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ARTICLE

Nutrient supply of plants in aquaponic systems

Andras Bittsanszky [a], Nikolett Uzinger [b], Gabor Gyulai [c], Alex Mathis [d], Ranka Junge [d], Morris Villarroel [e], Benzion Kotzen [f], Tamas Komives [a,g]

Plant Protection Institute, Hungarian Academy of Sciences, Centre for Agricultural Research, 1022 Budapest, Hungary, [b] Institute for Soil Science, Hungarian Academy of Sciences, Centre for Agricultural Research, 1022 Budapest, Hungary, [c] Department of Genetics and Plant Breeding, Szent István University, 2103 Gödöllő, Hungary, [d] Zurich University of Applied Sciences, Institute of Natural Resource Sciences, Grüental, 8820 Wädenswil, Switzerland, [e] Ciudad Universitaria s/n ETSI Agrónomos Universidad Politécnica de Madrid, 28040 Madrid, Spain, [f] Department of Architecture and Landscape, University of Greenwich, London SE10 9BD, UK, [g] Department of Environmental Science, Esterhazy Karoly University, 3200 Gyongyos, Hungary

E-mail of the corresponding author: bittsanszky.andras@agrar.mta.hu

Abstract – In this preliminary article we present data on plant nutrient concentrations in aquaponic systems, and compare them to nutrient concentrations in "standard" hydroponic solutions. Our data shows that the nutrient concentrations supplied by the fish in aquaponic system are significantly lower for most nutrients, compared to hydroponic systems. Nevertheless, plants do thrive in solutions that have lower nutrient levels than "standard" hydroponic solutions. This is especially true for green leafy vegetables that rarely need additional nutritional supplementation. It is concluded that in the highly complex system of aquaponics, special care has to be taken, *via* continuous monitoring of the chemical composition of the circulating water, to provide adequate concentrations and ratios of nutrients, and special attention has to be paid to the potentially toxic component, ammonium. If certain plants require nutrient supplementation, we consider that one based on organic substances would be most beneficial. However, protocols for the application of such nutrient amendments still need to be developed.

Keywords: aquaponics, plant nutrition, macronutrients, micronutrients, nutrient supplementation, mineral fertilizers, organic fertilizers

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In Bittsanszky et al. (2015), we recently, briefly discussed the problems related to plant protection in aquaponics and here we raise the equally important question of dealing with plant nutrition in these systems. The basic question we address is how to manage nutrient levels in a recirculating water system in order to provide plants with optimum concentrations whilst avoiding any negative impact on the fish and the beneficial microorganisms within the system.

Table 1. Essential elementary nutrient requirements of the three basic compartments of an aquaponic system

Aquaponic compartment	**Element**																						
	Boron	Calcium	Carbon	Chlorine	Cobalt	Copper	Chromium	Fluorine	Hydrogen	Iodine	Iron	Magnesium	Manganese	Molybdenum	Nitrogen	Nickel	Oxygen	Phosphorous	Potassium	Sodium	Sulfur	Zinc	Selenium	Silicone
Fish [a]	-	M	M	M	µ	µ	µ	µ	M	µ	µ	M	µ	µ	M		M	M	M	M	M	µ	µ	-
Plant [b]	µ	M	M	M	µ	µ	-	-	M	-	µ	M	µ	µ	M	µ	M	M	M	-	M	µ	µ	µ
Biofilter [c]	-	M	M	µ	µ	µ	-	-	M	-	µ	µ	µ	µ	M		M	M	M	µ	M	µ	µ	-

[a] This study; [b] (Epstein and Bloom, 2005) (Trejo-Téllez and Gomez-Merino, 2012); [c] (Kantartzi et al., 2006); M: macroelements; µ: microelements; -: not present.

Table 2. Concentrations of macronutrients in aquaponic and standard hydroponic* systems

Nutrient	**Concentration (mean ± standard error)** mg/l		**Concentration ratio** (hydroponic/aquaponic)
	Aquaponics (measured data)	**Hydroponics** (optimized for plants)	
P (as PO_4^{3-})	6.6 ± 1.0	36.9 ± 6.2	5.59
Total N	10.6 ± 2.1	321 ± 130	30.3
K^+	50.8 ± 11.9	340 ± 101	6.7
Ca^{2+}	129.6 ± 18.5	160 ± 10	1.2
Mg^{2+}	20.9 ± 1.1	40.9 ± 3.3	2.0
SO_4^{2-}	88.3 ± 12.2	134 ± 53	1.5

* Hydroponic data were calculated as means from concentrations in nutrient solutions described by Hoagland and Arnon, Hewitt, Cooper, Steiner (Epstein and Bloom, 2005) (Trejo-Téllez and Gomez-Merino, 2012), and Murashige and Skoog (1962) (Murashige and Skoog, 1962). Aquaponic data were measured and averaged as described in the Methods.

