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•N•ha^{-1} can significantly increase yield, while emissions per unit yield are much lower than at 450 kg•N•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•urea•ha^{-1} for dry chili, and 153~230 kg•N•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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