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# Nutrient Solution and Solution pH Influences on Onion Growth and Mineral Content*

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## ABSTRACT

The effects of hydroponic nutrient solution composition and pH on growth and mineral content of green onions was evaluated. Three onion varieties [*Allium cepa* L. ('Deep Purple' and 'Purplette') and *A. fistulosum* L. ('Kinka')] were propagated in three nutrient solutions (Peter's Hydro-Sol, modified Hoagland's, and half-strength modified Hoagland's) at two pH levels (5.8 and 6.5) in a three-by-two factorial design applied in a randomized block with three replications. Seeds were germinated in Cropking's Oasis Horticubes under greenhouse conditions and irrigated with tap water. Once the seedlings reached the flag stage, the plants were placed into hydroponic units within the greenhouse and grown under ambient conditions. Plants were harvested 30 d after transplanting to the hydroponic units. The results indicated nutrient solution, pH, and variety significantly affected several plant physiological variables. Total biomass and edible biomass production was as high for plants grown in half-strength Hoagland's nutrient solution as for those grown in the other solutions. Total biomass was greatest for plants grown at a solution pH of 6.5. 'Deep Purple' produced a significantly greater overall total biomass than did 'Purplette' or 'Kinka.' Hydro-Sol tended to produce onions with highest mineral content. Due to the fact that biomass production was as great in the half-strength Hoagland's as in the more concentrated solution and that a pH of 6.5 produced greater total biomass, the half-strength Hoagland's solution at pH 6.5 was the preferred nutrient solution evaluated in this research. Selection of an appropriate nutrient solution must consider both edible biomass production and mineral content. In the research reported here, the solution that produced the greatest biomass did not produce plant material with the highest mineral content.

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## INTRODUCTION

Hydroponics have been defined as the practice of growing plants using only water as a substrate with the addition of essential nutrients and is one of many methods used in nutrient-delivery systems (Goins et al., 1997; Resh, 1998). High plant-growth rates that produce a consistent yield may be maintained in a relatively small root zone by growing plants hydroponically (Steinberg et al., 2000). Since the 1980s, hydroponic units have been commercialized for vegetable and flower production, and today more than 60,000 Ha of vegetables are grown hydroponically in greenhouses worldwide (Jones, 1997).

System supports, water, nutrients, and root aeration factors must be considered when using hydroponic units, as plants are grown without soil (Jones et al., 1998). Oasis Horticubes (Smithers-Oasis, Kent, Ohio) are often used because they are sterile, provide good drainage, are easy to handle, and have a stable pH (Resh, 1991). Constant maintenance and pH monitoring are the main concerns when using hydroponic solutions.

Most modern hydroponic solutions are based on the work of Hoagland and Arnon (1950) and have been adapted to numerous crops (Whipker and Hammer, 1998). More recently, Spomer et al. (1997) recommend a nutrient solution equal to about one-half the strength of the original Hoagland's nutrient solution (Hoagland and Arnon, 1950). However, since many nutrients need to be added individually, preparing the Hoagland's nutrient solution can be a laborious process. Alternatively, a premixed hydroponic fertilizer called Hydro-Sol (Peter's Hydro-Sol, Scotts-Sierra Horticultural Product Co., Marysville, OH) is commercially available.

The form and concentration of nitrogen (N) are especially important in hydroponic systems. Barker and Mills (1980) reported that high concentrations of $NH_4^+$-N in solution can be toxic to plants. Conover and Poole (1986) reported that the grade, length, and height of several horticultural crops were increased when N sources contained 25% to 100% $NH_4^+$-N. Whipker and Hammer (1998) reported that 12.5% to 33% of the N in hydroponic solutions should be in the form of $NH_4^+$. The modified Hoagland's solution used by Jasoni et al. (2002) contained 16.7% $NH_4^+$, and Peter's Hydro-Sol contained 100% $NO_3^-$.

Trewanas (1983) reported that $NO_3^-$ frequently plays a role in plant developmental processes such as onion bulbing, which involves dormant structure formation and an increase in soluble carbohydrate-to-N ratio. Onion bulb weight-to-leaf blade ratio has been shown to increase with decreased soil-N levels (Brewster and Butler, 1989). Applications of N at early stages of growth promote onion bulbing, while lower levels delay it (Henriksen, 1987).

