Review of pH recommendations for soilless cultivation systems

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Abstract

Our human population is growing, and with that, so is our demand for food, food that today still is not a guarantee for all of us. To help increase global food security, the diversification of our food production through the implementation of soilless, hydroponic cultivation systems has been suggested. In soil-based cultivation pH is a crucial parameter for the success of the system. Hydroponic cultivation, being soilless, however, raises the question if the effect of pH still applies. To increase the complexity, multiple variants of hydroponic cultivation exist. The use of a growing media, such as sand, peat moss, or perlite, is optional and liquid based hydroponic systems are commonly used for commercial applications. These liquid based, media less, hydroponic systems can potentially diverge even more regarding the effects of pH on the growth of cultivated plants. Liquid based hydroponics can be further categorized into three primary production forms, 1) deep water culture, 2) nutrient film technique, and 3) aeroponics. To shed light, in hopes of bring clarity to this matter, this study aims to summarize and evaluate how pH effects biomass production, focusing on aeroponic cultivation.

The subject was approached trough collection and review of available literature, both experimental studies and ecological theory. In combination, the content of a commercially applied aeroponic nutrient solution was also estimated.

Only four experimental studies were found, however, multiple reports referred to a general pH recommendation for optimal nutrient availability in the pH range 5.5-6.5. It is however unclear as to how accurate this applies for the different types of hydroponic systems. The theoretical effect found states that pH can have a wide range of influence. This includes factors such as hydrogen ion toxicity and pH interactions with the microbial community. The pH also affects the availability of elements through changes in solubility, formation or dissolution of precipitates, sorption to particulates, or changes of the speciation of elements to different forms or into formation of soluble complexes. Since liquid based hydroponic systems can be generally believed to lack particulates, such as solid organics and mineral particles, sorption might not be of importance in this context. This, however, suggests a highly complex interaction of pH. A complexity also indicated by the experimental trials and illustrated by the estimated nutrient solution composition. Due to this complex nature of pH, the suggested increased availability, in pH range 5.5-6.5, will not necessarily correlate to biomass production, unless availability is the limiting factor. With that said, if optimization is desired, the pH in which plant nutrients are the most available could be preferred if all other parameters are optimal, something which might be hard to achieve in practice.

Keywords: soilless cultivation, hydroponics, aeroponics, NFT, nutrient film technique, DWC, deep water culture, pH, nutrient solution, speciation, availability, biomass production.

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Abbreviations

DOC	Dissolved organic carbon.
DWC	Deep water culture.
EDTA	Ethylene diamine tetraacetic acid.
NFT	Nutrient film technique.

1. Introduction

The United Nations second sustainability goal is about creating a world free of hunger by 2030. Projections now, however, indicate that we will not be able to attain this goal in time, nor are we, despite some progress, on track to meet the global nutrition targets. In 2020, around 9.9% of our global population, between 720- and 811 million people, were affected by hunger (FAO 2021). At the same time, our global population is increasing. Mid-November 2022 the global human population reached 8 billion, it is predicted to reach 9.7 billion by 2050 and could peak at nearly 10.4 billion mid-2080:s (United Nations n.d.).

To help increase global food security, the diversification of our food production systems through the implementation of hydroponic cultivation has been suggested as being a potential part of the solution (Gashgari et al. 2018; Lakhiar et al. 2018; Khan et al. 2021).

Today, the use of hydroponic systems for cultivation has already gained a lot of attention and is used, both in small-scale urban farming (Wortman 2015), and by large commercial growers, especially in the United States, Canada, Western Europe, and Japan (Jensen 1999).

In soil-based cultivation systems soil pH is an important factor for the growth and survival of plants and all organisms that live in the soil. The soil pH can, for example, directly affect the plant through hydrogen toxicity if the pH levels are too low for what the plant is adapted to. The soil pH can also indirectly affect plants by changing the availability of ions or by effecting other organisms that interact with the plant (Mengel & Kirkby 2001; Weil 2017).

In soilless cultivations systems, like hydroponics, however, due to the lack of soil, pH might not have the same effect. This might motivate different pH recommendations for hydroponic cultivation than for soil-based systems. Something that could apply especially for liquid based variants of hydroponics, hydroponic systems which, as described by Jensen (1999), are hydroponic systems were a growing aggregate (such as sand or peat moss, which are used in aggregate type hydroponics) is not used and the plant roots, instead, are in direct contact with the nutrient solution.

In order to facilitate the use of hydroponics as a means to increase food security and the current use of it as a cultivation system, a better understanding of the science behind it would be necessary and could lead to improved recommendations for its application. For example, the innovation company Optima Planta Sweden AB uses aeroponics, a type of liquid based hydroponic system, to produce different kinds of herbs and ornamental plants and has expressed an interest to better understand the effect of pH on nutrient uptake and growth of the plants produced in their systems.

One way to evaluate this topic is reviewing the literature of previously conducted experimental research. In addition, experimental trials could be used to further evaluate the topic. Furthermore, computer models, such as Visual MINTEQ, have also been used to evaluate the effect of pH on speciation in a hydroponic nutrient solution by, e.g., Lopez-Rayo et al. (2012) and further on availability of phosphorus in similar systems by Cerozi & Fitzsimmons (2016), which could be a potential way of approaching this topic.

2. Aim

The major aim of this thesis was to review currently available literature on the effects of nutrient solution pH on biomass production in liquid based soilless cultivation systems. In addition, the use of a chemical model was explored to estimate the potential effects of nutrient solution pH on biomass production in these liquid based systems. The following question was addressed:

How does nutrient solution pH affect biomass production in aeroponic systems?

