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Research Paper

Simultaneous pH and EC control in hydroponics through real-time manipulation of the ammonium-to-nitrate ratio in the nutrient solution

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Highlights

- Successful pH and EC control with simultaneous addition of nitrate and ammonium.
- No significant toxicity effects of ammonium despite xNH4+ >0.5 in the nutrient solution.
- Significant contribution of bacteria to system behaviour.

- Similar nutritional characteristics to nitrate fed kale.

Abstract

A control algorithm was developed and tested on a hydroponic ebb-and-flow system to assess the efficacy of the proposed control scheme. Three experimental runs were conducted with the purpose of testing the proposed control system on *Brassica oleracea* var. *acephala*. The first was an ideal case under sterile conditions, the second was under non-sterile conditions where bacteria were allowed to colonise the plant roots, and the last was a baseline run where nitrate was applied as the only nitrogen source. The system was able to control pH to within 0.5 of the set point (in this case 6.1) while EC control was sufficient to ensure that a steady stream of nutrients were available to the plants at all times. Relative growth rates were fast at maximum average values of between 0.20 day^{-1} and 0.21 day^{-1} for all of the runs and the yield of organic leaf matter was essentially the same across all the runs at 83 % to 86 % of total plant mass. Finally, the plants grown under the proposed control system were observed to exhibit some improvement in protein and chlorophyll content while the other nutritional characteristics considered were essentially unchanged between treatments. This was all accomplished without having to add any additional toxic ions like Cl^- and Na^+ as is the case in conventionally controlled systems.

Introduction

For much of the last century, nitrogen nutrition in hydroponics has been dominated by nitrates (Bugbee, 2004; Hoagland and Arnon, 1938; Savvas et al., 2013). However, research has highlighted that many potential benefits can be had by adding ammonium into the mix with nitrate (Fallovo et al., 2006; Song, G Li, et al., 2016, 2017; Wang et al., 2022). These include potentially increased growth rates, greater concentrations of some minerals and phytochemicals, increased protein concentrations, and the reduction in carcinogenic nitrate within the edible organs of the plant (Song et al., 2012, 2017; Tabatabaei et al., 2008; Zhu et al., 2018). Despite these benefits, the spectre of ammonium toxicity – the wilting and yellowing of leaves, reduction of growth rate, and sometimes even the death of the plant, when ammonium concentrations grow too large or the ratio of ammonium to nitrate grows too high (Assimakopoulou et al., 2019; Fallovo et al., 2006; Wang et al., 2022; Zhang et al.,

2007) – has served to constrain the use of ammonium more liberally in hydroponics (Bugbee, 2004). Although most common nutrient formulations add ammonium to the mix with the intention of moderating the pH change of the system, the amounts are paltry when compared to the amount of nitrate supplied and ultimately necessitate direct pH control anyway (Hoagland and Arnon, 1938; Savvas et al., 2013). The pH response of a plant in hydroponics is a function of the different ways in which molecules and ions are absorbed by plant roots. Many nutrients, in particular N containing molecules, are absorbed through active transport (Hopmans and Bristow, 2002; Petoussi and Kalogerakis, 2023). This involves the pumping of protons between the roots and the nutrient medium in order to create the necessary electrochemical gradient for anions and cations to flow from the nutrient medium into the roots (Petoussi and Kalogerakis, 2023; Mengel et al., 2001: 118, 120, 128). Broadly speaking, in order to absorb cations, protons are pumped out of the root into the nutrient solution. This creates a net positive charge in the nutrient solution that encourage cations like K^+, Ca^{2+}, and NH^+ to move from the nutrient solution into the roots. Conversely, when anions are absorbed, they often enter the cell via cotransport, whereby each anion is complexed with one or more protons. This complex carries a net positive charge, allowing it to flow down the same electrochemical gradient that the cations do. As a result, protons travel into the root from the nutrient solution. Naturally, both of these processes change the concentration of protons in the nutrient solution, necessitating pH control. Of particular interest is the ratio of protons released/absorbed per mole of ammonium/nitrate because nitrogenous ions like these represent the bulk of ions absorbed by plants. Theoretically, the absorption of 1 mol of nitrate should result in the absorption of 2/3 mol protons while the absorption of 1 mol of ammonium should release 4/3 mol of protons (Raven, 1985). As a result, ammonium heavy solutions tend to see a pH decrease while nitrate rich solutions tend to see a pH increase. van Rooyen and Nicol (2022) measured that the absorption of 1 mol of ammonium results in the release of 1 mol of proton while the absorption of 1 mol of nitrate results in the absorption of 0.5 mol of protons (and therefore the release of 0.5 mol of hydroxide ions). Both of these ratios were calculated in the presence of Hoagland solution, accounting for the difference from the theoretical values that would be caused by the other anions and cations that the plant needs.

As stated earlier, ammonium is often added to temper the pH response, though this is seldom relied on as a dedicated pH control strategy. Table 1 considers different studies and their control strategies in order to illustrate how rare this type of control is, especially in actively controlled systems.

