# Causes of pH drift in recirculating systems

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***Abstract*—Recirculating hydroponic systems are often managed as if nutrient solution pH were a stable setpoint that changes only when a grower deliberately adds acid or base. The supplied evidence indicates a more dynamic picture. Studies and reviews of closed-loop hydroponics show that pH drift emerges from continuing interactions among plant nutrient uptake, low solution buffering, source-water alkalinity, gas exchange, biological nitrogen transformations, and secondary solution reactions such as precipitation and dissolution [1], [2], [3]. Selective ion uptake is especially important because uptake of ammonium can acidify the rhizosphere through proton release, whereas nitrate uptake can raise rhizosphere pH through bicarbonate-associated charge balance processes [4]. At the same time, recirculating systems show uneven depletion and accumulation of individual ions, so pH movement reflects the whole solution context rather than a single universal mechanism [1], [3]. Evidence from irrigation-water chemistry and allied water-quality literature further shows that alkalinity, carbon dioxide exchange, and biological activity can alter acid-base behaviour without acting identically across all systems [2], [5], [6]. This paper synthesises the accepted evidence to explain why nutrient-solution pH drifts over time in recirculating systems and to clarify the practical implication that reliable interpretation of pH change requires attention to chemistry, biology, and water source together rather than isolated correction events.**

## I. Introduction

In recirculating hydroponic systems, nutrient solution pH is not simply a background number to be reset when it moves outside a preferred range. A lettuce nutrient film technique study showed that solution composition changed materially during recirculation, including rapid disappearance of ammonium nitrogen interpreted as nitrification and other chemical change, together with persistent imbalance among individual ions under electrical-conductivity based replenishment [1]. This matters because pH drift is produced inside the operating solution itself, not only by external dosing. When ions are removed, transformed, or left behind at different rates, the acid-base balance of the circulating solution also changes. The practical implication is that a stable electrical conductivity reading can coexist with chemically meaningful drift, so growers cannot assume that a seemingly maintained solution has retained the same pH behaviour or buffering context over time [1].

Closed-loop hydroponic reviews further indicate that pH fluctuation is structurally linked to low buffering capacity, root ion exchange, and nutrient-specific uptake patterns rather than to a single universal defect in management [3]. In a lightly buffered solution, even modest shifts in the balance between absorbed cations and anions can change the acid-base conditions around roots and then in the recirculating reservoir. This makes selective uptake central to the reader's question of why pH drifts despite no deliberate adjustment. The solution is being adjusted continuously by the crop itself. A key implication is that pH direction and rate depend on crop demand, nutrient formulation, and recirculation history, so identical dosing practices can produce different outcomes across otherwise similar systems [3], [7].

Source-water chemistry adds another reason that pH drift cannot be reduced to one cause. Reviews of irrigation water quality and hydroponic bicarbonate control distinguish pH from alkalinity and show that bicarbonate and carbonate chemistry, hardness, residual sodium carbonate, and precipitation behaviour shape how strongly a solution resists or expresses acid-base change [2], [6]. A grower may therefore observe upward drift, muted downward drift, or abrupt instability depending on how source water interacts with the fertiliser recipe and biological activity. This paper argues that pH drift in recirculating hydroponics is best understood as the combined result of plant uptake, biological transformations, gas exchange, source-water alkalinity, and solution reactions. The following sections define that scope, explain the principal mechanisms, synthesise the supporting evidence, and outline the practical limits of generalising from any one mechanism [2], [3], [6].

## II. Background and Scope

Water-quality literature oriented to aquaculture shows that acid-base conditions can be altered by alkalinity, carbon dioxide exchange, photosynthesis and respiration, nitrification, and denitrification, with each process becoming more or less important under different operating conditions [5]. Although that literature is not specific to hydroponic crop production, it is scientifically useful because it demonstrates that pH is an emergent water-chemistry outcome rather than a standalone variable. For recirculating hydroponics, this means pH drift should not be interpreted as proof of one dominant fault, such as poor dosing discipline or nutrient imbalance alone. The same measured drift could arise from different combinations of buffering, biological activity, gas transfer, and nutrient uptake history [5].

Hydroponic nutrient-management reviews bring this general chemistry closer to the target system by explaining that pH drift in closed-loop cultivation arises from low buffering capacity, root ion exchange, evapotranspiration-driven concentration changes, and uneven uptake of dissolved nutrients [3]. This literature contributes the important idea that recirculation

does not merely conserve water and fertiliser, it also intensifies feedback among plant demand, concentration shifts, and solution chemistry. As water is removed faster than ions, or as some ions are absorbed faster than others, the remaining solution changes character. Yet much of the hydroponic review literature emphasises monitoring and management more than mechanistic discrimination, which leaves a gap between practical advice and a clear explanation of why a grower may see upward or downward pH drift under apparently routine operation [3], [8], [9].

