.93 ef |
| Chorbadjiiski × O + Ch | 0.42 ± 0.01 efg | 0.27 ± 0.01 defg | 1.56 ± 0.02 fghi | 0.69 ± 0.02 ghi | 11109 ± 245.93 ghi |
| Chorbadjiiski × O | 0.44 ± 0.01 def | 0.24 ± 0.02 fgh | 1.85 ± 0.1 cdefgh | 0.68 ± 0.02 hi | 10948 ± 322.00 hi |
| Chorbadjiiski × Ct | 0.49 ± 0.01 cde | 0.31 ± 0.01 cde | 1.58 ± 0.01 efghi | 0.80 ± 0.01 fg | 12880 ± 185.91 fg |

Note: Ch—Chemical; O + Ch—Organic + Chemical; O—Organic; Ct—Control. Along each line, values followed by different letters are significantly different according to the Tukey's test at $p \leq 0.05$; d.w.—dry matter

Greenhouse experiments showed that moderately reducing nutrient solution supply by 20%~40% during the 6 days before harvest could improve nitrogen recovery efficiency and increase capsaicinoid and flavor compound content, while maintaining yield (Wang et al., 2022).

### 5.2 Split application versus basal application

Split nitrogen application helps synchronize fertilizer supply with crop uptake, reduces leaching losses, and often maintains or even increases yield at equal or lower nitrogen levels. Under saline-alkaline conditions, applying 150 kg•N•ha$^{-1}$ (N150) as ammonium nitrate through multiple fertigation events at key stages (vegetative growth, flowering, and harvesting) significantly improved plant growth, fruit number, and capsaicin content, especially when combined with effective microorganisms (Abdelkhalik et al., 2023).

In chili cultivation with polyethylene mulching in Indonesia, both split soil fertilization and drip fertigation performed better than single basal application, resulting in higher total and marketable yields (Susila and Oktavia, 2020).

Field studies comparing different fertilizer ratios (basal:topdressing = 100:0, 50:50, 30:70) showed that the 50:50 treatment, combined with livestock manure and chemical fertilizers, improved nitrogen use efficiency (NUE) while maintaining yield. In contrast, excessive basal nitrogen (100:0) increased early soil nitrate levels but did not improve yield (Lee et al., 2022).

### 5.3 Controlled-release fertilizers and fertigation technology

In systems without drip irrigation, controlled-release nitrogen fertilizers can partly replace the effect of split applications. In mulched sweet pepper production, pre-plant application of sulfur-coated urea and polymer-coated urea (90~180 kg•N•ha$^{-1}$) produced yields comparable to or higher than those achieved with 12 weekly fertigation events, with higher NUE at lower nitrogen rates, especially in coarse sandy soils (Reyes et al., 2008).

In fertigation-based chili production, appropriate fertilization intervals and frequency (e.g., every 3 days, 1~3 times per day) can promote plant growth and increase fruit number, although the effect on individual fruit weight is relatively small (Padmini et al., 2023).

Open-field studies indicate that optimizing the ratio between basal fertilizer and fertigation—by combining slow-release fertilizers or organic-inorganic compound fertilizers with partial fertigation—can maintain yield while reducing soil nitrate accumulation. In addition, short-term reduction of water and fertilizer supply before harvest can improve fruit quality and nutrient harvest index without reducing yield.

### 5.4 Synergistic management with other nutrients (P, K, and micronutrients)

Proper nitrogen management needs to be coordinated with phosphorus (P), potassium (K), and micronutrients to fully realize yield potential and capsaicinoid accumulation. Application of 75%~100% recommended NPK fertilizer significantly enhanced vegetative growth, yield components, and capsaicin content. The best performance was observed with 100% NPK combined with nano-micronutrients (Fe, Zn, B, Mn, Cu, Mo), which produced significantly higher yield and capsaicin content than the unfertilized control (Ahmed and Abdelkader, 2020).