3. Background

3.1 Soilless cultivation systems

Hydroponics is the process of growing terrestrial plants in a soilless manner. The nutrient solution of a hydroponic system is the source of nutrients to the cultivated plants, and water is the solvent. The plants grown commercially in hydroponics are currently only high-quality, garden-type vegetables, which for the USA mostly consists of tomatoes, cucumbers, and specialty lettuce. These vegetables, as well as eggplant, peppers, melons, strawberries, and herbs, are commercially grown in Europe and Japan. Most hydroponic systems are also commonly inside climate-controlled structures, e.g., greenhouses, to better regulate growing conditions, such as temperature and humidity.

There are different types of hydroponic systems, which can be divided into categories: 1) liquid hydroponic systems, which are media-less- or non-aggregate systems, and 2) aggregate hydroponic systems, which are systems with a growing media that, e.g., could be sand, gravel, vermiculite, perlite, rockwool, peat moss, coir, or sawdust. These systems can then be further categorized as open (i.e., the nutrient solution is not reused once it is delivered to the plant roots) or closed (i.e., the surplus of nutrient solution is recovered, replenished, and recycled back into the system). The liquid based, media-less, hydroponic systems can be further divided into three different main types of systems: 1) deep flow hydroponics (also referred to as deep water culture, DWC), 2) nutrient film technique (NFT), and 3) aeroponics (Jensen 1999).

Deep water culture

Deep water culture (DWC) or deep flow hydroponics is a closed production system, where plants are grown on floating rafts with their roots submerged in a pool of aerated nutrient solution (**Figure 1**). This method of cultivation is common in large-scale production facilities for the cultivation of leafy vegetables and herbs (Jensen 1999).

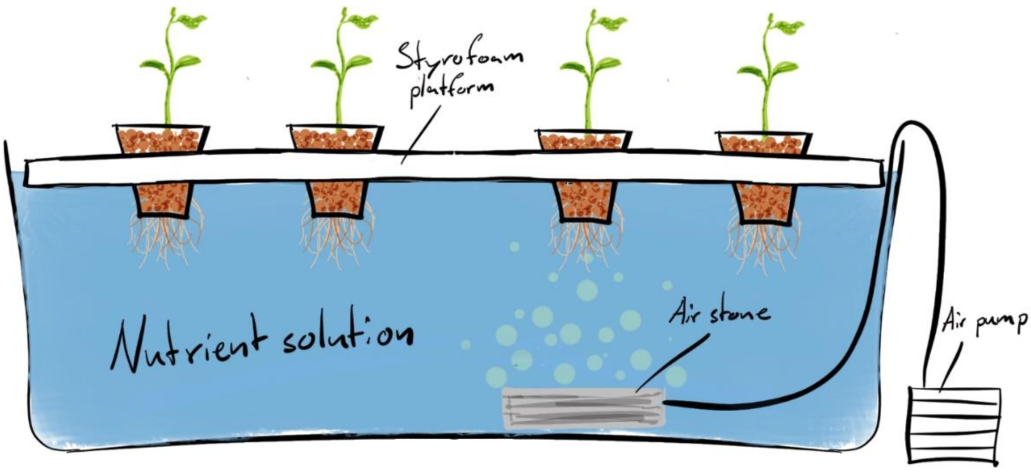

Figure 1. Schematic display of a deep water culture hydroponic system. Source: Elric Fabricius

Nutrient film technique

Nutrient film technique (NFT) is a typically closed production system where plants are grown on top of enclosed channels with their roots partially submerged into a thin film of nutrient solution that flows along the bottom of each channel. The nutrient solution is pumped up to the channels from a reservoir. It then flows by gravity to the end of the channel where it is collected and prepared for reuse and recirculation back into the reservoir. A capillary material is used in the channel to prevent young plants from drying out (**Figure 2**). This technique is used to produce leafy vegetables, mainly lettuce, but is also applied for the cultivation of tomatoes and other vegetables (Jensen 1999; Mengel & Kirkby 2001).

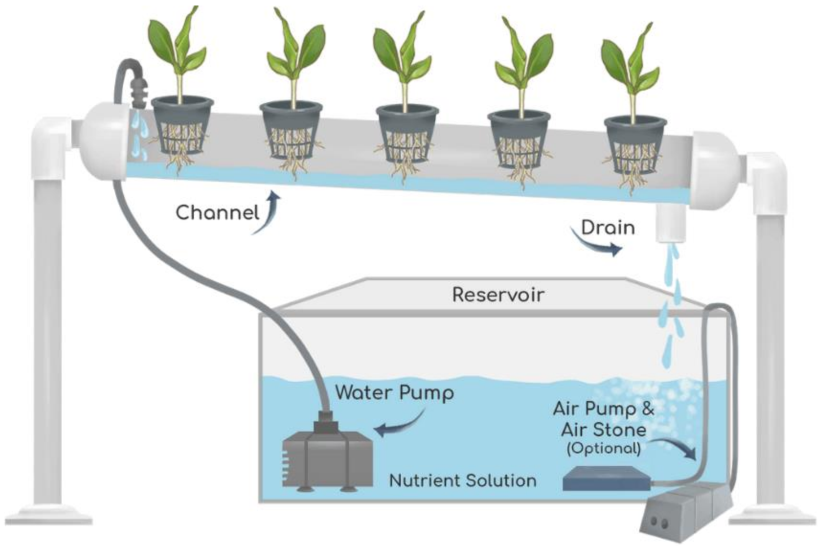

Figure 2. Schematic display of a nutrient film technique hydroponic system. Source: WhyFarmIt.com (https://whyfarmit.com/nft-hydroponics/)

Aeroponics

Aeroponics is a less common form of closed system hydroponics, where plants are grown on top of enclosed spraying boxes, which within the plant roots hang suspended midair (**Figure 3**). Within the enclosed boxes, the plant roots are spayed with a fine mist of nutrient solution by nozzles; the nutrient solution is pumped up to the sprayers from a reservoir. The nutrient solution is then collected at the bottom of the enclosed spraying box, and further treated and recirculated back to the reservoir (Jensen 1999; Lakhiar et al. 2018). Jensen (1999) states that there are no large-scale commercial growers in the United States that use aeroponics. However, several smaller companies market aeroponic systems for home use, in similarity to Optima Planta Sweden AB. Production units for leafy vegetables as well as the rooting of foliage plant cuttings are potential commercial applications of aeroponics (Jensen 1999).

