Essential macro and micronutrients

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***Abstract*—Essential mineral nutrients underpin plant growth because they provide the chemical components and physiological functions that higher plants cannot complete without. In practice, hydroponic and other soilless systems make this dependency especially visible, since the nutrient solution must supply the full set of required mineral elements in soluble forms that roots can absorb. Yet confusion often arises when the distinction between macronutrients and micronutrients is treated as a ranking of importance rather than as a statement about relative quantity requirement. This paper clarifies the accepted scientific criteria for plant mineral nutrient essentiality, identifies the recognised essential macro and micronutrients, and explains their broad physiological roles using evidence drawn from plant nutrition and hydroponic literature [1], [2], [3]. The synthesis shows that essentiality is defined by necessity for normal completion of the life cycle and by a direct functional role that cannot be fully replaced by another element, while macro versus micro classification refers only to the amount required by plant tissues [1]. The reviewed evidence also indicates that nutrient management contexts, including hydroponics, depend on this distinction for formulation and monitoring, but they do not by themselves redefine essentiality [4], [5], [6]. A clear separation between essentiality, quantity requirement, and broader beneficial effects is therefore central to accurate nutrient solution chemistry and to sound interpretation of plant nutrition evidence.**

I. Introduction

Plant mineral nutrition begins with a definitional question: what makes an element essential to higher plants. This question matters because plant nutrition science does not treat every helpful element as equivalent. Accepted criteria, developed from classical and modern plant nutrition thinking, require that an element be necessary for normal completion of the life cycle, that its function cannot be fully replaced by another element, and that it participates directly in plant metabolism or indispensable structural processes [1]. These criteria create an evidence-based boundary between essential nutrients and merely beneficial elements. The implication is important for nutrient solution chemistry, because formulation should start from elements whose absence prevents normal growth or reproduction, not from a broader list of substances that may only improve performance in specific species or conditions.

In applied systems such as hydroponics, the importance of essential mineral elements becomes immediate because the root environment supplies nutrients in a controlled and explicit way. Broad plant nutrition evidence links nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, zinc and other nutrients to core functions such as growth, metabolism, transport, structural development and micronutrient-dependent physiological regulation [7]. When these elements are supplied in inadequate form or amount, plant performance is constrained not simply by water availability or light capture, but by the inability to sustain the biochemical and structural functions those minerals support. This practical visibility makes hydroponic production a useful context for discussing essential nutrients, even though hydroponic management literature alone is not sufficient to define essentiality.

A second source of confusion is the common assumption that macronutrients are biologically more important than micronutrients. The evidence does not support that interpretation. The macro versus micro distinction reflects relative quantitative requirement in plant tissues, not relative value to plant life [1]. Some elements required only in trace amounts still perform indispensable catalytic or regulatory functions, while some non-essential elements can be beneficial under certain species-specific or stress-related conditions. This paper therefore argues that essentiality, quantity requirement, and beneficiality must be kept conceptually separate. It first defines essentiality, then identifies the recognised essential macro and micronutrients and their broad roles, and finally explains why quantity classification should not be mistaken for a hierarchy of biological importance.

II. Background and Scope

Current plant nutrition literature commonly recognises 17 essential elements for higher plants. Carbon, hydrogen and oxygen are obtained mainly from air and water, while the mineral elements supplied from the rooting environment are nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, manganese, zinc, copper, boron, molybdenum, chlorine and nickel [1]. Within this set, the standard mineral classification separates macronutrients, required in comparatively larger amounts, from micronutrients, required in smaller amounts. This paper is concerned specifically with those mineral elements and their recognised status in higher plants. The scope does not extend to a general survey of beneficial elements, although the distinction between essential and beneficial elements is important for interpreting the boundary of the category [1].