Excess N can encourage foliar growth and depress onion bulb growth (Brewster, 1990), but in later stages of plant development it can result in the formation of soft bulbs and may prolong the maturation process, in turn affecting product handling and post-harvest quality of bulbs (Riekels, 1977). Randle (2000) found that with an increased N concentration (0.97 $gL^{-1}$) in a hydroponic solution, onion bulb weight and firmness decreased while yield increased. This study also determined that an increase in N content in hydroponic solutions used to propagate onions increased total N content and Potassium (K) content and decreased boron (B), calcium (Ca), and magnesium (Mg), contents, but showed no direct effect on copper (Cu), iron (Fe), phosphorus (P), and zinc (Zn) (Randle, 2000). Siddiqi et al. (1998) reported that when using hydroponic systems, $NO_3^-$, P, and K concentrations may be reduced by up to 25% of the concentrations that were currently being used in commercial greenhouses without any adverse effects on tomato (*Lycopersicon esculentum* L.) fruit yield or quality. No adverse effects on tomato morphology (e.g., dry matter, elemental composition, appearance, size, and shape) were observed for tomatoes grown at lower nutrient concentrations (Siddiqi et al., 1998). Increased N concentrations resulted in increased tomato plant height and leaf length, increased flower number, and increased marketable fruits per plant (Adams et al., 1973).

Asher and Ozanne (1967) found that an increase in K in the nutrient solution increased the K content and yield of both the shoots and roots of several pasture crop species. Decreases were observed in the root:shoot ratio and the dry matter percentage of fresh shoots and roots when solution K was increased (Asher and Ozanne, 1967). The percentage of K in the leaves and the total uptake of K by tomatoes were controlled significantly by the N concentration in the nutrient solutions (Adams et al., 1973).

In addition to nutrient concentration, plant growth can be affected by pH. Even though there is a broad range for optimal pH, a pH of 5.8 is considered best for optimal nutrient availability in hydroponics (Bugbee, 2003). Islam et al. (1980) reported that a pH range of 5.5 to 6.5 is optimal for the availability of nutrients from most nutrient solutions for most species. The availability of Mg, Ca, K, and P is slightly decreased at higher pH, while the availability of manganese (Mn), Cu, Zn, and especially Fe is significantly reduced (Bugbee, 2003).

With limited information available on hydroponic solutions for onion production, a need exists to determine a suitable hydroponic nutrient solution that can be used for physiological and mineral-content studies of onions. Due to the ubiquity of the Hoagland's nutrient solution, the recommendation (Spomer et al., 1997) of using a half-strength Hoagland's solution, and the convenience of Peter's Hydro-Sol, these nutrient solutions were selected for this study. Additionally, the recommended pH levels of 5.8 and 6.5 were compared.

The objectives of this experiment were to assess the effects of nutrient solution composition (Hoagland's, half-strength Hoagland's, and Peter's Hydro-Sol) (Table 1), solution pH (5.8 and 6.5), and variety [*A. cepa* 'Deep purple' and 'Purplette' (Johnny's Selected Seeds; Albion, ME), and *A. fistulosum* 'Kinka'

Table 1
Composition of hydroponic nutrient solutions

| | Modified Hoagland's | Modified 1/2 Hoagland's | Hydro-Sol** |
|---|---|---|---|
| Macronutrients (mM) | | | |
| N | 12.0 | 6.0 | 10.7 |
| P | 2.0 | 1.0 | 1.6 |
| K | 6.0 | 3.0 | 5.4 |
| Ca | 4.0 | 2.0 | 3.2 |
| Mg | 2.0 | 1.0 | 1.2 |
| S | 2.0 | 1.0 | 0.4 |
| Micronutrients ($\mu$M) | | | |
| B | 50.0 | 25.0 | 46.3 |
| Mn | 10.6 | 5.3 | 9.1 |
| Zn | 7.7 | 3.8 | 2.3 |
| Cu | 8.0 | 4.0 | 2.4 |
| Mo | 0.5 | 0.26 | 1.0 |
| Cl | 121.0 | 60.7 | NR |
| Na | 100.0 | 50.0 | NR |
| Fe | 107.0 | 53.7 | 53.7 |

*Jasoni et al., 2002.
**Provided on product label (NR = Not Reported).

(Kyowa Seed Co., Chiba, Japan)] on physiological variables and mineral content of onions grown hydroponically.

## MATERIALS AND METHODS

Onions were grown hydroponically in custom-made hydroponic units. The hydroponic units (152 × 81 × 66 cm) were constructed from polyvinyl chloride (PVC) pipe and a fountain pump (115 V Versa Gold Series; Breckett Corp., Irving, TX) with gravitational flow producing a mean flow rate of 0.02 L $s^{-1}$. The hydroponic units were placed within the Texas Tech University Horticultural Gardens Greenhouse and Complex, Lubbock, Texas (lat 33°N, long 101°W). Nutrient solution was circulated past the plant roots and returned to a solution reservoir. Nutrient solution level was monitored daily and maintained at 80 L of solution. The average daytime temperature was 29.5° C, and the average nighttime temperature was 18.6°C. Temperature was recorded every 960 s using a data logger (Hobo H8 series; Onset Computer Corp., Bourne, MA). Greenhouse temperature was controlled using fan and cooling pad units and a 40% shade cloth. The average relative humidity ranged from nighttime 30.7% to daytime 63.5%. The three replications occurred between May 2002 and August 2002.

