Hardness, alkalinity and nutrient solution stability

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***Abstract*—Hardness and alkalinity are routinely discussed together in water assessment, yet they describe different chemical properties and affect hydroponic practice through different mechanisms. Hardness refers mainly to dissolved multivalent cations, especially calcium and magnesium, whereas alkalinity refers to the acid-neutralising capacity of water, usually arising from bicarbonate and carbonate species. Confusion persists because both variables are often reported as mg/L as CaCO3, even though they are not interchangeable [1]. This paper synthesises accepted review evidence to clarify the distinction and explain why it matters during hydroponic solution preparation and stability assessment. The evidence shows that hardness can contribute nutritionally through calcium and magnesium, but under suitable carbonate chemistry, elevated pH, and temperature, these same ions can also participate in precipitation and scaling [1], [2]. Alkalinity matters differently because bicarbonate and carbonate species buffer added acid and influence how readily the solution chemistry shifts during preparation, without requiring a full discussion of active pH control [1]. Across hydroponic and related soilless literature, the most consistent implication is that source water assessment must separate mineral contribution from acid-neutralising capacity, because failure to do so can distort nutrient formulation, promote precipitation, and reduce solution stability [3], [4].**

I. Introduction

In hydroponic production, source water is not a neutral starting point but a chemical input that can alter nutrient formulation before any fertiliser schedule is applied. Two of the most commonly misunderstood descriptors of that input are hardness and alkalinity. Accepted evidence defines total hardness primarily in relation to divalent cations, especially calcium and magnesium, while total alkalinity is defined by titratable bases, usually dominated by bicarbonate and carbonate species. These properties are often confused because both are commonly expressed as mg/L as CaCO3, yet they represent different chemical phenomena and therefore demand different interpretations in practice [1]. The distinction matters because hydroponic nutrient solutions are formulated around soluble ions, predictable nutrient availability, and stable recirculating chemistry, so conflating hardness with alkalinity can lead to incorrect assumptions about both nutrient contribution and solution behaviour [5].

The practical importance of this distinction becomes clearer when carbonate chemistry is considered. Accepted irrigation-water evidence shows that bicarbonate and carbonate species, especially at elevated pH and temperature, can drive the precipitation of calcium and magnesium carbonates, leading to scale formation and clogging in water delivery infrastructure [2]. In a hydroponic context, this means that water suitability is shaped not only by how much calcium and magnesium it contains, but also by whether the water chemistry promotes those ions remaining dissolved after fertilisers are added. The same concentration of hardness ions may be operationally benign in one water source and problematic in another if carbonate conditions differ. Accordingly, nutrient solution stability cannot be understood from a single bulk water metric [6].

Alkalinity adds a second and separate layer of relevance because it expresses acid-neutralising capacity rather than mineral loading. The accepted evidence explains that this buffering behaviour is grounded mainly in bicarbonate and carbonate equilibria, which resist chemical change when acid is introduced [1]. For hydroponic preparation, the immediate implication is not a full programme of pH management, which lies outside the present scope, but a narrower point: waters with higher alkalinity can alter the chemical effort required to move from raw source water to a stable nutrient solution. This paper therefore argues that hardness and alkalinity should be treated as related but non-equivalent controls on hydroponic solution preparation, with hardness speaking mainly to dissolved multivalent mineral content and scaling potential, and alkalinity speaking mainly to buffering and acid-neutralising capacity.

II. Background and Scope

Prior review literature from irrigation science clarifies why hardness-related operational problems are often first detected in delivery hardware rather than in plant symptoms. Accepted evidence reports that when pH rises above about 7.2 and temperature is high, calcium and magnesium carbonates can precipitate in laterals and drippers, creating encrustation and clogging. The same review also notes operational conditions associated with clogging risk, including total suspended solids above 50 mg/L and extreme heating in black tubing that can exceed 80°C [2]. Although these findings come from micro-irrigation rather than hydroponic formulation studies, they are directly relevant to hydroponics because nutrient solutions are distributed through comparably narrow flow paths. The implication is that source water chemistry should be evaluated before mixing, since precipitation risk can become an infrastructure problem as well as a nutrient-balance problem.

