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.