Three onion varieties ('Deep Purple,' 'Purplette,' and 'Kinka') were propagated in three nutrient solutions: modified Hoagland's (Jasoni et al., 2002), half-strength modified Hoagland's, and Peter's Hydro-Sol water-soluble fertilizer at two pH levels (5.8 and 6.5) in a three-by-two factorial applied in a complete randomized block design with three replications. The composition of the modified Hoagland's concentrate was 2 mM $NH_4H_2PO_4$, 6 mM $KNO_3$, 4 mM Ca $(NO_3)_2{\cdot}4H_2O$, 2 mM $MgSO_4{\cdot}7H_2O$, 50 $\mu$M $H_3BO_3$, 10 $\mu$M $MnCl_2{\cdot}4H_2O$, 7.6 $\mu$M $ZnSO_4{\cdot}7H_2O$, 8 $\mu$M $CuSO_4{\cdot}5H_2O$, 0.40 $\mu$M $Na_2MoO_4$, 0.10 mM NaCl, 90 $\mu$M Na EDTA, and 89 $\mu$M $FeSO_4{\cdot}7H_2O$ (Jasoni et al., 2002). The nutrient concentrations of the modified Hoagland's solution were reduced to one-half to prepare the half-strength modified Hoagland's solution. The Hoagland's, half-strength Hoagland's, and Hydro-Sol pH levels were 5.0, 4.4, and 4.2, respectively, prior to adjustment. The nutrient solution pH was adjusted using KOH and monitored using a pH meter (Piccolo, Hanna Instruments, Bedfordshire, UK).

Onion seeds ('Deep Purple,' Purplette,' and 'Kinka') were germinated in Cropking's Oasis Horticubes growing media. The Oasis was cut to a 2 cm height with both top and bottom sides level, forming a 6 cm diameter puck. The Oasis Horticubes pucks were autoclaved for 2 h at 15 psi and 121°C prior to sowing. Six seeds were sown 0.75 mm deep in a circular arrangement in each puck. One set of 80 pucks was sown per onion variety. The pucks were placed in 38 × 53 cm trays in the greenhouse and irrigated with tap water. Once seedlings reached the flag stage at approximately 12 d after planting (dap), they were placed randomly into the hydroponic units within the greenhouse. The onions were thinned to one plant per puck and grown under ambient conditions for 30 d. Each hydroponic unit contained 12 plants of each onion variety.

The plants within the Oasis pucks were harvested at approximately 42 dap. The plants were placed individually in Ziplock bags and labeled according to variety and treatment. The following phenotypic data were collected (fresh-weight basis): total biomass, root mass, shoot mass, and bulb mass (slightly bulbing region for 'Deep Purple' and 'Kinka'). To provide adequate biomass for analyses, the plants were composited into shoots, bulbs, and roots by variety and treatment. The plant shoots, bulbs, and roots were chopped into pieces of less than 5 cm and immediately frozen in liquid $N_2$. After freezing, plant material was ground in a coffee grinder (Mr. Coffee, Hattiesburg, MS) for approximately 60 s. The ground plant material was immediately placed into Ziplock bags and stored in a −20°C freezer.

To determine dry-matter percentage, duplicate 1 g samples of frozen plant material powder were placed into small, pre-weighed ceramic crucibles, placed into a vacuum oven, and dried for at least 16 h at 100°C (AOAC, 1990). Samples were removed from the oven and placed into a desiccator to cool. Once the samples were cooled, duplicate samples were weighed to determine dry weight. Dry-matter percentage was calculated by dividing the fresh weight into the dry weight, and multiplying by 100. Duplicate samples were averaged.

To determine percentage ash, approximately 1 g of frozen plant material was placed into a pre-weighed ceramic crucible. Samples were dried and placed into a muffle furnace for at least 16 h at 500°C following AOAC Method 900.02 (AOAC, 1990). Samples were removed, placed into a desiccator for cooling, and weighed. The weight recorded minus the weight of the crucible was recorded as the ash weight. To calculate percentage ash, the ash weight was divided by the fresh weight and multiplied by 100. Duplicate samples were analyzed when sufficient plant material was available.

Mineral (Ca, Mg, K, Zn, and Na) content was determined as described by Perkin-Elmer Corporation (1976) on a 2380 Atomic Absorption Spectrophotometer (Norwalk, CT). The dry ash was allowed to dry for 5 h, in accordance with AOAC Method 900.02 (AOAC, 1990). After the sample was dissolved using 15 mL of 20% $HNO_3$, the solution was filtered through Whatman 40 grade ashless filter paper (Clifton, NJ) and diluted to a total volume of 100 mL with distilled water; duplicate samples were prepared when possible. One mL of each sample was placed into one of two separate tubes and 10 mL of distilled water was added. To one set of the tubes, 0.5 mL of 5% $LaCl_2$ was added as releasing agent. This tube was used for Ca and Mg quantification.

Data were analyzed by the GLM procedure using SAS statistical software, and treatment differences were separated using Duncan's multiple range test at the 5% level (unless otherwise indicated). The main effects of nutrient solution, solution pH, and onion variety on phenotypic and selected mineral-content variables were evaluated.