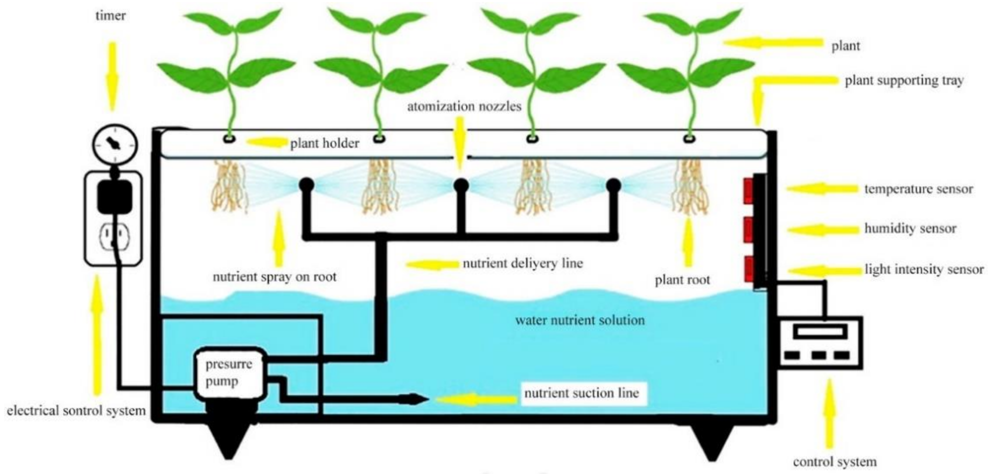

Figure 3. Schematic display of an aeroponic system. (Lakhiar et al. 2018).

3.2 Availability of plant nutrients

Nutrients are the chemical compounds that are required by plants. Plants can take up nutrients in the form of dissolved ions (**Table 1**), however, some organic complexes and -compounds can also be taken up or facilitate uptake and availability (Mengel & Kirkby 2001; Weil 2017).

Table 1. List of plant available nutrient forms (Mengel & Kirkby 2001).

Nutrient		Form for plant uptake
Nitrogen	N	NO_3^-, NH_4^+
Phosphorus	P	HPO_4^{2-}, $H_2PO_4^-$
Potassium	K	K^+
Sulphur	S	SO_4^{2-}
Calcium	Ca	Ca^{2+}
Magnesium	Mg	Mg^{2+}
Iron	Fe	Fe-ion or chelate
Manganese	Mn	Mn-ion
Boron	B	Boric acid ($B(OH)_3$), borate
Zink	Zn	Zn-ion or chelate
Copper	Cu	Cu-ion or chelate
Molybdenum	Mo	Mo-ion or chelate

Metallo-organic complexes are important for the dissolution and transport of metals and can both increase and decrease availability of elements depending on the solubility of the complex. Chelates are organic compounds with two or more atoms capable of binding to the same metal atom and thereby forming organic complexes. Chelates can be synthesized and excreted into the soil solution by plant roots or microorganisms, can be present in the soil organic matter or as synthetic compounds in micronutrient fertilizers, or can be added directly to the soil to enhance the availability of micronutrients. Ethylene diamine tetraacetic acid (EDTA) is an example of a chelate that is used to enhance the availability of micronutrients, however, EDTA does not only bind to micronutrients (Mengel & Kirkby 2001; Weil 2017). Weil (2017) discusses stability constants for metal-chelate complexes and states that even though Ca^{2+} generally has a lower stability constant than some micronutrients, e.g., for EDTA complexation, it still often replaces micronutrients from chelates because of its far greater concentration in the soil solution. This can potentially result in a need for higher chelate concentrations in order to assure the increased availability of micronutrients.

4. Methodology

The method used in this thesis was a combination of two approaches. The first approach was a review of currently available literature, in the form of an overview of both reports from experimental trails and the related ecological theory. The second approach was to collect information on what a commercial aeroponic nutrient solution could look like and to explore the possibility to estimate the concentration of its components in a modelling approach to evaluate pH-dependent changes in nutrient speciation and activity.

4.1 Literature review

The initial list of search words was refined and literature, which was then manually filtered for relevancy, was found using two search engines: PRIMO and Web of Science Core Collection.

After a list of possible search words was formulated (Appendix 1), searching for literature began using two different search engines. The first search engine used was PRIMO, a search engine provided by the SLU library. The second search engine used was Web of Science Core Collection. From the search results, new search words were found and formulated until the scope of the searches was deemed adequate. From the search results, the relevant literature was then filtered manually. This was done in two rounds, first by filtering based on the titles, where all potentially useful titles were picked. Second, the filtering was followed by ranking the relevancy of the articles based on titles and abstracts. Articles that contained experimental trials were ranked as most relevant, followed by articles that contained recommendations on pH-levels for liquid based hydroponic systems. All potentially relevant articles were sorted for if they contained experimental trials, however, due to time constraints, only some of the possibly relevant articles were checked in detail to see if they mentioned pH recommendations. This method of manual filtering was done for both the search results through PRIMO and Web of Science Core collection. However, whereas all the search results in Web of Science were filtered in this way, only the first page of results was filtered in PRIMO and the remaining, non-filtered articles where not used.