A further strand of evidence concerns source-water alkalinity. Engineering work on bicarbonate control in hydroponic irrigation shows that alkalinity is not interchangeable with pH and that residual bicarbonate strongly affects how nutrient solutions respond to acid addition and ongoing biological or chemical acidity generation [6]. Irrigation-water reviews similarly show that bicarbonate and carbonate chemistry, hardness, and precipitation tendencies shape water behaviour before plants even begin selective uptake [2]. These sources help define the scope of this paper: the focus is why pH drifts over time in recirculating nutrient solutions, not general hydraulics or sensor design. The gap addressed here is explanatory synthesis. Existing sources contribute pieces of the story, but the reader needs a single account showing how plant processes, water chemistry, gas exchange, and biological activity jointly produce pH drift without implying that any one process is universally decisive [2], [5], [6].

## III. Core Concepts and Mechanisms

Selective ion uptake is one of the clearest scientifically supported causes of pH drift. Evidence from soilless substrate research states directly that ammonium uptake can acidify the rhizosphere by release of hydrogen ions, whereas nitrate uptake can raise rhizosphere pH through bicarbonate-associated charge balance processes [4]. In practical terms, when roots absorb different nitrogen forms, they do not leave the surrounding solution chemically neutral. Instead, they alter proton balance at the root interface, and those local shifts can propagate into the recirculating solution. This directly answers why pH can drift without deliberate adjustment: plant feeding itself can drive acidity or alkalinity trends. A key limitation, however, is that the magnitude and direction of the effect depend on nutrient form, crop behaviour, and the buffering environment of the system rather than on nitrogen chemistry alone [3], [4].

Root-zone chemistry also extends beyond simple uptake ratios. A review on the soil-root nexus notes that root exudates can alter pH and help solubilise nutrients, indicating that roots actively modify their chemical surroundings rather than passively drawing ions from solution [10]. In a recirculating hydroponic system, this means pH drift may reflect biologically mediated microenvironment changes near roots that accumulate over time in a shared reservoir. Exudation does not replace the acid-base effects of selective ion uptake, and the source does not directly quantify those charge-balance pathways, but it strengthens the broader mechanism that root activity itself is chemically transformative [10]. The implication is that root-zone pH behaviour should be understood as a combined effect of nutrient uptake and biologically active root chemistry, especially in systems with limited buffering where local changes are more easily expressed at system scale [3], [10].

Recirculating nutrient studies show how these root-scale processes become whole-system drift. In nutrient film technique lettuce production, individual nutrients were depleted or accumulated unevenly across the recirculating solution, indicating that replacement based on overall conductivity does not preserve the original ionic composition [1]. This matters because pH is sensitive not only to the concentration of total dissolved ions but also to which ions remain in solution and which have been preferentially removed or transformed. A solution can therefore retain an acceptable conductivity while moving toward a different acid-base state. The evidence from this study does not fully elaborate the proton and bicarbonate bookkeeping behind each ion change, but it clearly supports the mechanism that selective uptake and recirculation history reshape solution composition in ways consistent with ongoing pH drift [1], [3].

Biological nitrogen transformations provide a second major mechanistic pathway. Reviews dealing with bioponics and broader water chemistry show that nitrification, ammonium dominance, and related microbial processes can materially alter nutrient solutions, with nitrification in particular associated with acidity generation and destruction of alkalinity [5], [11]. In recirculating systems, this means that dissolved nitrogen forms are not governed solely by fertiliser composition and plant uptake. Microbial communities can convert ammonium to nitrate, changing both nutrient speciation and acid-base balance over time. The implication is that a grower may observe pH decline even when plant uptake alone would not fully explain the trend. At the same time, the strength of this mechanism will depend on microbial activity, oxygenation, nitrogen form, and residence time, so it should be interpreted as one driver within a broader interacting system [1], [5], [11].

## IV. Evidence Synthesis

When the accepted sources are read together, they converge on a picture of pH drift as a multi-cause process with several chemically linked pathways. The bioponics review is not centred on conventional mineral hydroponics, yet it is still mechanistically valuable because it identifies nitrification, ammonium dominance, residual organics, and pH control as influential features of nutrient solutions [11]. Coupled with the recirculating lettuce evidence, this suggests that nitrogen transformations can contribute to pH movement both by changing which ions plants encounter and by changing the alkalinity balance of the circulating water [1], [11]. The limitation is transferability: organic-input systems differ from conventional hydroponics. Even so, the chemistry supports the broader conclusion that recirculating solutions are biochemically active environments, not inert storage media, and that this activity helps explain unprompted pH drift [11].

Source-water contributors form another consistent line of evidence. Irrigation-water reviews show that bicarbonate and carbonate chemistry, hardness, and scaling tendency influence how water responds to acids, bases, and dissolved minerals [2]. Hydroponic bicarbonate-control work sharpens this point by distinguishing alkalinity from pH and showing why residual bicarbonate matters for nutrient solution management [6]. Together, these sources explain why two systems adjusted to the same initial pH may not drift similarly after recirculation begins. Water with higher alkalinity can buffer acidity more strongly, mute expected downward movement, or promote conditions in which precipitation reactions change the dissolved composition differently from a low-alkalinity feed water. These sources do not describe every hydroponic scenario directly, but they strongly support the claim that source-water chemistry conditions the direction and speed of later pH drift [2], [6].