## RESULTS

Shoot mass was affected by nutrient solution, pH, and variety ($P < 0.0001$) (Table 2). Onions grown in Hoagland's produced significantly greater shoot mass than did onions grown in Hydro-Sol (Table 2). Onions grown at pH 6.5 produced a significantly greater shoot mass than did those grown at pH 5.8 (Table 2). 'Deep Purple' produced significantly greater shoot mass than did 'Purplette' or 'Kinka' and 'Purplette' produced significantly greater shoot mass than did 'Kinka' (Table 2).

Bulb mass was significantly ($P < 0.0001$) affected by variety (Table 2). 'Purplette' produced significantly greater bulb mass than did 'Deep Purple' or 'Kinka,' and 'Deep Purple' produced significantly greater bulb mass than did 'Kinka' (Table 2). Bulb mass was not significantly affected by nutrient solution composition or pH (Table 2). 'Purplette' was the only variety that is a bulbing onion and therefore was expected to produce the greatest bulb mass.

Root mass was significantly ($P < 0.0001$) affected by variety (Table 2). 'Deep Purple' produced a significantly greater root mass than did 'Purplette' or 'Kinka,' and 'Purplette' produced a significantly greater root mass than did 'Kinka' (Table 2). Root mass was not significantly affected by nutrient solution composition or pH (Table 2).

Table 2
Main effects of nutrient solution, pH, and onion variety on shoot mass (SM), bulb mass (BM), root mass (RM), total biomass (TB), edible biomass (EB), and percentage edible biomass (%EB) of onions grown hydroponically and harvested 42 d after planting

| Treatment | SM | BM | RM | TB | EB | %EB |
|---|---|---|---|---|---|---|
| | | | (g) | | | |
| Nutrient Solution | | | | | | |
| Hoagland's | 4.19 a* | 0.50 a | 1.16 a | 5.85 ab | 5.11 a | 82.26 a |
| 1/2 Hoagland's | 4.55 ab | 0.56 a | 1.28 a | 6.39 a | 4.69 ab | 81.20 a |
| Hydro-Sol | 3.60 b | 0.46 a | 1.08 a | 5.13 b | 4.05 b | 80.44 a |
| SE | 0.83 | 0.22 | 0.41 | 1.56 | 0.955 | 9.01 |
| pH | | | | | | |
| 5.8 | 3.82 b | 0.49 a | 1.06 a | 5.37 b | 4.31 b | 81.30 a |
| 6.5 | 4.41 a | 0.52 a | 1.28 a | 6.21 a | 4.93 a | 81.29 a |
| SE | 0.83 | 0.22 | 0.41 | 1.56 | 0.955 | 9.01 |
| Variety | | | | | | |
| 'Deep Purple' | 5.68 a | 0.50 b | 1.82 a | 7.99 a | 6.17 a | 78.12 b |
| 'Kinka' | 2.68 c | 0.28 c | 0.60 c | 3.55 c | 2.96 c | 83.27 a |
| 'Purplette' | 3.98 b | 0.74 a | 1.11 b | 5.83 b | 4.72 b | 82.51 a |
| SE | 0.83 | 0.22 | 0.41 | 1.56 | 0.955 | 9.01 |

*Means within each column and main effect followed by different letters are different $P \leq 0.05$ ($n = 3$).

Total biomass was significantly affected by nutrient solution composition, pH, and variety ($P < 0.0001$) (Table 2). Onions grown in half-strength Hoagland's produced significantly greater total biomass than did onions grown in Hydro-Sol (Table 2). Onions grown at pH 6.5 produced significantly greater total biomass than did onions grown at pH 5.8 (Table 2). 'Deep Purple' produced significantly greater total biomass than 'Purplette,' which produced significantly greater biomass than did 'Kinka' (Table 2).

Edible biomass was significantly affected by nutrient solution composition, pH, and variety ($P < 0.0001$) (Table 2). Onions grown in Hoagland's produced a significantly greater edible biomass than did onions grown in Hydro-Sol, but there was no difference in edible biomass for onions grown in Hoagland's and half-strength Hoagland's. The onions grown at pH 6.5 produced significantly greater edible biomass than did onions grown at pH 5.8 (Table 2). 'Deep Purple' produced significantly greater edible biomass than did 'Kinka' and 'Purplette,' and 'Purplette' produced significantly greater edible biomass than did 'Kinka' (Table 2).

The percentage edible biomass was significantly ($P < 0.0001$) affected by variety (Table 2). 'Purplette' and 'Kinka' produced a significantly greater percentage edible biomass than did 'Deep Purple' (Table 2). The percentage edible biomass was not significantly affected by nutrient solution composition or pH (Table 2).