4.2 Nutrient solution composition

The content of a given commercial aeroponics nutrient solution was estimated. It was estimated to, based on its content, get a representation of its complexity to evaluate potential pH interactions when used in a soilless system. It was also estimated in preparation for a future potential evaluation of the speciation of the plant nutrients present in the solution. This was done by looking at the requirements needed to simulate accurate speciation for different pH values using the mathematical model Visual MINTEQ, a freeware chemical equilibrium model.

The name of a nutrient concentrate currently used for commercial aeroponic cultivation (product name: Wallco 51 10 43 + micro växtnäring 200L), as well as a list of the nutrient concentrations in that solution, was provided by Optima Planta Sweden AB, an indoor, vertical, aeroponics growing and innovation company located in Uppsala, Sweden. Through contact with the producer of the nutrient, Miljöcenter AB, more precise information on its content was obtained (**Table 2**).

Table 2. List of the content and concentrations of nutrients present, per 100 g [a)], in the commercial nutrient concentrate solution "Wallco 51 10 43 + micro växtnäring 200L" as provided by its producer, Miljöcenter AB.

Component/Nutrient		Weight-% [b)]	g/l [b)]
Nitrogen [c)]	N	4.6	51
Phosphorus	P	0.9	10
Potassium	K	3.8	43
Sulphur	S	0.35	4
Calcium	Ca	0.26	3
Magnesium	Mg	0.35	4
Iron	Fe	0.015	0.17
Manganese	Mn	0.017	0.2
Boron	B	0.009	0.1
Zink	Zn	0.0026	0.03
Copper	Cu	0.0013	0.015
Molybdenum	Mo	0.00035	0.004
Chelating agent	EDTA	Not specified [d)]	Not specified [d)]

[a)] Density (g/cm^3) 20ºC: 1.145 g/cm^3, pH: 3

[b)] Nutrients in oxide form.

[c)] NH^4-N/NO^3-N = 40/60

[d)] All precent trace elements (micronutrients), except Boron, are chelated using EDTA.

Estimates on dilution factors for use of the nutrient concentrate, and initial electrical conductivity of the nutrient solution used for cultivation, was also provided by Optima Planta Sweden AB. Based on this information, the potential concentrations of the nutrients in the solution were estimated (Appendix 2) and presented in the results section. A list of potential oxide forms was also comprised.

5. Results

5.1 Literature review

5.1.1 Theory of pH effects on plants

In soil-based cultivation systems, soil pH is an important factor for the growth and survival of plants and all organisms that live in the soil. Soil pH refers to the negative decadic logarithm of the concentration of hydrogen ions, [H^+], in the soil solution.

The H^+ concentration can, for example, directly affect the plant through hydrogen toxicity, if the pH levels are lower than the plant is adapted to. How well plants are adapted, can vary widely between species and even between cultivars and genotypes (Mengel & Kirkby 2001; Weil 2017). In general, Weil (2017) suggested that at pH levels below 4.0-4.5, the concentration of H^+ is toxic to some plants, mainly by causing damage to root membranes.

The direct effect of high H^+ concentrations (i.e., low pH values) on bacteria can also have an indirect effect on plants. Weil (2017) further suggested that pH levels below 4.0-4.5 kill certain soil bacteria, e.g. *Rhizobium* bacteria that enable legume plants to fixate nitrogen by supplying it to the plant. Mengel & Kirkby (2001) suggest that bacteria, in general, are more sensitive to low pH conditions than fungi and plants, and, further, that this means that bacterial breakdown of organic matter, as well as ammonification, nitrate and nitrite formation and denitrification is affected in acidic soils, especially at pH levels below 5.

The soil pH can also indirectly affect plants by changing the availability of other ions, some of which are plant nutrients whilst others can be toxic. The soil pH can change the availability of ions, e.g. by changing their solubility, favoring formation or dissolution of precipitates, by favoring adsorption or desorption of ions to organic solids and mineral particles or by changing the speciation of the ions to different forms or into forming soluble complexes (Mengel & Kirkby 2001; Weil 2017).

5.1.2 Results from experimental trials

Out of all the literature, 93 papers were deemed possibly relevant (Appendix 3). Out of these possibly relevant articles, only four reports on experimental studies were found that looked at the effect of nutrient solution pH on biomass production in media-less, liquid based, hydroponic systems: Bres & Weston (1992), Gillespie et al. (2020), Gillespie et al. (2021), Samarakoon et al. (2020).

Bres & Weston (1992) evaluated the yield of lettuce in a nutrient film technique (NFT) system at pH-levels 5.0, 5.5, 6.0, 6.5 and found no significant influence of solution pH on yield. They did, however, observe a minimally significant increase in fresh weight with increasing pH-levels. Despite the lack of an effect on fresh weight, they observed a significant influence of solution pH on foliar nutrient concentrations of P, Ca, and Mg, as the concentrations of these nutrients increased with decreasing pH.

Gillespie et al. (2020) found that the biomass production of basil in a deep water culture (DWC) system did not show any significant effect of pH (for pH 4.0, 4.5, 5.0, 5.5), where plants exhibited normal growth at pH as low as 4.0. They did however see a decline in leaf nutrient concentrations of P, Ca, Mg, S, B, Mn, and Zn and an increase in Al and K concentration with decreasing pH. They also tested adjusting the composition of the nutrient solution (0.5*(Cu, Zn Mn, B), 2*(Mo)) to compensate for the change in pH, this also showed no significant effects on growth. They concluded that more research should be conducted to better understand species-specific responses to pH and nutrient requirements before attempting to apply the practice of compensating for changes in pH by adjusting solution composition in commercial practice. They did, however, find that low pH can be an effective management strategy for suppressing *Pythium aphanidermatum,* an oomycete that causes root rot on basil.