Hydroponic review literature adds the crucial interaction with precipitation and nutrient availability. Reviews note that solution pH affects nutrient solubility, precipitation behaviour, and the need for careful monitoring in reused nutrient solutions [7], [8]. This means pH drift is not only an outcome of other processes, it can also feed back into the chemistry by changing which nutrients stay dissolved and available. As the solution drifts, dissolution and precipitation can alter the ionic pattern that the plants and microbes then encounter, reinforcing the view that drift is dynamic rather than linear [8]. The literature is less explicit on the relative importance of each pathway, and it often emphasises operational control over mechanism. Nevertheless, taken together with sources on uptake, alkalinity, and biological activity, the evidence supports a coherent synthesis: pH drift emerges from interacting chemical and biological processes whose influence varies with buffering, nutrient form, and recirculation context [3], [7], [8].

## V. Practical Implications and Limitations

The most important practical implication is that pH drift should be interpreted as information about changing solution context, not simply as a trigger for correction. Hydroponic reviews indicate that pH behaviour depends on low buffering, root ion exchange, evapotranspiration-driven concentration change, and uneven uptake, while also affecting precipitation and nutrient availability [3], [8]. A grower who sees drift is therefore observing the combined outcome of water source, crop demand, and internal transformations. Corrective dosing may restore a target reading, but it does not reveal which underlying mechanism dominated. This limits the usefulness of a universal rule such as assuming all upward drift reflects nitrate uptake or all downward drift reflects nitrification. The evidence instead supports a diagnostic approach that considers nutrient form, replenishment strategy, alkalinity, and recirculation history together [3], [8].

A second implication is that monitoring remains necessary, but monitoring alone does not resolve causation. Broad reviews of soilless agriculture and hydroponic practice consistently emphasise regular observation of nutrient balance, water balance, and pH, and some literature links hydroponic success to tight pH control and real-time sensing [7], [9], [12]. These recommendations are justified because recirculating systems can change materially during operation. However, the same sources are limited in that they do not fully specify the principal mechanisms responsible for a given drift event [9], [12]. This means instrumentation should be paired with chemical interpretation. pH time series are most informative when read alongside knowledge of source-water alkalinity, fertiliser nitrogen form, and evidence of selective ion depletion, rather than being treated as an isolated control variable [1], [6], [9].

The role of gas exchange and broader biological activity must also be framed carefully. Aquaculture water-chemistry literature shows that carbon dioxide exchange, alkalinity buffering, photosynthesis and respiration, nitrification, and denitrification can all alter water pH, while wastewater hydroponics literature supports a role for aeration and treatment biology in shaping solution conditions [5], [13]. These parallels are scientifically useful because they confirm that gas exchange and microbial processes are capable of shifting acid-base balance over time. Yet the accepted evidence does not justify presenting any one of these processes as the universal driver of pH drift in crop nutrient solutions. Their contribution will vary with system design, microbial load, nitrogen chemistry, and contact with the atmosphere. The main limitation of the evidence base is therefore not absence of mechanism, but limited direct comparison of mechanism strength across standard recirculating hydroponic scenarios [5], [13], [14].

A final limitation concerns scope and transferability. Some accepted sources are highly relevant but indirect, including reviews from aquaculture, wastewater hydroponics, or organic hydroponic processing [5], [11], [13]. They expand mechanistic understanding, especially for alkalinity destruction, gas exchange, and biological activity, but they do not provide a universal quantitative hierarchy for conventional recirculating hydroponic crops. Consequently, strong claims about the dominant cause of drift in every system would exceed the evidence. The best-supported conclusion is more conditional: pH drift results from ongoing chemical and biological processes whose expression depends on the whole solution context, including ion uptake patterns, buffering capacity, nitrogen transformation, and water source characteristics [2], [3], [6].

## VI. Conclusion

The accepted evidence shows that nutrient-solution pH drifts in recirculating hydroponic systems because the solution is continuously being reshaped by plant uptake, root-zone chemistry, biological nitrogen transformations, source-water alkalinity, gas exchange, and secondary reactions such as precipitation and dissolution [1], [2], [3], [5]. Selective uptake provides the clearest direct root-zone mechanism: ammonium uptake tends to acidify, whereas nitrate uptake tends to raise rhizosphere pH through associated charge-balance processes [4]. Yet that mechanism operates inside a wider context of low buffering and variable alkalinity, so drift direction and rate cannot be reduced to one universal rule. The central

implication is that pH drift is a system signal, not merely a correction problem [3], [6].

The highest-value next work, within the limits of the present evidence, is more direct comparative study of how uptake patterns, residual bicarbonate, microbial nitrogen conversion, and gas exchange interact in standard recirculating hydroponic conditions [1], [5], [6]. Until such comparisons are better resolved, the most scientifically defensible interpretation is that growers should read pH movement in relation to the whole nutrient and water context. Doing so best explains why pH changes even when no deliberate adjustment has been made and why the same apparent drift can reflect different underlying chemical and biological causes [2], [3], [7].

## ACKNOWLEDGMENT

The author used artificial intelligence tools to assist with manuscript drafting and revision, and with LaTeX and bibliography preparation. The author reviewed all AI-assisted output and remains responsible for the final content.

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