Shoot dry-matter percentage was significantly affected by nutrient solution composition and onion variety (Table 3), and a nutrient solution × pH interaction existed. Onions grown in Hydro-Sol produced significantly greater shoot

Table 3
Nutrient solution, pH, and onion variety effects on dry matter, ash, Mg, Ca, Zn, Na, and K content of hydroponically grown onions harvested 42 d after planting

| | (%) | | (mg 100 g $^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|
| Plant part/Treatment | Dry Matter | Ash | Mg | Ca | Zn | Na | K |
| Shoot | | | | | | | |
| Nutrient solution | | | | | | | |
| Hoagland's | 5.8 b[z] | 0.8 b | 6.3 b | 63.1 | 0.67 b | 40.2 a | 108. ab |
| 1/2 Hoagland's | 5.9 b | 0.8 b | 6.8 b | 67.6 | 1.4 a | 33.1 b | 103. b |
| Hydro-Sol | 6.4 a | 1.0 a | 11.4 a | 67.0 | 0.96 ab | 35.6 ab | 121. a |
| SE | 0.62 | 0.18 | 2.9 | 12.9 | 0.70 | 8.4 | 20.5 |
| PH | | | | | | | |
| 5.8 | 6.1 a | 0.93 a | 7.8 a | 65.9 a | 1.1 a | 34.5 a | 112. a |
| 6.5 | 6.0 a | 0.85 a | 8.6 a | 65.9 a | 0.86 a | 38.1 a | 109. a |
| SE | 0.62 | 0.18 | 3.0 | 12.9 | 0.70 | 8.41 | 20.5 |
| Variety | | | | | | | |
| 'Deep Purple' | 5.27 b | 0.88 a | 7.2 a | 61.3 a | 0.90 a | 35.2 a | 113. a |
| 'Kinka' | 7.17 a | 0.84 a | 9.2 a | 69.5 a | 1.1 | 36.2 a | 105. a |
| 'Purplette' | 5.67 b | 0.95 a | 8.1 a | 66.9 a | 1.0 a | 7.4 a | 114. a |
| SE | 0.62 | 0.18 | 2.95 | 12.9 | 0.70 | 8.41 | 20.5 |
| Bulb | | | | | | | |
| Nutrient solution | | | | | | | |
| Hoagland's | 8.5 ab | 0.66 b | 16.3 b | 45.3 a | 0.82 a | 19.8 a | 161. a |
| 1/2 Hoagland's | 8.3 b | 0.71 b | 15.8 b | 37.7 b | 0.67 a | 19.4 a | 142. a |
| Hydro-Sol | 9.1 a | 0.81 a | 21.5 a | 30.8 c | 0.86 a | 20.2 a | 176. a |
| SE | 0.79 | 0.01 | 11.9 | 9.73 | 0.35 | 6.41 | 49.3 |
| pH | | | | | | | |
| 5.8 | 8.5 a | 0.72 a | 18.0 a | 37.9 a | 0.85 a | 17.3 b | 159. a |
| 6.5 | 8.8 a | 0.73 a | 17.7 a | 38.0 a | 0.72 a | 22.3 a | 160. a |
| SE | 0.79 | 0.01 | 11.9 | 9.73 | 0.35 | 6.41 | 49.3 |
| Variety | | | | | | | |
| 'Deep Purple' | 8.2 b | 0.91 a | 17.6 b | 37.0 a | 0.77 a | 20.2 a | 148. a |
| 'Kinka' | 9.3 a | 0.58 c | 20.3 a | 35.3 a | 0.89 a | 19.8 a | 193. a |
| 'Purplette' | 8.5 b | 0.69 b | 15.8 b | 41.5 a | 0.69 a | 19.4 a | 137. a |
| SE | 0.79 | 0.01 | 11.91 | 9.73 | 0.35 | 6.41 | 49.3 |

[z]Mean separation in columns by Duncan's multiple range test at $P \leq 0.05$.

Table 4
Nutrient solution by pH interaction effects on shoot dry-matter percentage, bulb Ca, and bulb Zn content of hydroponically grown onions harvested 42 d after planting

| Variable | pH 5.8 | pH 6.5 |
|---|---|---|
| Shoot Dry Matter (%) | | |
| Hoagland's | 5.9 bc* | 5.8 bc |
| 1/2 Hoagland's | 5.5 c | 6.2 ab |
| Hydro-Sol | 6.8 a | 5.9 bc |
| Bulb Ca (mg 100 $g^{-1}$) | | |
| Hoagland's | 40.1 b | 50.3 a |
| 1/2 Hoagland's | 39.1 b | 36.2 bc |
| Hydro-Sol | 34.2 bc | 27.4 c |
| Bulb Zn (mg 100 $g^{-1}$) | | |
| Hoagland's | 0.97 a | 0.73 ab |
| 1/2 Hoagland's | 0.85 ab | 0.49 b |
| Hydro-Sol | 0.73 ab | 0.99 a |

*Variable means of each nutrient solution and pH followed by different letters are different $P \leq 0.05$ ($n = 3$).

dry-matter percentage than did onions grown in Hoagland's or half-strength Hoagland's (Table 2). 'Kinka' produced the largest overall shoot dry-matter percentage, which was significantly ($P < 0.0001$) greater than that produced by 'Deep Purple' and 'Purplette' (Table 3). Onions grown in Hydro-Sol at pH 5.8 produced significantly greater shoot dry-matter percentage than did onions grown in Hydro-Sol at pH 6.5, Hoagland's at pH 5.8 and pH 6.5, and half-strength Hoagland's at pH 5.8. Solution pH had no significant influence on the shoot dry-matter percentage (Table 4).