Hydroponic review literature complements that irrigation perspective by showing how solution chemistry constrains nutrient availability once the water enters the fertiliser regime. Accepted evidence indicates that hydroponic nutrient solutions are commonly maintained within a pH range of about 5 to 7, and that above pH 7 the solubility of iron and phosphate

decreases while calcium and magnesium precipitates can form [3]. This evidence does not by itself define hardness or alkalinity, but it establishes the hydroponic consequence of misunderstanding them. Calcium and magnesium are not only essential nutrients associated with hardness, they are also ions whose useful dissolved status can be lost under unfavourable carbonate and pH conditions. The resulting issue is not merely that raw water contains minerals, but that some of those minerals may become chemically unavailable or physically troublesome during preparation and recirculation.

A broader chemical explanation comes from accepted review evidence in aquaculture, which directly distinguishes calcium and magnesium as major hardness ions from bicarbonate and carbonate as principal alkalinity species, while also explaining how dissolved CO2, CaCO3 dissolution, gypsum inputs, and buffering relationships influence their concentrations in water [1]. This literature does not originate in hydroponics, yet it addresses the exact conceptual gap that hydroponic reviews often leave unresolved. Accordingly, the present paper is an evidence-based synthesis rather than an experimental report. Its scope is limited to explaining what hardness and alkalinity are, how they differ, and why they matter for nutrient solution preparation and stability. It does not extend into full treatment design, complete water remediation protocols, or general pH control strategy, except where those topics are necessary to interpret accepted evidence about solution behaviour.

III. Core Concepts and Mechanisms

The central mechanism behind hardness relevance is that dissolved calcium and magnesium can be both beneficial nutrients and participants in unwanted mineral transformations. Accepted evidence explains that calcium-based mineral contributions become operationally important under specific carbonate conditions: CaCO3 can dissolve under atmospheric CO2, precipitation may occur when photosynthetic CO2 removal shifts equilibria, and hardness and alkalinity do not always rise together, as shown by situations in which added calcium sulfate is recommended when alkalinity is high but hardness is low [1]. This matters for hydroponics because calcium and magnesium measured in source water cannot be interpreted as a simple bonus nutrient supply without considering the chemical form and equilibrium context. A water source may contribute useful hardness ions, yet still behave poorly if carbonate chemistry encourages instability after the nutrient stock is diluted into working solution.

A second mechanism concerns how high pH conditions alter solution composition through precipitation and reduced solubility. Accepted hydroponic nutrient-solution management evidence states that high pH can precipitate calcium and magnesium while also reducing iron and phosphate solubility, directly linking water chemistry to practical hydroponic preparation and renewal [4]. The significance of this mechanism is that hardness does not operate in isolation from the rest of the nutrient profile. Once calcium and magnesium precipitate, they no longer function as reliably dissolved nutrients, and their loss can coincide with reduced availability of other ions that plants require. In operational terms, this means that apparently adequate source-water mineral content can still produce an unstable or nutritionally distorted solution if the chemical environment favours precipitation rather than retention in solution.

The role of alkalinity is different and should not be collapsed into general hardness language. Accepted background evidence from soil science shows that shifts in acidity affect the availability of calcium, magnesium, iron, zinc, and phosphate, although that literature is framed around soil-root systems rather than hydroponic solution preparation [7]. Even with that limitation, the evidence supports a useful interpretive point: the consequences of altered acid-base conditions are expressed through nutrient availability, not merely through a pH number on its own. In hydroponics, alkalinity matters because bicarbonate and carbonate species resist acidification and therefore shape the chemical pathway by which a mixed nutrient solution reaches a stable dissolved state. This does not require expanding into full pH-management doctrine; it is enough to recognise that alkalinity represents buffering capacity, whereas hardness represents multivalent mineral content, and each influences stability through a distinct mechanism.

IV. Evidence Synthesis

Across the accepted evidence base, the most consistent synthesis is that mineral contribution and solution stability must be interpreted together but not confused. Soil-root evidence shows that pH shifts alter the availability of calcium, magnesium, iron, zinc, manganese, and phosphate [7]. Although this is not a hydroponic scaling study, it helps explain why dissolved mineral content alone does not predict agronomic usefulness. A hydroponic solution can begin with chemically measurable calcium and magnesium, yet if associated conditions shift solubility or promote precipitation, those ions may no longer support plant uptake in the expected way. The hydroponic relevance therefore lies in bounding interpretation: hardness can indicate the presence of nutritionally significant ions, but it cannot, by itself, guarantee stable nutrient availability once the solution chemistry evolves during preparation or recirculation.