In semi-arid sandy soils, combining soil fertilization with foliar application (e.g., 50% soil + 50% foliar) significantly increased leaf area, fruit number, fruit weight, and plant NPK nutritional status compared to soil fertilization alone (Hemida et al., 2023).

Compared with unfertilized treatments, integrated use of chemical and organic fertilizers in an NPK system significantly improved yield and capsaicin content, although responses varied among cultivars. Under low phosphorus conditions, mycorrhizal inoculation enhanced N, P, K, and capsaicin content in chili fruits, indicating that proper phosphorus supply and microbial symbiosis can work together with nitrogen to improve pungency and nutritional quality.

Furthermore, an appropriate $NH_4^+$:$NO_3^-$ ratio (25:75) increased N, P, and K accumulation and capsaicin content by upregulating the GS/GOGAT pathway and genes related to capsaicin biosynthesis (Zhang et al., 2020).

## 6 Case Studies

### 6.1 High-yield chili production systems under optimized nitrogen input

Studies in both greenhouse and open-field chili production systems show that high yield does not depend on excessive fertilization, but on moderate and well-matched nitrogen application. In northwest China, sweet pepper grown under drip fertigation achieved the highest or near-highest yield when nitrogen was applied at 150~190 $kg{\bullet}N{\bullet}ha^{-1}$ combined with 75%~80% ETc. At the same time, fruit quality remained good, and water and nitrogen use efficiency were significantly improved compared with higher nitrogen and irrigation levels (Xiang et al., 2018).

In subtropical monsoon regions, when soil moisture is maintained at 65%~80% of field capacity and nitrogen is applied at 6 g/plant, green pepper yield can reach about 580~620 g/plant. A slightly lower nitrogen level (3 g/plant) results in the highest water use efficiency (WUE) and nitrogen use efficiency (NUE) (Dai et al., 2022).

By optimizing nitrogen rates and combining them with controlled-release fertilizers or nitrification inhibitors, integrated nitrogen management can further increase yield and nitrogen recovery in open-field chili production. At the same time, nitrogen input can be reduced by about 38% compared with conventional farmer practices (Ma et al., 2022).

### 6.2 Strategies to improve capsaicin content in specialty chili cultivars

For high-pungency dried chili, a medium urea rate (562.5 kg/ha) can produce the highest capsaicinoid content and yield. This is mainly due to increased placenta biomass, higher total phenol content, enhanced activity of PAL and capsaicin synthase, and upregulation of genes related to capsaicinoid biosynthesis, while the activity of degradation enzymes is reduced (Zhang et al., 2024).

In the cultivar “Longjiao No. 5”, adjusting the $NH_4^+$:$NO_3^-$ ratio to 25:75 increases capsaicin and dihydrocapsaicin content in the placenta. It also enhances GS/GOGAT enzyme activity and related gene expression, and promotes fruit weight gain (Zhang et al., 2020).

Under low-phosphorus soil conditions, inoculation with mycorrhizal fungi improves the uptake of nitrogen, phosphorus, and potassium, and increases capsaicin content in chili fruits. This provides an effective way to achieve high pungency and high mineral nutrition with lower input (Pereira et al., 2024).

Comparisons between greenhouse and open-field cultivation show that the local piquín variety has significantly higher pungency under greenhouse conditions, indicating that controlled environments play an important role in enhancing capsaicin potential (Díaz-Sánchez et al., 2021).

### 6.3 Comparative analysis of conventional and precision nitrogen management

Precision water and nitrogen management performs better than traditional high-input and fixed nitrogen application systems in terms of resource use efficiency and environmental outcomes, while maintaining yield.

In greenhouse sweet pepper, long-term drip fertigation experiments show that moderate water and nitrogen combinations (such as 75%~90% ETc and 150~225 $kg{\bullet}N{\bullet}ha^{-1}$) significantly improve yield, water use efficiency (WUE), and nitrogen partial factor productivity compared with the conventional treatment of 105% ETc and 300 $kg{\bullet}N{\bullet}ha^{-1}$ (Wang et al., 2022).