Bulb dry-matter percentage was significantly affected by nutrient solution composition and variety (Table 3). Onions grown in Hydro-Sol produced a significantly greater bulb dry-matter percentage than did onions grown in half-strength Hoagland's (Table 3). 'Kinka' produced significantly ($P < 0.005$) greater bulb dry-matter percentage than did 'Deep Purple' and 'Purplette' (Table 3). Solution pH did not significantly influence the bulb dry-matter percentage (Table 3).

Percentage shoot ash was significantly affected by nutrient solution composition (Table 3). Onions grown in Hydro-Sol produced significantly greater shoot-ash percentage than did onions grown in Hoagland's and half-strength Hoagland's (Table 3). Shoot-ash percentage was not significantly affected by pH or variety (Table 3).

Bulb-ash percentage was significantly affected by nutrient solution composition ($P < 0.005$) and variety ($P < 0.0001$) (Table 3); there was a significant solution × variety interaction. Onions grown in Hydro-Sol produced significantly greater bulb-ash percentage than did onions grown in Hoagland's and half-strength Hoagland's (Table 3). 'Deep Purple' bulb-ash percentage was significantly greater than that of 'Purplette,' which was significantly greater than that of 'Kinka' (Table 3). 'Deep Purple' grown in Hydro-Sol produced a significantly greater bulb-ash percentage than did 'Deep Purple' grown in Hoagland's or half-strength Hoagland's, as well as 'Kinka' or 'Purplette' grown in Hoagland's, half-strength Hoagland's, or Hydro-Sol. Solution pH had no significant effect on bulb-ash percentage (Table 3).

Shoot Mg concentration was significantly ($P < 0.0001$) affected by nutrient solution (Table 3). Onions grown in Hydro-Sol produced a significantly greater shoot Mg concentration than did onions grown in Hoagland's or half-strength Hoagland's (Table 3). Shoot Mg concentration was not significantly affected by pH or variety (Table 3).

Bulb Mg concentration was significantly ($P < 0.005$) affected by nutrient-solution composition and variety (Table 3). Onions grown in Hydro-Sol produced a significantly greater bulb Mg concentration than did onions grown in Hoagland's or half-strength Hoagland's (Table 3). 'Kinka' produced a significantly greater concentration of bulb Mg than did 'Deep Purple' and 'Purplette' (Table 3). Solution pH did not significantly influence the bulb Mg concentration (Table 3).

Shoot Ca concentration was not significantly affected by nutrient solution composition, pH, or variety (Table 3). Bulb Ca concentration was significantly affected × nutrient solution by pH interaction ($P < 0.005$) (Table 4). Onions grown in Hoagland's produced a significantly greater bulb Ca concentration than did onions grown in half-strength Hoagland's, whose Ca concentration was significantly greater than onions grown in Hydro-Sol (Table 3). Onions grown in Hoagland's at pH 6.5 produced a significantly greater bulb Ca concentration than did onions grown in Hoagland's at pH 5.8, half-strength Hoagland's at pH 5.8 and pH 6.5, and Hydro-Sol at pH 5.8 and pH 6.5. Bulb Ca concentration was not significantly affected by pH or variety (Table 4).

Shoot Zn concentration was significantly affected by nutrient solution composition (Table 3). Onions grown in half-strength Hoagland's produced significantly greater shoot Zn concentration than did onions grown in Hoagland's (Table 3). Shoot Zn concentration was not significantly affected by pH or variety (Table 3).

Bulb Zn concentration was significantly affected by a solution × pH interaction. Onions grown in Hydro-Sol at pH 6.5 and Hoagland's at pH 5.8 produced significantly greater bulb Zn concentrations than did onions grown in half-strength Hoagland's at pH 6.5 (Table 4). Bulb Zn was not significantly different among the three varieties (Table 3).

Shoot Na concentration was significantly affected by nutrient solution composition (Table 3). Onions grown in Hoagland's produced a significantly greater shoot Na concentration than did onions grown in half-strength Hoagland's

(Table 3). Shoot Na concentration was not significantly affected by pH or variety (Table 3).

Bulb Na concentration was significantly affected by solution pH (Table 3). Onions grown at solution pH 6.5 produced a significantly greater bulb Na concentration than did onions grown at solution pH 5.8 (Table 4). Bulb Na concentration was not significantly affected by nutrient solution composition or variety (Table 3).