The broader soilless literature reinforces the importance of chemical sensitivity while also revealing limits in the direct evidence. Accepted bioponics review evidence repeatedly notes ammonium-rich, pH-sensitive organic solutions and mineral imbalances, showing that nutrient solutions in non-soil systems can be chemically unstable and difficult to interpret when multiple reactive species coexist [8]. This does not specifically resolve calcium, magnesium, carbonate, and bicarbonate chemistry, but it supports a broader conclusion relevant to hydroponics: nutrient solutions are dynamic mixtures, and source-water properties can interact with formulation choices rather than remaining passive background conditions. The implication is methodological as well as technical. Water assessment should separate the question of what ions are

initially present from the question of how those ions will behave after mixing, buffering, and circulation.

Accepted soilless-cultivation evidence provides a similar message from a more hydroponic direction. Reviews of soilless systems note that nutrient solution pH and electrical conductivity govern nutrient availability, and that pH significantly altered phosphorus, calcium, and manganese concentrations in aeroponics [9]. This evidence again stops short of detailing carbonate and bicarbonate mechanisms, yet it aligns with hydroponic and aquaculture reviews in a useful way. Together, the sources suggest that the main hydroponic risk is not merely high mineral content or high buffering capacity in isolation, but a mismatch between source-water chemistry and intended nutrient formulation. Hardness matters because calcium and magnesium enter the ionic budget, while alkalinity matters because bicarbonate and carbonate govern acid-neutralising behaviour and can influence whether those ions remain dissolved. The shared conclusion is that stable nutrient preparation depends on recognising both roles at once.

V. Practical Implications and Limitations

For practitioners, the first implication is analytical discipline: hardness and alkalinity should be measured and interpreted as separate descriptors of source water. Accepted irrigation-water evidence describes hardness-linked cations and carbonate-saturation indices, which helps infer why the two properties are often associated in practice, but that same evidence does not itself provide a clean scientific definition that contrasts them [2]. This limitation matters because operational guidance built only from scaling indices can obscure the underlying conceptual distinction. In hydroponic preparation, a water source with appreciable calcium and magnesium may contribute to the nutrient inventory, whereas a water source with high alkalinity may chiefly determine how strongly the solution resists acidification. Treating one as a proxy for the other can therefore misstate both nutrient contribution and stability risk.

The second implication concerns the proper interpretation of alkalinity. Accepted irrigation-water evidence uses carbonate chemistry and indices relevant to corrosivity and scaling, which contextualise why bicarbonate-rich waters can become operationally difficult, but the same source does not frame alkalinity explicitly as acid-neutralising capacity [2]. Accepted aquaculture evidence fills that gap by defining alkalinity through titratable bases and bicarbonate-carbonate buffering [1]. When these sources are synthesised, the practical lesson for hydroponics is restrained but important: alkalinity matters because it changes the chemical effort needed to move from raw water to a stable dissolved nutrient state, not because it is simply another name for hardness. This distinction helps keep the discussion within scope. It explains why alkalinity is relevant to preparation and stability, while deferring detailed active pH-management protocols to more specialised treatment discussions.

The evidence base also sets clear limits on what can presently be claimed. Accepted hydroponic review evidence notes that high pH can cause calcium and magnesium precipitates and defines EC, but it does not clearly distinguish hardness from alkalinity [3]. Other accepted sources discuss operating ranges for pH, EC, and dissolved oxygen, pretreatment options such as reverse osmosis or lime softening, and broader water-treatment relevance, yet they do not fully establish hydroponic-specific thresholds for when hardness-driven scaling becomes unavoidable across all systems [10], [11]. Accordingly, the strongest defensible conclusion is conditional rather than absolute. Hardness-related scaling and mineral contribution become operationally relevant when dissolved calcium and magnesium interact with carbonate chemistry, elevated pH, temperature, and delivery conditions that favour precipitation. More hydroponic-specific comparative studies would be needed to convert that conclusion into universal design thresholds.