Gillespie et al. (2021) tried cultivating spinach in a DWC system at pH levels 4.0, 4.5, 5.0 and 5.5, and found that the growth was significantly decreased by lowering nutrient solution pH and that plants showed stunted overall growth and severely inhibited root development at pH 4.0. The spinach showed normal growth at pH 4.5 and 5.0, however, significantly less than that of pH 5.5. By increasing the nutrient concentration from an electrical conductivity (EC) of 1.4 dS/m to 3.4 dS/m, they were able to effectively increase plant growth at pH 4.5, however it still showed lower growth than that of the plants grown in pH 5.5 with an EC of 1.4 dS/m. A significant decrease in leaf nutrient concentration of N, P, K, Mg, S, Cu, Fe, Mn, and Zn was observed for decreasing pH. With the increased concentration of the nutrient solution, the leaf tissue concentrations for pH 4.5 was similar or higher to that at pH 5.5, EC 1.4 dS/m, except for Mg and Zn concentrations. Gillespie et al. (2021) suggested that the lower growth observed at pH 4.5 and 5.0 most likely was due to decreased nutrient uptake and that the severe effects of stunted growth at pH 4.0 were due to direct H^+ toxicity.

Samarakoon et al. (2020) tested biomass production of lettuce grown in a NFT system at pH-levels 5.8, 6.0, 6.2, and 6.4 with an EC of 1.8 mS/cm. They found that the maximum yield was obtained between pH 6.0 and 6.2.

Multiple reports, however, suggest that optimum pH for nutrient uptake in hydroponic systems was between pH 5.5-6.5, many of them referred back to a single source: Hochmuth (1990, revised June 2001 & April 2022). Hochmuth (1990, revised June 2001 & April 2022) stated the following under section MEDIA REACTION, PH:

> "The pH of the media refers to the concentration of hydrogen ions (H+) in the media solution. The concentration is determined by a pH electrode or can be approximated by a pH color-strip paper dipped into the solution. The pH of the media solution is important because certain plant nutrition aspects are influenced by pH such as solubility of essential elements. Most elements are absorbed best from a media with a pH of 5.5 to 6.5. Media pH above 7.0 results in reduced micronutrient and phosphorus solubility. Extremely acidic pH can lead to micronutrient toxicities especially on soil-based media if manganese and aluminum are present."

What this statement was based on, however, was not found.

5.2 Estimation of nutrient solution composition

Trough contact with Optima Planta Sweden AB and Miljöcenter AB the composition of Optima Plantas nutrient solution was estimated (**Table 3**). The nutrient concentration could however not be converted from oxide form, in which they were provided by the producers, to the actual concentration of plant nutrients. This was because the oxide form was not specified, and because the term "oxide form", that is referred to when using it to describe nutrient compositions of fertilizers, can vary (**Table 4**). Because of this uncertainty, the molecular molar mass and the moles of nutrient atoms needed to convert from oxide form to plant nutrient form could not be accurately determined.

In order to use the Visual MINTEQ model to simulate the speciation and activity of a solution, the concentration of its components needs to be given as input values. Since the concentrations of all the nutrient solution components could not be accurately determined, the model simulation could not be performed for this report.

Table 3. List of the potential content and concentrations of nutrients present in Optima Planta Sweden ABs commercially applied aeroponics nutrient solution based on estimations.

Component/Nutrient		mg/l
Nitrogen [b)]	N	250 [a)]
Phosphorus	P	50 [a)]
Potassium	K	210 [a)]
Sulphur	S	20 [a)]
Calcium	Ca	15 [a)]
Magnesium	Mg	20 [a)]
Iron	Fe	0.85 [a)]
Manganese	Mn	1.0 [a)]
Boron	B	0.50 [a)]
Zink	Zn	0.15 [a)]
Copper	Cu	0.075 [a)]
Molybdenum	Mo	0.020 [a)]
Chelating agent	EDTA	Not determined [c)]
Dissolved organic carbon	DOC	10
Alkalinity	CO_2	3 Atm. [d)]

[a)] Nutrients in oxide form with concentrations rounded to two significant figures.

[b)] NH^4-N/NO^3-N = 40/60

[c)] Precent trace elements (micronutrients), except Boron, are chelated using EDTA.

[d)] Three times the atmospheric CO_2 pressure.

Table 4. List of some potential forms of plant nutrients referred to as oxide form.

Nutrient	Potential oxide forms		Forms sometimes referred to as oxide form	
Nitrogen	NO_2 [a)]	NO [a)]	NO_3^- [b)]	NH_4^+ [b)]
Phosphorus	P_2O_5 [a) b)]			
Potassium	K_2O [a) b)]			
Sulphur	SO_3 [a)]	SO_2 [a)]	SO_4^{2-} [b)]	
Calcium	CaO [a) b)]		$CaCO_3$ [b)]	
Magnesium	MgO [a) b)]		$MgCO_3$ [b)]	
Iron	FeO [a)]	Fe_2O_3 [a) c)]		
Manganese	MnO [a)]	MnO_2 [a) c)]		
Boron	B_2O_3 [a) c)]			
Zink	ZnO [a) c)]			
Copper	CuO [a) c)]	Cu_2O [a)]		
Molybdenum	MoO_3 [a) c)]	MoO_2 [a)]		

[a)] Source: Karin Hamnér

[b)] Source: (YARA 2022)

[c)] Source: Google search for “*Name of nutrient* oxide form”

6. Discussion

6.1 Literature

6.1.1 Theory

Based on the theory presented in the background, and because hydroponic cultivation typically is conducted in controlled environments, the effect of nutrient solution pH is expected to be an important factor affecting plant nutrient uptake and, in turn, growth.

In soilless cultivation systems, some of the mentioned effects of pH, however, are no longer valid because of the lack of soil and more precise control over the content of the nutrient solution. This is even more prominent for the liquid based variants of hydroponics, such as aeroponics, NFT- and DWC-systems, that can be assumed to generally lack organic solids and mineral particles that otherwise would function as adsorption places for plant nutrients. However, factors such as hydrogen ion toxicity, pH effects on the microbial community, changes in solubility, formation or dissolution of precipitates, or changes of the speciation of elements to different forms or into formation of soluble complexes, should still apply even in soilless systems.