Shoot K concentration was significantly affected by nutrient solution composition (Table 3). Onions grown in Hydro-Sol produced a significantly greater shoot K concentration than did onions grown in half-strength Hoagland's (Table 3). Shoot K concentration was not significantly affected by pH or variety (Table 3).

The bulb K concentration was significantly affected by variety (Table 3). 'Kinka' produced a significantly greater concentration of bulb K than did 'Deep Purple' or 'Purplette' (Table 3). Bulb K concentration was not significantly affected by nutrient solution composition or pH (Table 3).

The nutritional contribution of the *Alliums* by plant part, cultivar, pH, and variety is indicated in Table 5 as a percentage of the daily value (DV) based on a 2000 kcal/d diet. The daily value on a nutritional label is either the reference daily intake (RDI) for the minerals Mg, Ca, and Zn and reflects the minimum suggested amount that should be consumed on a daily basis by a healthy adult and children older than four years of age. The daily reference values (DRV) for the minerals Na and K are the suggested maximum amounts on a daily basis for healthy adults and children older than four years of age (FDA, 2004). The shoots in the present study provided similar nutritional value regardless of the cultivar or pH. The nutritional value was influenced by nutrient solution but no consistent trend was noted. Using 'Deep Purple' as an example, a 100 g serving of raw shoots would not be a significant source of Mg (providing less than 2% of the RDI) but would supply about 6% of the RDI for Ca and Zn. The shoots would be considered a low-sodium food and would supply about 3.2% of the DRV of K. The bulb would be a better source of Mg than would the shoots, but contained less Ca and Zn. The bulbs were also low in Na and contributed slightly more K than the shoots.

## DISCUSSION

Under the conditions of this study, total biomass production was greater for onions grown in half-strength Hoagland's solution than for those grown in Hydrosol (Table 2). No difference in total biomass production was seen for full-strength vs. half-strength Hoagland's. This finding agrees with Spomer et al. (1997) who recommended a nutrient solution because to about one-half the strength of the original Hoagland's nutrient solution because the presence of higher concentrations of nutrients did not increase biomass production (Hoagland and Arnon, 1950). Biomass was greatest for plants grown at pH 6.5,

Table 5
Nutritional contribution based on the reference daily intakes (RDI) or daily reference values (DRV) of *Alliums* grown hydroponically and harvested 42 d after planting by plant part for nutrient solution, pH, and variety

| | (% RDI or DRV)** | | | | |
|---|---|---|---|---|---|
| Plant Part/Treatment | Mg | Ca | Zn | Na | K |
| Shoot | | | | | |
| Nutrient solution | | | | | |
| Hoagland's | 1.6 b | 6.3 | 4.5 b | 1.7 a | 3.1 ab |
| 1/2 Hoagland's | 1.7 b | 6.8 | 9.1 a | 1.4 b | 2.9 b |
| Hydro-Sol | 2.8 a | 6.7 | 6.4 ab | 1.5 ab | 3.4 a |
| pH | | | | | |
| 5.8 | 1.9 a | 6.6 a | 7.5 a | 1.4 a | 3.2 a |
| 6.5 | 2.2 a | 6.6 a | 5.7 a | 1.6 a | 3.1 a |
| Variety | | | | | |
| 'Deep Purple' | 1.8 a | 6.1 a | 6.0 a | 1.5 a | 3.2 a |
| 'Kinka' | 2.3 a | 7.0 a | 7.5 a | 1.5 a | 3.0 a |
| 'Purplette' | 2.0 a | 6.7 a | 6.4 a | 1.6 a | 3.2 a |
| Bulb | | | | | |
| Nutrient solution | | | | | |
| Hoagland's | 4.1 b | 4.5 a | 5.5 a | 0.8 a | 4.6 a |
| 1/2 Hoagland's | 4.0 b | 3.8 b | 4.5 a | 0.8 a | 4.0 a |
| Hydro-Sol | 5.4 a | 3.1 c | 5.7 a | 0.8 a | 5.0 a |
| pH | | | | | |
| 5.8 | 4.5 a | 3.8 a | 5.7 a | 0.7 b | 4.5 a |
| 6.5 | 4.4 a | 3.8 a | 4.8 a | 0.9 a | 4.6 a |
| Variety | | | | | |
| 'Deep Purple' | 4.4 b | 3.7 a | 5.1 a | 0.8 a | 4.2 a |
| 'Kinka' | 5.1 a | 3.5 a | 5.9 a | 0.8 a | 5.5 a |
| 'Purplette' | 4.0 b | 4.2 a | 4.6 a | 0.8 a | 3.9 a |

*Means within each column and main effect followed by different letters are different $P \leq 0.05$ (n = 3).

**Reference daily intake for Mg = 400, Ca = 1000, and Zn = 15 mg/d. Daily reference values for Na = 2400 and K = 3500 mg/d.

which was within the range of 5.5 to 6.5 considered optimal for the availability of nutrients from most nutrient solutions for most species (Islam et al., 1980). The variety producing the greatest total and edible biomass was 'Deep Purple' (Table 2).