VI. Conclusion

The accepted evidence supports a clear distinction between hardness and alkalinity and shows why that distinction matters for hydroponic nutrient solution stability. Hardness refers mainly to dissolved multivalent minerals, especially calcium and magnesium, whereas alkalinity refers mainly to acid-neutralising capacity arising from bicarbonate and carbonate species [1]. These properties often coexist and are often reported in the same units, but they influence hydroponic management through different mechanisms. Hardness affects the mineral starting point and potential contribution of calcium and magnesium, while alkalinity affects buffering behaviour and therefore the chemical pathway to a stable mixed solution. When carbonate chemistry, elevated pH, and thermal conditions favour precipitation, calcium and magnesium can shift from useful dissolved nutrients to scale-forming solids [2], [4].

The most valuable next step for practice and research is therefore not broader generalisation but tighter hydroponic-specific validation. Existing reviews justify separating hardness assessment from alkalinity assessment and relating both to nutrient solubility and precipitation risk, yet they also show that much of the detailed mechanism has been developed in adjacent fields or broader soilless contexts rather than in dedicated hydroponic water studies [3], [9]. Future work would be most useful if it tested how source-water hardness, alkalinity, and carbonate conditions jointly affect formulation stability across representative hydroponic systems. Until then, the most reliable evidence-based position is that stable preparation begins with recognising that hardness and alkalinity are chemically different, operationally connected, and not interchangeable.

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REFERENCES

[1] C. E. Boyd, C. S. Tucker, and B. Somridhivej, "Alkalinity and hardness: Critical but elusive concepts in aquaculture," *Journal of the World Aquaculture Society*, 2016.

[2] G. W. Anyangoa, G. D. Bhowmicka, and N. S. Bhattacharyab, "A critical review of irrigation water quality index and water quality management practices in micro-irrigation for efficient policy making," *Desalination and Water Treatment*, 2024.

[3] R. S. Velazquez-Gonzalez, A. L. Garcia-Garcia, J. O. Barceinas-Sanchez, E. Ventura-Zapata, and J. C. Sosa-Savedra, "A review on hydroponics and the technologies associated for medium- and small-scale operations," *Agriculture*, 2022.

[4] E. Fathidarehnijeh, M. Nadeem, M. Cheema, R. Thomas, M. Krishnapillai, and L. Galagedara, "Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems," *Canadian Journal of Plant Science*, 2024.

[5] I. A. Lakhiar, H. Yan, T. N. Syed, C. Zhang, S. A. Shaikh, M. Rakibuzzaman, and R. B. Vistro, "Soilless agricultural systems: Opportunities, challenges, and applications for enhancing horticultural resilience to climate change and urbanization," *Horticulturae*, 2025.

[6] J. C. Majsztrik, R. T. Fernandez, P. R. Fisher, D. R. Hitchcock, J. Lea-Cox, J. S. Owen, Jr., L. R. Oki, and S. A. White, "Water use and treatment in container-grown specialty crop production: A review," *Water, Air, & Soil Pollution*, 2017.

[7] N. Joshi, R. Kaur, and T. Nawaz, "The soil-root nexus: how soil health shapes plant nutrient uptake and food nutritional security," *Plant and Soil*, 2026.

[8] I. Szekely and M. H. Jijakli, "Bioponics as a promising approach to sustainable agriculture: A review of the main methods for producing organic nutrient solution for hydroponics," *Water*, 2022.

[9] A. Tuxun, Y. Xiang, Y. Shao, J. E. Son, M. Yamada, S. Yamada, K. Tagawa, B. Baiyin, and Q. Yang, "Soilless cultivation: Precise nutrient provision and growth environment regulation under different substrates," *Plants*, 2025.

[10] M. Elakrouch, M. Mohaddab, A. Rachid, and M. H. Jijakli, "Soilless agriculture at a crossroads: Strengths, challenges, and prospects of hydroponics, aquaponics, and bioponics in relation to precision farming," *Sustainability*, 2026.

[11] O. V. Obayomi, D. C. Olawoyin, O. Oguntimehin, L. S. Mustapha, S. O. Kolade, P. O. Oladoye, S. Oh, and K. S. Obayomi, "Exploring emerging water treatment technologies for the removal of microbial pathogens," *Current Research in Biotechnology*, 2024.