In general, pH as a single parameter is not effective for determining biomass production. The pH-level is just one factor in a complex web of interactions of the nutrient solutions components, its surroundings, the organisms it hosts and the plants it interacts with. However, extreme pH-levels exist and can negatively affect a plant which is not adapted to that environment. Growing parameters should thereby be kept within the physiological limits of the plant that is cultivated. What the physiological limits are, however, can vary between species and possibly cultivars. Only an estimate of the lower limit was found in the literature (below 4.0-4.5 (Weil 2017)), however, it would be reasonably assumed that an upper limit also exists, where the concentration of hydroxide ions would become toxic to the plant. The effect of pH within these limits, however, depends, as stated above, greatly on the combination of other factors. Hence, for the cultivation of a specific plant species or cultivar, the effect of pH will depend on the concentrations of nutrients and other components such as dissolved organic carbons and chelates, and its microbial community.

6.1.2 Experimental trials

The 93 articles deemed possibly relevant were chosen because they were expected to contain either results of experimental trials, evaluations of the effects of pH on biomass production, or pH recommendations for production in liquid based hydroponic systems. When the articles were sorted for relevance, the papers that reported on experimental trials were deemed most relevant and got processed first. The remaining articles were then sifted through by using the search function to look for the word “pH”, to see if any recommendations on pH where mentioned. That sifting, however, proved very time consuming and only 27 out of the 89 remaining articles could be checked for this report. It is therefore possible that I missed information on possibly mentioned pH recommendations.

The four experimental studies found, Bres & Weston (1992), Gillespie et al. (2020), Gillespie et al. (2021), Samarakoon et al. (2020), suggested very different results. Gillespie et al. (2020) and Bres & Weston (1992) found that there was no significant difference in growth of basil in a deep water culture (DWC) system, or lettuce in a nutrient film technique (NFT) system, respectively, with a change in pH. Whereas Samarakoon et al. (2020) found that the maximum yield of lettuce in a NFT system was between pH 6.0-6.2, and Gillespie et al. (2021) found that the growth of spinach in a DWC system decreases with lower pH levels.

The reason for the differential results could possibly be due to differences in physiological limits and sensitivity between basil, spinach, and the different cultivars of lettuce. It could also be due to a difference in nutrient solution composition, resulting in decreased nutrient availability, or toxicity, becoming the main growth limiting factor for the DWC spinach and NFT lettuce of Samarakoon et al. (2020), whereas it did not become the main limiting factor for the DWC basil or lettuce of Bres & Weston (1992). Bres & Weston (1992), Gillespie et al. (2020), and Gillespie et al. (2021) did see a significant change in the leaf nutrient composition and thus nutritional quality when these plants are used as food. This difference could suggest a change in availability, which also was suggested by Gillespie et al. (2021), who observed increased leaf nutrient concentration at lower pH by altering the nutrient solution. Gillespie et al. (2021) changed the effect of pH by changing the composition of the nutrient solution, a procedure in line with the theoretically expected effects of pH. This suggests that the nutrient composition is an important factor affecting nutrient relations and plant growth, but that pH alone is not adequate for describing its effect on biomass production.

The fact that different pH ranges were tested might also be a contributing factor to the difference in results, where the DWC basil was tested for pH-levels 4.0, 4.5, 5.0, 5.5, and the NFT lettuce for pH 5.8, 6.0, 6.2, and 6.4. Because of this, it could be possible that a difference in the growth of basil would have been observed if the tested range had been broader and included higher pH levels. The difference in the growth of DWC spinach was within the same range as that of DWC basil, which suggests a difference in physiological limitations between the two plant species.

The conclusion that decreased pH-levels could be an effective management strategy for *Pythium aphanidermatum*-caused basil root rot by Gillespie et al. (2020) is in line with the theoretical results. It suggests that a decrease in pH can have a positive effect on growth if pathogens, such as *Pythium aphanidermatum*, are present that otherwise would cause root rot and hamper plant growth.

The general pH recommendation for nutrient availability in hydroponics, referred to by multiple articles, was in the pH range 5.5-6.5. Many of them, in the end, referred back to Hochmuth (1990, revised June 2001 & April 2022). Since the source of the statement was not found, however, it is therefore unclear what this refers to and how well it applies to different conditions and types of hydroponic systems. Hochmuth (1990, revised June 2001 & April 2022) does not mention aggregate- nor liquid based systems, which, based on the available theory, could make a difference in nutrient availability to the plants. As previously mentioned, and due to the complex nature of pH in terms of biomass production, nutrient availability is not the only determining factor. Availability can contribute; however, it is not necessarily equal to actual plant nutrient uptake, and it will not necessarily affect biomass production, unless nutrient availability is the limiting factor. With that said, if optimization is desired, the pH in which plant nutrients are the most available could be preferred if all other parameters are optimal, something which might be hard to achieve in practice.

The low number of experimental trials might suggest that the topic is not well researched. One reason may be that the standard pH recommendation often referred to is generally accepted and hence not questioned, because other factors such as nutrient solution composition, for example, are deemed more interesting to evaluate. Another reason for this may be due to the complexity of the interactions between pH, the availability of different nutrient elements, interactions between nutrients, and other factors affecting nutrient uptake and plant growth, which makes it difficult to evaluate the pH responses properly.

6.2 Nutrient solution composition

The components and concentrations of Optima Planta Sweden ABs nutrient solution are presented in Table 3. These results are, however, based on simplifications and estimates and do not represent the actual concentrations of the solution. It was found that the information provided on the nutrient solution was insufficient to determine all its components and their respective concentrations. It was therefore insufficient to use as input values into Visual MINTEQ and the model simulation could not be conducted.