In addition to total biomass produced, percentage edible biomass is an important variable that influences waste generation. Onions grown in half-strength Hoagland's or at pH 6.5 produced significantly greater shoot mass than did onions grown in half-strength Hoagland's or Hydro-Sol at pH 5.8 (Table 2).

'Purplette' produced significantly greater bulb mass than did the other varieties (Table 2). This result can be explained by the fact that 'Purplette' is a bulbing onion while 'Deep Purple' and 'Kinka' are non-bulbing onions. 'Deep Purple' had a significantly greater shoot mass than did 'Purplette' or 'Kinka' (Table 2).

Shoot mass and bulb mass combine to provide the overall percentage of the plant edible portion (percentage edible biomass). Onions grown in half-strength Hoagland's produced as much biomass and edible biomass as did those grown in the other solutions (Table 2). This result represents relatively higher nutrient utilization efficiency, as production occurred in a more diluted nutrient solution.

Nutrient concentrations within the onions varied with plant part and nutrient. Hydro-Sol produced the highest concentrations of Mg in the shoots and the bulbs; however, concentrations in the root were unaffected by nutrient solution, with no significant effect present in the roots (Table 3). No significant effect on shoot and root Ca existed (Table 3). Hoagland's produced the highest concentration of bulb Ca (Table 3). The bulb Zn concentration was significantly influenced by a solution $\times$ a pH interaction; Hydro-Sol at pH 6.5 and Hoagland's at pH 5.8 produced the greatest concentrations of bulb Zn (Table 4). The onions grown in Hoagland's produced the highest concentrations of shoot Na, and the onions grown at pH 6.5 produced the highest concentrations of bulb Na, with no effect on the roots (Table 4). Onions grown in Hydro-Sol produced the highest shoot K concentrations, and 'Kinka' had the highest bulb K concentrations (Table 3). The Oasis medium in which the plants were grown is chemically inert, so it does not interfere with the mineral absorption, allowing the plant to have unlimited uptake of minerals and increasing the overall ash content of the onion plant (Resh, 1991). Sanchez-Castillo et al. (1998) reported that the addition of fertilizer, the age of the plant tissue, and the chemical composition of the medium in which the crop is grown all could have an effect on the mineral composition of the plant material. Randle (2000) stated that increasing N decreased Ca and Mg content and increased K. In the research reported here, the solutions differed not only in N concentration but also in the concentrations of other elements. Therefore, the effects of N cannot be separated from the effects of the other elements. Furthermore, varieties and species differ in their ability to absorb any given nutrient, and these differences may be due to the differences in the root systems or the specific transport enzymes in cell membranes (Sanchez-Castillo et al., 1998). Given the lack of consistent results, selection of appropriate nutrient solution may need to be based on factors other than nutrient content, or nutrient solutions could be modified based on additional research designed to optimize mineral content.

From a nutritional standpoint, the shoots or bulb parts were not considered a significant source of Mg, Ca, or Zn in that neither part—regardless of nutrient solution, pH, or variety—contributed 10% or more of the RDI. When grown in half-strength Hoagland's solution, however, the levels of Zn increased to just over 9%. Regardless of treatment, both parts would be considered low in Na and contributed only 2.9%–4.6% of the 3500 mg/d DRV for K.

## CONCLUSIONS

The results of this study indicate that nutrient solution, pH, and variety significantly affected several plant physiological variables. Total biomass and edible biomass production were as high for plants grown in half-strength Hoagland's nutrient solution as for those grown in the other solutions. Total biomass was greatest for plants grown at a solution pH of 6.5. 'Deep Purple' produced a significantly greater overall total biomass than did 'Purplette' or 'Kinka.' Onions grown in Hydro-Sol produced a significantly higher dry-matter percentage, higher percentage ash, and Mg and K concentrations. Onions grown in half-strength Hoagland's produced significantly greater Zn concentrations, and onions grown in Hoagland's produced significantly greater Ca and Zn concentrations. 'Kinka' produced significantly greater dry-matter percentage, Mg, and K. 'Deep Purple' produced significantly greater percentage ash than did the other varieties.

Due to the fact that biomass production was as great in the half-strength Hoagland's as in the more concentrated solution and that a pH of 6.5 produced greater total biomass, the half-strength Hoagland's solution at pH 6.5 was the preferred nutrient solution evaluated in this research; however, Hydro-Sol tended to produce onions with the highest mineral content. Mineral content varied with plant part, nutrient solution, solution pH, and onion variety. Selection of an appropriate nutrient solution, therefore, must consider both edible-biomass production and mineral content. In the research reported here, the solution that produced the greatest biomass did not produce plant material with the highest mineral content. Future research may lead to the development of a modified nutrient solution that optimizes both edible biomass production and mineral content.

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