Macronutrient deficiency mechanisms

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***Abstract*—Macronutrient deficiency is a physiological failure arising when nutrient availability cannot meet plant demand. It is not adequately characterised by leaf colour alone because root-zone chemistry, nutrient acquisition, internal redistribution and developmental stage jointly determine plant responses. This paper synthesises evidence on why shortages of different macronutrients produce distinct physiological effects and symptom patterns. Root-zone pH, substrate properties and plant roots influence nutrient uptake, while phloem mobility and remobilisation influence whether symptoms emerge in older or younger foliage. Controlled nutrient-omission evidence demonstrates effects on growth, yield and visible symptoms, but also identifies substantial variation among crops and conditions. The synthesis concludes that symptom location is useful evidence of nutrient allocation, but visual diagnosis requires corroboration from root-zone conditions, plant development and alternative explanations for impaired nutrition.**

I. Introduction

Macronutrient deficiency occurs when an essential mineral nutrient cannot be acquired in sufficient quantity to support plant function and development. Functional availability depends on more than the amount of nutrient introduced to the growing medium. Soil pH, organic matter, cation exchange capacity, root activity and rhizosphere processes influence nutrient accessibility and movement towards roots. A plant can consequently experience deficiency where fertiliser is present but root-zone conditions restrict uptake. This mechanism distinguishes an external nutrient supply from the nutrient availability that ultimately supports plant physiology [1].

Symptoms differ because plant tissues do not have equal access to internally available nutrients. Controlled nutrient-deficiency treatments associate lower-canopy symptoms with nutrients that can be redistributed from older foliage, whereas upper-canopy symptoms are associated with nutrients that are less readily relocated. Symptom position therefore reflects competition between established leaves and developing organs under nutrient limitation. It is valuable mechanistic evidence, but it cannot identify a deficiency independently because crop identity, developmental stage and growing conditions can alter visible expression [2].

This paper explains macronutrient deficiencies as mechanism-based disruptions rather than fixed visual categories. It considers the route from root-zone availability to nutrient acquisition, then examines internal mobility, remobilisation and the limits of visual interpretation. The central argument is that shortage effects depend on nutrient function, mobility, developmental stage and severity. A defensible diagnosis must therefore connect symptoms with the processes that caused them, rather than treating colour patterns as complete evidence [2].

II. Background and Scope

Controlled omission studies establish that deficiencies of nitrogen, phosphorus, potassium, calcium, magnesium and sulphur can alter growth, yield and visible condition. Their strength is causal clarity because a particular nutrient is deliberately withheld while plant responses are observed. These experiments demonstrate that nutrient shortage affects production and plant function, not merely appearance. However, observations from a specific crop and cultivation environment cannot become universal symptom rules. Plant species, cultivar and growth conditions remain important limits on the transferability of visual descriptions [2].

Diagnostic approaches based on plant appearance, pH, electrical conductivity and classification models can identify conditions associated with nutrient disorders. However, pH and electrical conductivity describe aspects of the root environment rather than the complete physiological pathway from supply to symptom. Classification evidence also records confusion between nutrient-deficient, healthy and diseased plants. A visible pattern can therefore be compatible with nutrient shortage without proving it. The explanatory gap is the need to relate observed symptoms to nutrient availability, root acquisition and internal transport [3].

Senescence illustrates why development matters. During deficiency, nitrogen, phosphorus, potassium, sulphur and magnesium can be remobilised from leaves. This alters nutrient status in source leaves and in tissues receiving redistributed nutrients. Deficiency expression is consequently shaped by the plant's allocation response as well as by external supply. This paper focuses on the physiological links among nutrient function, root-zone availability and internal redistribution, rather than proposing a universal catalogue of foliage symptoms [4].

III. Core Concepts and Mechanisms

Phloem mobility connects nutrient shortage with symptom location. A mobile nutrient can be withdrawn from older leaves and directed to actively developing tissues when external supply is inadequate. Older foliage may then become deficient first because it contributes to the internal nutrient pool. Conversely, limited remobilisation can expose developing tissues more directly to shortage. This mechanism explains why deficiencies may occur in different canopy positions, but it also shows why position should be interpreted with

developmental demand and root-zone information, not as a stand-alone diagnostic rule [4].

Nutrient imbalance can produce deficient function even where a nutrient solution appears generally adequate. Hydroponic nutrient-management research relates nutrient solution composition, ion imbalance, deficiency and nitrogen-use mechanisms. Electrical conductivity is useful as an indicator of total ionic conditions, yet it cannot determine the concentration or availability of individual nutrients. The implication is that a single aggregate measurement may identify a problem without resolving which nutrient is limiting or whether nutrient proportions are contributing to impaired uptake [5].

