

Article

# Utilizing Anaerobic Digestates as Nutrient Solutions in Hydroponic Production Systems

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Received: 27 October 2020; Accepted: 1 December 2020; Published: 2 December 2020



**Abstract:** Moving food production into the urban and peri-urban areas is one way of facilitating a closed-loop approach, integrating waste handling with food production in order to recirculate nutrients and at the same time reduce the use of mined and fossil resources in the production. Using anaerobic digestion as a way of converting urban wastes to an energy source (methane) and a nutrient-rich biodigestate with subsequent use as fertilizer for food production seems like a feasible approach. However, utilizing urban wastes in plant production systems implies some challenges, such as high salinity of the waste, imbalanced composition of nutrients, and abundance of less favorable forms of nitrogen. In a series of experiments, these problems were addressed. Vegetables (Pak Choi) were cultivated hydroponically in a controlled climate. Experiments included increased salinity, elevated levels of nitrite, and different concentrations of the biogas digestate-based nutrient solution, with mineral based solutions as controls. In general, the mineral controls yielded around 50% higher fresh biomass than the organic solutions. However, the quality of the produce with respect to content of secondary metabolites such as vitamins was enhanced when the plants were cultivated with organic nutrient solutions. Increasing the concentration of NaCl to 241 mg Cl L<sup>-1</sup> did not negatively affect plant performance. Increasing the concentration of nitrite negatively affected plant growth, with reductions in biomass production by up to 50%. Given this well-functioning nitrification process that did not result in high nitrite concentrations, the use of anaerobic digestates seems feasible for hydroponic production of vegetables.

**Keywords:** biogas digestates; circular systems; hydroponic cultivation; nitrite; urban farming

## 1. Introduction

Currently, different approaches for increasing circularity in food production systems are being introduced and evaluated worldwide. Closing the loops between producers and consumers is essential for achieving sustainability in food production. The traditional “take, make, and dispose” approach, using mined sources of plant nutrients and disposing community wastes without recycling the plant nutrients, is not sustainable and needs to be replaced with circular procedures [1]. This implies that organic wastes such as food waste need to be utilized as nutrient sources in production systems for human foods. Using organic sources as fertilizers in plant production systems has the benefit of recycling nutrients and decreasing the demand for mined minerals. Introducing organic substances into the system could also have other positive effects by supplying beneficial organic biostimulants to the production systems [2–4]. However, using wastes as plant fertilizers also comes with challenges, such as high salinity, imbalanced nutrient contents, possibly toxic pollutants, and infectious agents [5]. In addition, nutrients bound to organic substances are not immediately available to plant roots but need microbial degradation before they can be taken up by plants. Using organic nutrients in a hydroponic production system is a significant challenge because all the nutrients have to come from a supply

without any soil nutrients to rely on. The nutrient source has to be complete and, to a degree, also have a good balance of nutrient composition to enable vigorous growth [6].

Anaerobic digestion (AD) is a treatment of solid wastes that comes with multiple advantages; a high-value energy source in the form of methane is produced, in addition, the solid material going into the digester is homogenized and degraded so that its value as a fertilizer for plants is increased [5]. Biogas production through AD of different types of agro-industrial wastes has been implemented on a large scale in many countries as an important energy producing technology and the remaining digestate is an easily available resource [7]. However, using liquid or solid digestates as fertilizers for plants comes with some challenges. Due to the anoxic conditions during the fermentation process, most of the mineralized nitrogen in the digestate is in its reduced form, ammonia ( $\text{NH}_4^+$ ), which can be used as a N source by plants but can also be toxic to plants in higher concentrations [8,9], as opposed to the nitrate form ( $\text{NO}_3^-$ ).  $\text{NH}_4^+$  can also cause secondary adverse effects to plant growth due to acidification of the root environment [10]. A maximum share of  $\text{NH}_4^+$  of around 50% of total mineral nitrogen concentration is generally recommended [11]. Therefore, the digestate has to undergo a nitrification process before being introduced into a hydroponic growing system. Nitrification is an aerobic process, where  $\text{NH}_4^+$  is oxidized to  $\text{NO}_3^-$  in a chain of microbial conversions, during which pH drops, and this decrease needs to be considered when developing a nutrients solution optimized for plant growth and during the actual use of the solution in the growing system [12]. In addition, accumulation of nitrite, due to instabilities in the nitrification process, can occur [13,14] and this may affect plant growth. Furthermore, not only nitrogen dynamics need to be considered, depending on the input material, the digestates produced might be imbalanced in nutrient composition, or contain unacceptable concentrations of NaCl, heavy metals such as Cd, or other substances toxic to plants or humans. A high concentration of NaCl can be expected if a part of the biogas substrate is made up of food residues. Increased NaCl concentration has proven to affect hydroponic production in two ways. The increased salinity, per se, leads to decreased water potential and higher ionic strength with lower photosynthesis, and therefore impaired water and nutrient uptake [15]. The other effect of salinity is the direct toxicity of the  $\text{Na}^+$  and  $\text{Cl}^-$  ions with known effects to decrease the uptake of, for example, Ca and K by  $\text{Na}^+$  and decreased  $\text{NO}_3^-$  uptake due to  $\text{Cl}^-$  [16,17].