As mentioned, the components with respective concentrations are only estimates and, in reality, the nutrient solution is, for example, pH adjusted, with either H_3PO_4 (phosphoric acid) or KOH (potassium hydroxide), after dilution of the nutrient concentrate, which would in turn change the nutrient composition. In most cases, the pH probably is only slightly adjusted, so the actual concentration would probably not be too different from the estimated values. The water used to dilute the nutrient concentrate is deionized, and can contain some dissolved ions, which may have a small effect on speciation of the nutrients, if the results would be used for modelling for example. The concentrations of ions of deionized water, however, are negligible in comparison to that of the nutrient solution, so it would not affect the results in a significant manner.

The nutrient concentrations presented in Table 3 are given in oxide form and not in ion form. This conversion could not be done for this report, since no information about the oxide forms could be retrieved. A possible oxide form could have been chosen; however, it was deemed too inaccurate.

The EDTA concentration was not specified and not able to be estimated accurately. Based on Miljöcenter ABs statement that all micronutrients, except boron, where chelated, it may be possible to estimate the concentration of EDTA using the theory presented in the background. The EDTA concentration could be estimated by assuming that it is proportional to the concentration of ions it can bind to in the nutrient solution. Since EDTA binds not only to micronutrients, but also to other metal ions such as Ca^{2+} ions, the concentration of Ca^{2+} of the nutrient solution might need to be compensated for. This might also be true for Mg, which can form a complex with EDTA, however, the stability constant for Mg is even lower than that of Ca, so it might not be as influential. However, if the EDTA concentrations were to be estimated, the ionic concentrations of at least all micronutrients, except boron, in combination with Ca^{2+} would also need to be estimated. Since the oxide form was not specified, however, it was deemed to inaccurate to estimate.

As described in the literature, plants can synthesize and excrete organic compounds, root exudates, and in order to compensate for this potential exudation, dissolved organic carbon (DOC) was added as a possible component of the nutrient solution at a concentration of 10 mg/l. However, this concentration was only an estimate and had no references to validate its accuracy. The actual DOC can, therefore, be vastly different. In response to the believed DOC of the solution, the alkalinity of the nutrient solution, expressed in dissolved CO_2, was estimated to be 3 times atmospheric CO_2 pressure. This was done since the presence of DOC likely would result in increased microbial activity and brake down which could increase the alkalinity of the solution. Because of the nature of an aeroponic system, however, it is possible that the gas exchange of the fine droplets of the mist spayed by the nozzles would be high enough to lower the dissolved CO_2 concentration closer to that of the air inside the sprayer box. What the CO_2 concentration inside the sprayer box is would need to be determined, however. It is also possible that the alkalinity would change dependent on the nutrient solution pH. Microbial activity and brake down would decrease if the pH were to be outside of their adapted range. Since bacteria are generally more sensitive to low pH levels it is possible that there would be a decrease in alkalinity, especially at pH levels below 5. The actual microbial activity of the nutrient solution, however, has not been determined. It is possible that it has been evaluated previously, although no information was found on that topic during this work. It would, however, be of interest to validate to be able to estimate its potential role and effect in a nutrient solution.

If it had been possible to specify the oxide forms, they could have been used to formulate rough estimates of the nutrient contents in the nutrient solution. With such an approach, the components with respective concentrations could potentially be added into a computer model, e.g., Visual MINTEQ, to give a rough estimate of the potential pH effect on speciation and activity of the nutrients. This could then potentially be used to estimate the effect on availability of nutrients and, through that, give an indication as to the effect pH could have on plant nutrient uptake and ultimately biomass production. The model could then also be used to evaluate the standard pH recommendation mentioned by some of the quoted rapports that referred back 5.5-6.5 as recommended by Hochmuth (1990, revised June 2001 & April 2022).

Finally, since aeroponics is a closed system, where the nutrient solution is recycled, even if the solution is prepared in between cycles, it is possible that the composition of the solution could change over time. If this is the case, the effect of pH could potentially vary as the composition changes.

This estimation can still give a rough idea as to what the composition of a commercially used nutrient solution for aeroponic cultivation may look like and serves as a demonstration of the complexity of a nutrient solution and its effect on plant nutrient uptake and growth. The fact that it can contain EDTA, for example, is an important remark, since the presence of EDTA, as a chelate, can affect and change the potential pH effect on nutrient availability and, in turn, its potential effect on biomass production.

To get more accurate results from potential future modelling, however, the nutrient solution should be analyzed to accurately determine its components and their respective concentrations. Since, e.g, plants and microorganisms can synthesize and excrete chelates of their own, it is possible that the nutrient solution is even more complex than suggested by this estimation.

6.3 Potential future studies

Chemical modelling could potentially be performed as a means of estimating the effect of pH on plant nutrient uptake and growth. To get the most accurate results, however, the components of the nutrient solution need to be determined as accurately as possible, preferably by analyzing the solution.

Experimental trials could be performed to get a more accurate effect of pH determined on the actual biomass production. Because of the complexity of the interaction of pH, however, since the effect of pH on nutrient uptake and growth can vary dependent on crop species and cultivar, the composition of the nutrient solution and the microorganisms it hosts, these parameters should be as close as possible to the actual growing conditions of the crop in question. A potential set up for such a trial could be to growing the same cultivar of plants in an array of different pH-levels, in similarity to the experimental trials that were found in this thesis, in the same type of cultivation system, e.g. aeroponics, with the same nutrient solution. Preferably this array of pH-levels would be as wide as possible to include extreme values in order to get a more complete picture, e.g. in the range of pH 1.0-13.0, e.g. with intervals of 0.5 pH levels. Symptoms of potentially stunted growth and final dry- and fresh weight could then be measured after cultivation to determine the effects of pH. In addition, analysis of both plant-, e.g. leaf, nutrient concentrations and nutrient solution concentrations could be performed to potentially give a reason as to why a potential change occurred. Nutrient solution microbial activity could also be a parameter of further interest to evaluate in these trials, something which might also give a further explanation to a potential change. The plant species, cultivar, production system and nutrient solution should, however, be as close as possible to the actual conditions in the commercial production system where it is grown.