Table 3. Concentrations of micronutrients in aquaponic and standard hydroponic* systems

Nutrient	**Concentration (mean ± standard error)** mg/l		**Concentration ratio** (hydroponic/aquaponic)
	Aquaponics (measured data)	**Hydroponics** (optimized for plants)	
B (as $B[OH_4]^-$)	0.0799 ± 0.0017	0.573 ± 0.134	7.2
Co^{2+}	0.0014 ± 0.0001	0.0065**	4.6
Cu^{2+}	0.0783 ± 0.0032	0.0420 ± 0.0174	0.5
Fe^{2+}	0.0852 ± 0.0068	5.18 ± 1.79	60.8
Mn^{2+}	1.195 ± 0.0022	1.83 ± 0.96	138.7
Mo (as MoO_4^{2-})	0.0032 ± 0.0001	0.0872 ± 0.0374	27.25
Zn^{2+}	0.168 ± 0.0042	0.455 ± 0.374	13.8

* Hydroponic data were calculated from concentrations in nutrient solutions described by Hoagland and Arnon, Hewitt, Cooper, Steiner (Epstein and Bloom, 2005) (Trejo-Téllez and Gomez-Merino, 2012), and Murashige and Skoog (Murashige and Skoog, 1962). ** Cobalt is listed only in Murashige-Skoog (1962) solution but not in others.

Plants require 17 essential nutrient elements (Table 1) without which they are unable to complete a normal life cycle (Epstein and Bloom, 2005) (Trejo-Tellez and Gomez-Merino, 2012). Cobalt is only listed in the Murashige-Skoog nutrient solution (Murashige and Skoog, 1962). Of these nutrient elements oxygen (O), hydrogen (H), and carbon (C) are typically categorized as non-mineral. Nitrogen (N), phosphorus (N), and potassium (K) are considered as primary macro-nutrients, and calcium (Ca), sulfur (S), and magnesium (Mg) as secondary ones. Boron (B), chlorine (Cl), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo), and nickel (Ni) are categorized as micronutrients or trace minerals. All plants, with the exception of parasitic and carnivorous ones, absorb the essential nutrient elements from the air or soil solution (Epstein and Bloom, 2005).

It should be noted that in contrast to plants, fish nutrition is very different. The composition of fish feeds depends on the nature of the fish: whether it is carnivorous, omnivorous, or herbivorous. Typically, fish feed contains an energy source (carbohydrates and/or lipids), essential amino acids (10 amino acids that fish cannot synthesize out of the 20 protein-building ones), vitamins, as well as other organic molecules that are necessary for normal metabolism but that fish cells cannot synthesize, and altogether 21 different macro- and micro-minerals (Table 1) (Davis, 2015). Nutrient deficiencies in fish are often accompanied by disturbances in the balance of other minerals (Bijvelds et al., 1998).

Microbial communities (consisting of bacteria, protozoa, and micrometazoa, located in the biofilter and on the roots of plants) play major roles in the nutrient dynamics in aquaponic systems (Munguia-Fragozo et al., 2015). Their primary role is to convert ammonium to virtually non-toxic nitrate but they also contribute to the processing of particulate matter and dissolved waste in the system. Both functions are absolutely crucial for the stability of an aquaponic system (Goddek et al., 2016, Munguia-Fragozo et al., 2015). Unfortunately, very little is known about the nutrient requirements and potential sensitivities of these microbial communities to variations in the availability of nutrients (Kantartzi et al., 2006). (Data for *Nitrobacter* and *Nitrosomonas* bacteria are presented in Table 1).