Hydroponic systems have been introduced as alternatives to traditional field farming, with benefits such as high water and nutrient use efficiency, high production per area unit, reduced risk of plant pests or contamination of the produce, and independence from soil conditions [18,19]. Used in traditional large-scale production of vegetables during the last three to four decades, hydroponics is now moving closer to the consumers and into the cities, not seldom in vertical or multi-layer production systems. Fast technological development within lighting technology, robotics, and sensor technology is likely to further accelerate this trend in the near future. This brings about possibilities for local cycles of nutrients by integrating biogas production and hydroponic food production. *Brassica campestris* v. *chinensis* (Pak Choi) is a fast-growing vegetable with high nutritional value, well suited for production in hydroponic systems. Bergstrand and Hultin [20] demonstrated its high potential production in such systems. The health benefits associated with consumption of the *Brassica* species relies mainly on its contents of vitamins C and E, carotenoids, glucosinolates, anthocyanins, and other secondary metabolites [21].

The objectives of this study was to identify constraints for, and benefits of using biogas digestates as a base for nutrient solutions in hydroponic systems, and how these constraints could be mitigated. Our hypotheses were the following: (i) Using organic nutrient solution will not decrease photosynthesis and growth as compared with using mineral nutrient solutions. (ii) Using an organic nutrient solution will improve the quality of the produce. (iii) Higher concentrations of NaCl in the organic solution will be a major constraint to the productivity of a system based on biogas digestates. (iv) Nitrite concentrations below  $100 \text{ mg L}^{-1}$  will not negatively affect plant performance.

## 2. Materials and Methods

### 2.1. Experiment 1: Different Nutrient Concentrations

#### 2.1.1. Experimental Setup

The experiment was performed in a greenhouse chamber (50 m<sup>2</sup>) at the Swedish University of Agricultural Sciences in Alnarp, Sweden from mid-September to mid-October 2019. The heating setpoint was 20 °C and the ventilation setpoint was 22 °C. Supplementary lighting (high pressure sodium lamps, Philips GreenPower 400 W, Philips, Eindhoven, The Netherlands) was supplied for 16 h day<sup>-1</sup> at an intensity of 68 ± 8 μmol m<sup>-2</sup> s<sup>-1</sup>.

Nutrient film technique (NFT-) systems were used for the experiments. Each individual system, making up one sample, consisted of a 1.5 m gutter connected to a 60 L tank. The nutrient solution was continuously circulated through the gutter at a flow rate of 2 L min<sup>-1</sup> by a submersible pump (Eheim GmbH & Co., Deizisau, Germany).

*Brassica campestris* v. *chinensis* cv. Joi Choi (Pak Choi) was used as model plant. Seeds were sown in rockwool plugs (ø 23 mm, Rockwool BV, Roermond, The Netherlands). Eighteen days after seeding (DAS), the plants were transferred to grid pots (ø 50 mm) filled with pumice (Hekla 2–8 mm, Bara Mineraler AB, Bara, Sweden) and transferred to the NFT system, 5 pots per gutter. The nutrient solution in the gutter approximately reached the bottom 5 mm of the pot.