Hydroponic review literature helps translate the recognised nutrient set into practical formulation language by grouping elements as primary, secondary and trace nutrients, and by identifying the ionic forms typically supplied to plants [2]. This framing is useful because it connects classification with the real chemical environment of the root zone. Nitrogen is commonly supplied as nitrate or ammonium, phosphorus as phosphate, potassium as potassium ion, calcium and magnesium as divalent cations, and several micronutrients as

carefully managed soluble species [2]. However, this applied grouping should not be confused with the scientific test for essentiality. Hydroponic manuals and reviews usually assume the accepted list of essential nutrients rather than establishing it experimentally, so they support explanation of use and delivery more strongly than definition.

Broader soilless cultivation reviews extend this applied perspective by listing standard macronutrients and micronutrients in nutrient solutions and by linking them to crop demand across growth stages [3]. Such sources show why the topic matters in controlled agriculture: nutrient solutions are designed around the known essential set, and management decisions depend on balancing supply, uptake and solution chemistry. Even so, these reviews usually focus on operational control, crop performance and system design rather than on the philosophical or evidentiary basis of essentiality [3]. The gap addressed here is therefore not a lack of practical nutrient lists, but a need for a clear synthesis that joins accepted essentiality criteria with the recognised macro and micronutrient categories, while explaining that low quantity requirement does not imply low biological significance.

III. Core Concepts and Mechanisms

The broad physiological roles of recognised essential nutrients explain why classification by quantity cannot be treated as a ranking of function. Nitrogen is central to amino acids, proteins and other nitrogen-containing metabolites; phosphorus contributes to energy transfer and phosphorylated intermediates; potassium supports osmotic regulation and enzyme activation; calcium contributes to structural and signalling functions; magnesium is integral to chlorophyll and enzymatic processes; and micronutrients participate in catalytic, redox and regulatory activities that are indispensable despite their low tissue concentrations [6]. The mechanism behind essentiality is therefore functional indispensability, not bulk abundance. A nutrient may be needed in trace amounts yet still govern reactions or structures without which normal plant development cannot proceed.

Evidence from lettuce grown in a hydroponic nutrient film technique system reinforces the idea that essential nutrients differ not only in required amount, but also in uptake behaviour, retention and fate within a managed solution [4]. Nitrogen, phosphorus, potassium, calcium, magnesium, iron and manganese do not move through the solution-plant system in identical ways, and their uptake efficiencies can vary during cultivation [4]. This matters because nutrient solution chemistry must account for both essential status and dynamic availability. The implication is that a complete essential nutrient list is only the starting point. Effective supply depends on soluble form, root uptake processes and changing demand, which is why practical management cannot be reduced to adding a generic fertiliser mix even when all essential elements are nominally present.

Related evidence from bioponic systems shows the same conceptual point in a different management context. Crop growth still depends on provision of the recognised essential nutrients, but the chemical form in which nutrients become available may vary, especially for nitrogen where ammonium and nitrate dynamics affect usability and management [8]. This demonstrates that the mechanism of nutrient function is tied to both elemental identity and bioavailable form. The classification of an element as essential does not guarantee that any source or transformation pathway will be equally suitable. At the same time, bioponic evidence is not designed to redefine which elements are essential. Its contribution is to show that the recognised essential set remains constant even when delivery pathways and nutrient processing differ.

IV. Evidence Synthesis

Across hydroponic literature, a consistent assumption is that nutrient solutions must provide the essential mineral elements required for plant growth [2]. This operational consensus is valuable because it confirms the practical stability of the recognised nutrient set. Yet these sources generally begin from accepted plant nutrition doctrine rather than from the classical tests that establish essentiality. As a result, they are strong evidence for how essential nutrients are supplied and categorised in practice, but weaker evidence for why those elements belong to the essential category in the first place. A sound synthesis must therefore combine applied hydroponic sources with plant nutrition scholarship that explicitly discusses essentiality criteria [1], [2]. Without that combination, practical nutrient grouping can be mistaken for a definition rather than an implementation of prior scientific classification.