Triplicate samples for this study were taken on 23 March, 2016, and 15 September 2015 from three stable aquaponic systems operating in Hungary (Plant Protection Institute) and Switzerland (Institute of Natural Resource Sciences), respectively. The two systems (ebb and flow, Hydroton) in Hungary had a 55 L water holding capacity with African catfish (*Clarias gariepinus*, 21 months old) at a density of 8.2 kg in 45 L water. Fish and fish feed (88.0% dry matter; 42.0% crude protein; 11.0% crude fat; 1.2% crude fiber; 2.1% lysine; 1.0% methionine; 1.1% methionine + cystine; 1.4% Ca; 1.3% P; 0.3% Na; supplied once a day at 1% fish mass ratio) were obtained from the Fish Research Institute, Szarvas, Hungary. The plants grown in the system were tomatoes (*Solanum lycopersicum*, San Marzano variety, 7 weeks old, total fresh weight 385 g at the time samples were taken). The general outline of the system in Switzerland is described by Graber et al. (2014). The aquaculture subunit (3.7 m^3) consisted of a fish tank, drum filter, moving-bed biofilter, oxygenation zone, and solids thickening unit (radial flow settler - RFS). Biofilters were connected to the plant sump, to where water was pumped every 30 minutes. In contrast to the regular operation mode, the system was operated as decoupled system: from the aquaculture unit, water was pumped continuously to an algae cultivation unit, where it evaporated, so no water was being recycled to the fish tank. The fish tank was stocked with 149 Nile tilapia (*Oreochromis niloticus*), with an average weight of 0.57 kg (total biomass was 84.5 kg) on the 26th of August 2015 (the nearest assessment date. Fish were fed approximately 2% of their body weight per day, distributed over six automated feedings (7:00, 8:00, 10:00, 12:00, 15:00, 17:00) with swimming pelleted feed (Tilapia Vegi, 4.5 mm, supplied by Hokovit – Hofmann Nutrition AG, Switzerland). There was no nutrient supplementation.

The “total” and soluble element contents were determined using a sequential ULTIMA 2 ICP-AES instrument (Jobin-Yvon Ultima 2 sequential instrument, Horiba Ltd., Japan). For element analyses, Merck calibration standards were used. The measurements were performed according to the manual of the instrument.

The results are listed in Tables 1, 2, and 3. The data clearly show that most plant nutrients (with the exception of Cu^{2+}, SO_4^{2-}, and Ca^{2+}) were at significantly lower concentrations in the research aquaponic systems as compared with the standard hydroponic solutions. The differences were highest in the case of Fe^{2+} and Mn^{2+} (with ratios 68.5 and 138.7, respectively). Unfortunately, a clear interpretation of the data is very challenging. The reason is that very recently (Parent et al., 2013, Baxter, 2015) in plant nutrition the nearly two-century-old “Liebig's law” (briefly, plant growth is controlled by the scarcest resource) has been superseded by complex algorithms that take the interactions between the individual nutrient chemicals into account. These methods do not allow a simple evaluation of the effects of changes in nutrient concentrations in a hydroponic or aquaponic system.

Also, we must bear in mind that a perfect formulation of nutritional requirements for a particular crop does not exist. The nutritional requirements vary with variety, life cycle stage, day length, and weather conditions.

Usually, in aquaponics, with appropriate fish stocking rates the levels of nitrate are sufficient for good plant growth, whereas the levels of K^+ are generally insufficient for maximum plant growth. Additionally, phosphorous, calcium and iron could be limiting (A. Mathis, unpublished).

The question thus arises whether it is necessary and effective to add nutrients to aquaponic systems. According to the experience in Waedenswil (A. Mathis, unpublished data) the necessity to add nutrients depends on the growth stage of the plant in consideration. Provided that the system is stocked with enough fish, it is not necessary to add nutrients for plants with short cropping cycle which do not produce fruits (e.g. salads). In contrast to, for example, lettuce, tomatoes which need to bear fruit, mature and ripen, need supplemental nutrients. In such cases, HydroBuddy is available as free software (Fernandez, 2016) to calculate the amount of required mineral nutrient supplements.

In addition to our experience in supplementing mineral nutrients, we suggest that tests are conducted using commercially available organic hydroponic fertilizers in order to ascertain which ones are less harmful to fish life. Recently, the treatment of the fish sludge in a digester, and re-introduction of this digestate into the water system has been suggested to increase nutrient supply to plants (Goddek et al. 2016). Another possible benefit of supplying the aquaponic system with organic, instead of mineral, nutrients could be a positive effect on the microbial population.

In conclusion, we consider aquaponics as a very promising and, at the same time, complex food production technology. Such complex systems can only be operated successfully, if special care is taken through the continuous monitoring of the chemical composition of the recirculating water for adequate concentrations and ratios of nutrients and of the potentially toxic component, ammonium. Further research is necessary to develop the protocols for the use of organic fertilizers.

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