A “prescription-adjustment” fertilization system based on crop evapotranspiration (ETc), nitrogen uptake models, and soil $NO_3^-$ monitoring can reduce irrigation by 17% and nitrogen input by 35% without reducing yield. At the same time, nitrate leaching is reduced by about 58% compared with conventional management (Granados et al., 2013).

## 7 Challenges and Future Perspectives

### 7.1 Environmental issues (nitrogen leaching and greenhouse gas emissions)

In intensive chili production systems, nitrogen fertilizer is often applied far beyond the actual crop demand, which leads to increased nitrate leaching and $N_2O$ emissions. Evaluations in Southwest China show that chili production has higher global warming potential, eutrophication potential, and acidification potential compared with other vegetable systems. This is mainly related to excessive nitrogen application and low nitrogen use efficiency (NUE). In subtropical chili systems, $N_2O$ emissions increase exponentially with nitrogen input. An application rate of 150 $kg{\bullet}N{\bullet}ha^{-1}$ can significantly increase yield, while emissions per unit yield are much lower than at 450 $kg{\bullet}N{\bullet}ha^{-1}$ (Zhao et al., 2020). In addition, the use of controlled-release fertilizers and high-efficiency fertilizers can reduce $N_2O$ emissions by 30%~50% while maintaining or even increasing yield (Zhang et al., 2023; Baek et al., 2024).

### 7.2 Balancing yield and quality in intensive systems

One key challenge is to avoid the trade-off between high yield and high capsaicin content. Moderate nitrogen levels (e.g., about 562.5 $kg{\bullet}urea{\bullet}ha^{-1}$ for dry chili, and 153~230 $kg{\bullet}N{\bullet}ha^{-1}$ for fresh chili) can maximize both yield and capsaicin content. Both nitrogen deficiency and excess can reduce pungency or limit plant growth. A slight reduction in nutrient supply before harvest can maintain stable yield while increasing capsaicin and flavor compounds, and also improve fertilizer use efficiency. The “high yield-high NUE” model, with slightly lower nitrogen and phosphorus inputs but higher potassium input, achieved a 35% yield increase and significantly reduced environmental impacts (Wang et al., 2018).

### 7.3 Advances in precision agriculture and smart fertilization technologies

Sensor-based irrigation–fertilization integrated systems and decision support tools are gradually being applied in chili production to achieve precise nitrogen management. Automated water and fertilizer management driven by soil moisture, using 75% of field capacity combined with 125% of the recommended nitrogen rate, significantly improved yield and nutrient use efficiency compared with conventional management (Ningoji et al., 2024). In addition, region-specific recommendation tools (such as Ferads), combined with automated fertilization systems, can produce near-quadratic yield responses. In some cultivars, fertilizer recommendations can be reduced to about 70%~79% without affecting yield (Susila and Suketi, 2023).

### 7.4 Genetic improvement of nitrogen use efficiency and capsaicin synthesis

Genotypic variation provides a long-term solution for maintaining pungency under reduced nitrogen input. Transcriptome analysis under low-nitrogen conditions shows clear differences between tolerant and sensitive chili genotypes in nitrogen-responsive genes. These genes are involved in photosynthesis, protein metabolism, secondary metabolism, and stress responses, and they are important targets for improving NUE (Wang et al., 2021). In terms of quality, key genes regulating capsaicin biosynthesis and their metabolic pathways (such as AT3/Pun1 and GS/GOGAT-related pathways) respond to nitrogen form and application level. This creates the possibility of breeding or engineering varieties that maintain high capsaicin synthesis under moderate nitrogen conditions. More broadly, biotechnological approaches even consider transferring the capsaicin biosynthesis pathway into other species, highlighting the potential of metabolic engineering to stabilize pungency under different environmental conditions.

## Author Contributions

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## Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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