Soilless cultivation reviews add a second layer of synthesis by showing that nutrient solution design is built around standard macro and micronutrient categories across different production settings [3]. These reviews connect nutrient classes with broad crop needs through establishment, vegetative growth and reproductive development, which helps explain why quantity-based grouping remains useful in practice. Nevertheless, they also reveal an analytical limit: a list of standard components in a solution does not itself establish the direct physiological necessity of each element [3]. The classification still depends on the essentiality framework articulated in plant nutrition literature. In other words, hydroponic and soilless sources are persuasive about deployment and management, while foundational plant nutrition sources remain decisive about conceptual legitimacy and category boundaries.

Evidence on growing media and root-zone behaviour further sharpens this distinction. Reviews of soilless media emphasise nutrient holding, pH behaviour, biological activity and possible immobilisation effects, all of which influence whether supplied nutrients remain available to plants [9]. This is highly relevant to nutrient solution chemistry because the presence of an essential element in a formulation does not guarantee effective delivery at the root interface. However, such evidence does not systematically identify the recognised essential nutrients or define their physiological roles [9]. Its main value is to demonstrate that essentiality and availability are separate but interacting concepts. An element can be essential by definition, yet poorly available in a given root-zone environment, creating

practical nutrient limitation without changing the underlying scientific classification.

V. Practical Implications and Limitations

For practical hydroponic management, the most important implication is that nutrient monitoring variables such as pH, electrical conductivity and operational range should be interpreted as tools for maintaining access to essential nutrients, not as substitutes for understanding essentiality itself [5]. Monitoring frameworks can indicate whether the root environment is likely to support balanced uptake, but they do not determine which elements are essential to the plant. This distinction matters because it prevents a purely engineering view of nutrient management from obscuring the biological basis of formulation. A technically well monitored system can still be conceptually flawed if it treats macro and micronutrients as a priority ranking instead of as categories of relative quantitative demand [5].

General reviews of soil and soilless cultivation likewise stress nutrient management and optimal root-zone conditions, especially pH and solution control, as central to successful cultivation [10]. These insights are useful because many essential nutrients become more or less available depending on solution chemistry, and micronutrients can be particularly sensitive to those shifts. Still, this body of evidence does not set out the accepted criteria for plant mineral nutrient essentiality [10]. The limitation is therefore interpretive: environmental control literature helps explain how recognised essential nutrients can be supplied effectively, but it cannot by itself answer the reader question of what makes an element essential. A scientifically careful account must avoid deriving essentiality from cultivation convenience, crop response alone, or management tradition.

A further implication concerns the language used to describe nutrient categories. Because hydroponic and precision management literature often focuses on measurable control variables, there is a risk that educational or operational summaries reduce micronutrients to trace additives of secondary concern [5]. The evidence reviewed here argues against that simplification. Micronutrients are required in smaller quantities, but the functions they support remain indispensable to normal metabolism and development when the element is part of the recognised essential set [1], [6]. The present evidence base is strong enough to support that conceptual conclusion, but it is not intended to provide a deficiency diagnosis framework or a species-by-species account of demand. Those topics would require a broader and differently targeted evidence set than the one synthesised in this paper.

VI. Conclusion

The evidence supports three main conclusions. First, an element is essential to higher plants when its absence prevents normal completion of the life cycle, when its function cannot be fully replaced by another element, and when it has a direct and indispensable role in plant structure or metabolism [1]. Second, the recognised essential mineral nutrients comprise the standard macro and micronutrient set used across plant nutrition and hydroponic practice, with macronutrients required in larger amounts and micronutrients in smaller amounts [1], [2], [3]. Third, that quantity distinction must not be interpreted as a scale of biological importance, because trace-required nutrients can still perform indispensable functions [1], [6].

For nutrient solution chemistry, the practical lesson is that formulation and monitoring should begin from the accepted essential set while recognising that supply form, uptake dynamics and root-zone conditions shape actual availability [4], [5], [9]. The reviewed hydroponic literature is valuable for showing how essential nutrients are delivered and managed, but foundational plant nutrition evidence remains necessary to explain why those elements are essential and why beneficial elements should not be conflated with them [1]. The highest-value next work would be synthesis that links this essentiality framework more explicitly to ion form, species-specific demand and controlled-environment management, while preserving the distinction between quantity requirement and biological necessity.

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