Root acquisition precedes visible canopy expression. Root hairs contribute to nutrient acquisition at the root surface, and evidence concerning phosphorus and iron deficiency links root-hair function with plant responses to limited nutrient availability. Although this evidence does not provide a full macronutrient symptom framework, it demonstrates that deficiency is partly mediated by root processes. Foliar symptoms may therefore be delayed outcomes of a constraint that begins at the root interface. Interpretation should include root function as well as foliage condition [6].

IV. Evidence Synthesis

Taken together, the evidence describes a pathway from root-zone conditions to canopy symptoms. Root hairs influence nutrient acquisition, while remobilisation governs how internally available nutrients are allocated during shortage. These processes can delay symptoms, change their position or alter their severity as developmental demand changes. Two plants with comparable external supplies may therefore show different visible responses where their stage of development or capacity for nutrient redistribution differs. Deficiency patterns are plant responses to nutrient limitation, not simple reflections of the composition of the growing medium [4], [6].

Crop and production-system conditions complicate that pathway. Hydroponic evidence identifies pH, electrical conductivity, disease and substrate conditions as factors that can affect plant responses, while offering limited direct symptom comparison across crops. This means that a visible disorder may arise from inadequate nutrient supply, impaired root performance or another stress condition with similar signs. The appropriate use of symptoms is therefore investigative rather than conclusive: they should trigger assessment of root-zone conditions and plant development rather than immediate attribution to one nutrient [7].

Substrate characteristics can affect nutrient availability before nutrients enter the plant. Evidence on growing media addresses substrate properties and nutrient immobilisation, although it only indirectly supports tissue-level deficiency physiology. Its relevance is that deficient uptake may occur when the root environment limits the accessible nutrient pool despite an intended nutrient regime. This reinforces the distinction between supply and functional availability. Any diagnosis based only on foliage risks overlooking the substrate-mediated conditions that affect nutrient movement and acquisition [8].

V. Practical Implications and Limitations

pH and electrical conductivity can support deficiency prediction, but neither indicator directly explains nutrient mobility or canopy symptom location. A root-zone measurement can indicate conditions that may constrain availability, yet it cannot show how nutrients are subsequently allocated among leaves and developing organs. Practical assessment should combine pH and electrical conductivity with observations of crop stage, symptom distribution and nutrient supply. This approach recognises the value of environmental measurements while avoiding the error of treating them as proof of a specific physiological deficiency [3].

Substrate pH affects macronutrient solubility and can influence nutrient availability in soilless production. Nutrient-solution formulation, substrate components and liming materials also affect the chemical environment around roots. However, solution or extract concentrations do not always correspond directly to plant nutrient status because root processes can modify the rhizosphere. pH should therefore be used to identify a plausible availability constraint, not as a substitute for evidence about uptake, internal redistribution and plant response [9].

Root-hair responses provide useful mechanistic evidence, but their interpretation is limited by condition-specific findings. Evidence from Arabidopsis demonstrates links between nutrient availability, root-hair function and acquisition responses, but it offers limited comparison of symptom expression across crops. Crop-specific validation is therefore required before a root response or foliage pattern is generalised. The most reliable interpretation remains an integrated assessment of root-zone conditions, plant development, nutrient mobility and observed symptoms [6].

VI. Conclusion

Macronutrient deficiencies produce different effects because nutrients differ in their availability to roots, physiological functions and capacity for internal redistribution. Root-zone chemistry and substrate conditions affect acquisition, while phloem mobility and remobilisation influence where symptoms become visible. Symptom location may therefore reflect nutrient mobility, but crop variation, developmental stage, senescence and environmental stress prevent it from being definitive evidence. Macronutrient deficiency is best understood as a failure of nutrient acquisition, allocation and plant function rather than a visual colour change [1], [2], [4].

Reliable diagnosis requires symptoms to be interpreted with nutrient supply, pH, electrical conductivity, substrate conditions and root function. Controlled deficiency evidence supports this integrated approach, while diagnostic classification evidence demonstrates the risk of overlap with healthy and diseased plants. Comparative validation across crops and defined root-zone conditions would improve the reliability of symptom-based assessment. Until then, a mechanism-based interpretation provides a more defensible explanation of nutrient disorders than visual classification alone [2], [3], [6].

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