Table 1 gives the impression that a plethora of novel ammonium based systems are in use, however, this is not the case. As the addendum to the table shows, simple acid/base addition dominates the reference list. Moreover, handbooks on the subject tend to counsel the use of acid and base dosing. While it is common for hydroponic systems to add ammonium to moderate the pH response (Hoagland and Arnon, 1938; Savvas et al., 2013), active pH control systems that leverage the pH relationship between ammonium and nitrate are decidedly rarer, accounting for only two of the studies found (Scherholz and Curtis, 2013; Pitts and Stutte, 1999). Of these, one was a computer simulation (Pitts and Stutte, 1999). The best example that could be found of a sophisticated use of ammonium to control pH is the study by Scherholz and Curtis (2013), in which an attempt was made to control pH through the addition of ammonium and nitrate to an algae culture in the hope that the simultaneous consumption of both would maintain a constant pH. Although failing when conducted as a batch experiment, the system was able to control pH when a fed batch system was implemented whereby ammonium nitrate was dosed to a nitrate medium containing the algae. Algae have the tendency to consume solely ammonium if given the opportunity (Fern ́andez and C ́ardenas, 1982; Florencio and Vega, 1983). As such, adding ammonium in the presence of nitrate has an immediate pH effect as the algae switch to ammonium nutrition before going back to consuming nitrate after the ammonium is depleted. Unlike algae, terrestrial plants tend to consume ammonium and nitrate in ratios corresponding to their concentration in the root zone (Song et al., 2016), making pH control through nutrient manipulation somewhat more nuanced. Moreover, if too much ammonium is present, this can have potentially lethal implications for the plants in the system as they will start suffering from ammonium toxicity (Assi-makopoulou et al., 2019; Britto and Kronzucker, 2002; Cramer and Lewis, 1993; Wang et al., 2022). This point alone discourages people from using ammonium in hydroponics, foregoing the possible benefits of operating the system at an appropriate ammonium-to-nitrate ratio.

The aim of this study is to develop a control scheme whereby pH and electrical conductivity (EC) are controlled simultaneously via the tactical addition of ammonium and nitrate. In principle, this should allow the system to harness the benefits of ammonium nutrition while avoiding the pitfalls of ammonium toxicity (Song et al., 2017). This aim is supported by two objectives. Firstly, the preference kale for ammonium and nitrate was assessed, and used to calculate the pH homeostasis point – the ammonium to nitrate ratio where the pH rise due to the absorption of nitrate is cancelled out by the pH drop from the absorption of ammonium. Secondly, having proven that the pH homeostasis point is not in the ammonium concentration range where ammonium toxicity begins to manifest, a control algorithm was developed to maintain this ratio without the need to explicitly measure the concentration of either ion.

Having identified the various mechanisms used by plants to absorb different ions, and in doing so confirmed that plants are selective of the ions they absorb, the uptake kinetics for kale were found from literature. These kinetics, in conjunction with knowledge regarding the pH effect on the root zone of the absorption and assimilation of nitrate and ammonium, were used to develop a dynamic computer model of the plant. This model was then used to develop and tune a simultaneous control algorithm making use of proportional-integral-differential (PID) control algorithm for the pH and proportional- integral (PI) control for the EC. Finally, this controller was trialled on an ebb-and-flow hydroponic system to confirm its efficacy. The results of this run were then compared to the results of a control experiment using nitrate as the only source of nitrogen to demonstrate that the inclusion of ammonium does not induce worse yields or generate less nutritious leaves than the traditional nitrate-only approach.

Section snippets

Overview

All the plants used in this study were grown from kale seeds (*B. oleracea* var. *acephala* or Vate's Blue Curled Kale), purchased from Raw™. All nutrient ions were provided by stock solutions that were made from analytical standard chemicals. Deionised water was used exclusively in all experiments for all applications that needed water.…

Analytical instruments

A UV–vis spectrophotometer (Agilent Technologies™, Cary 60 UV–vis, G6860 A) was the only analytical instrument used in this study. It was used in conjunction with…

Successful simultaneous control of pH and EC using ammonium and nitrate

The results of the sterile and non-sterile runs are shown in Fig. 4.

It is clear that in both the sterile and non-sterile runs that the system successfully con-trolled pH within the bounds of 5 and 7. pH control was actually much tighter than the required range, never deviating more than 0.5 from the set point of 6.1 except in cases of component failures. Both the sterile and non-sterile runs witnessed gradual pH oscillations around the set point with the pH getting "stuck" either above or below …

Conclusions and recommendations

As a means of controlling pH, the system is a success. pH was maintained close to the set point under both sterile and non-sterile conditions. EC was also maintained, though a more aggressive controller would probably be better, especially after the two week mark where the rate of nutrient absorption begins to outpace that of nutrient supply. Although the total nitrogen concentration was seen to decrease over time and the ammonium fraction in solution did on occasion breach the 50 % safety…

CRediT authorship contribution statement

Roger Clive Bosman: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ignatius Leopoldus van Rooyen:** Investigation. **Jacalyn Brancken:** Investigation. **Hendrik Gideon Brink:** Writing – original draft, Supervision, Formal analysis. **Willie Nicol:** Conceptualization, Supervision, Writing – review & editing.…

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Roger Clive Bosman reports financial support was provided by National Research Foundation, South Africa. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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