Further evaluations, in the form of experimental trials, could also be conducted to find the physiological pH limitations for different plants cultivated in liquid based hydroponic systems, since it does not seem to be determined.

7. Conclusion

In conclusion, if the plant is not adapted to the pH of the nutrient solution, then it can be directly toxic to the plant. However, as suggested by the theoretical effect of pH and further suggested by the differences in results observed in the experimental trials, the other indirect effects of pH are dependent on a combination of multiple factors to have an influence on the plant, for example on its biomass production.

The question addressed by this thesis was ‘How does nutrient solution pH affect biomass production in aeroponic systems?’, and the answer is: It depends! The nutrient solution pH only plays a small part in a complex web of interactions regarding the nutrient solution composition, its environment, the organisms it hosts and the plants that are cultivated. Nutrient solution composition, such as the described representation of a commercially applied aeroponics solution, demonstrates some of its potential components, components that further increase the complexity of these interactions. Hosted organisms, such as the pathogens described in the experimental trials, possibly controlled by pH regulation, and if present, can turn an otherwise less desirable pH into a more appropriate one. Plants, even cultivars, as suggested by theory and further indicated by trials, can show vast differences in susceptibility and tolerance of different pH-levels. The effect of nutrient solution pH is, therefore, highly situational and should be tailored to the specific conditions that apply in the growing environment.

The low number of discovered experimental trials may also be a testament to the complexity of these interactions. Or potentially a sign of general acceptance of the commonly referred to pH recommendation of 5.5-6.5.

Nevertheless, these interactions, and the mechanisms behind them, are important to grasp in order to be able to effectively manage these systems - these potential bringers of increased food security to our hungry world.

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From the bottom of my heart, thank you.

Appendix 1

This appendix contains a list of all searches that were made, and how many of the search results that were deemed possibly relevant.

Webb of Science Core Collection searches:

Topic: pH
AND Topic: aeroponi*
Results: 38
Filter: Citation Topics Meso: Crop Science or Soil Science
Results: 13

Topic: pH
AND Topic: aeroponi* OR DWC OR "Deep water culture" OR NFT OR "Nutrient film technique"
Results: 199

Topic: pH
AND Topic: aeroponi* OR DWC OR "Deep water culture" OR NFT OR "Nutrient film technique"
AND Topic: yield OR biomass OR growth
Results: 111
1:st sorting: 53

PRIMO searches:

pH nutrien* availab* hydroponi*
pH nutrien* availab*
opti* pH* hydroponi*
pH* recommend* hydroponi* (filter for hydroponics)
The nature and properties of soils
Principles of plant nutrition
Handbook of plant nutrition

Appendix 2

This appendix contains the calculations of the estimation of Optima Planta ABs potential nutrient solution.

Estimation of dilution factor (F_D), both calculated based on electrical conductivity (EC) and Optima Plantas estimated dilution:

Optima plantas estimated dilution:

Provided information: 5 ml Wallco per 1 l deionized water.

5 ml nutrient concentration ($V_{conc.}$) / 1 l deionized water $\left(V_{diH_2O}\right)$ =>

$$F_D = \frac{V_{tot.}}{V_{Conc.}} = \frac{V_{Conc.} + V_{diH_2O}}{V_{Conc.}} =>$$

$$=> F_D = \frac{V_{Conc.} + V_{diH_2O}}{V_{Conc.}} = \frac{5\,ml + 1000\,ml}{5\,ml} = \frac{1005\,ml}{5\,ml} = 201$$

Dilution factor calculated from EC:

Provided information: Initial EC of nutrient solution $= 1000\ \mu S/cm$

$$1000\ \mu S/cm = 1\ mS/cm$$

Formula to convert EC to total dissolved solids (TDS):

$$1\ mS/cm = 640\ mg/l \pm 64\ mg/l =>$$

$$=> TDS_{Solution} = 640\ mg/l \pm 64\ mg/l =>$$

$$=> TDS_{Solution\ Max} = 640\ mg/l + 64\ mg/l = 704\ mg/l$$

$$=> TDS_{Solution\ Min} = 640\ mg/l - 64\ mg/l = 576\ mg/l$$

$$Tabel\ 2 => TDS_{Conc.} = 115.519\ g/l\ = 115{,}519\ mg/l$$

$$F_D = \frac{TDS_{Conc.}}{TDS_{Solution}} =>$$

$$=> F_{D\ Max} = \frac{TDS_{Conc.}}{TDS_{Solution\ Min}} = \frac{115{,}519\ mg/l}{576\ mg/l} \approx 201$$

$$=> F_{D\ Min} = \frac{TDS_{Conc.}}{TDS_{Solution\ Max}} = \frac{115{,}519\ mg/l}{704\ mg/l} \approx 164$$

Conclusion of dilution factor (F_D):

Optima Plantas estimated dilution factor correlates closely enough to the one calculated based on initial nutrient solution EC. Optima Plantas dilution factor is therefore accepted as the one used.

Calculation of diluted concentrations, i.e., the conversion from nutrient concentrate concentrations ($[nutrient]_{Conc.}$) to aeroponic nutrient solution concentrations ($[nutrient]_{Solution}$):

Formula used:

$$\frac{c_{Conc.}}{F_D} = c_{Solution} = \frac{[nutrient]_{Conc.}}{201} = [nutrient]_{Solution}$$

Appendix 3

This appendix is a complete list of all the literature that was found and deemed possibly relevant.

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