#### 2.1.2. Treatments

Four different treatments were included in the experiment, one control treatment with a nutrient solution completely based on mineral fertilizers, and three different organic treatments with organic nutrient solutions based on liquid biogas digestates. The mineral solution ("MIN") was composed from equal parts of YaraTera Kristalon™ Purple and YaraTera Calcinit (Yara, Oslo, Norway) and adjusted to an electric conductivity (EC) of 2.0 mS cm<sup>-1</sup>, and to a pH of 5.5 by the addition of 1 M H<sub>2</sub>SO<sub>4</sub> or 1 M NaOH. The organic solution was based on liquid biogas digestate from a commercial biogas plant (Karpalund Biogas Plant, Kristianstad, Sweden). The biogas reactor was fed with organic household waste 37%, manure 31%, slaughter residues 19%, other organic food waste 13%, and iron chloride 0.03% was added as a process enhancer. The process was certified according to SPCR 120 [22] which ensured that included wastes had their origin in the food or feed chain and that the quality of the digestate was high considering the risk for contaminations. The digestate was nitrified with the aid of aeration and bio-carriers for two weeks. Un-nitrified solution, pH 8.1, was added in 50 mL portions when the pH in the nitrifying tank was below 5.5 to maintain a pH of 5.5–6.0 during the nitrification process. After the nitrifying process, the digestate was arranged in three organic treatments by adjusting the EC to the following, in mS cm<sup>-1</sup>: 1 ("ORG-1"), 2 ("ORG-2"), and 4 ("ORG-4"), respectively, by dilution with water, and a pH of 5.5 (see Table 1 for details on the four treatments). The use of EC to control the strength of the nutrient solution is common practice in most hydroponic production systems.

During the growing trial, the electric conductivity (EC) was controlled by additions of the undiluted nitrified solution (org) or, for the inorganic control, a stock solution of the mineral fertilizer. Tap water was added to the tanks to maintain the same water level throughout the cultivation period.

**Table 1.** The different treatments employed in the experiment, and the nutritional properties of the nutrient solution used for each treatment.

Treatment	Min.	ORG-1	ORG-2	ORG-4
Type	Mineral	Organic	Organic	Organic
EC (mS cm <sup>-1</sup> )	2	1	2	4
NO <sub>3</sub> -N (mg L <sup>-1</sup> )	210	45	90	180
NH <sub>4</sub> -N (mg L <sup>-1</sup> )	61	38	75	150
NO <sub>2</sub> -N (mg L <sup>-1</sup> )	0	36	72	144
P (mg L <sup>-1</sup> )	38	2.1	4.1	8.2
K (mg L <sup>-1</sup> )	200	60	120	240
Ca (mg L <sup>-1</sup> )	190	39.8	59.5	99
Mg (mg L <sup>-1</sup> )	23	3.3	5.1	8.6
S (mg L <sup>-1</sup> )	48	11.0	19.3	36
Fe (mg L <sup>-1</sup> )	0.28	0.87	1.68	3.3
Zn (mg L <sup>-1</sup> )	0.72	0.06	0.10	0.17
Mn (mg L <sup>-1</sup> )	0.57	0.04	0.07	0.14
Mo (mg L <sup>-1</sup> )	0.036	0.005	0.009	0.018
Cu (mg L <sup>-1</sup> )	0.13	0.02	0.05	0.09
B (mg L <sup>-1</sup> )	0.24	0.02	0.05	0.09
Na (mg L <sup>-1</sup> )	16	36	64	120
Cl (mg L <sup>-1</sup> )	29	87	148	270

### 2.1.3. Sampling, Analysis, and Measurements

At the beginning of the experiments, the nutrient solutions were analyzed with respect to their contents of mineral nutrients. The analyses were performed by a commercial accredited laboratory (Eurofins AB, Kristianstad, Sweden).

The photosynthetic capacity of the plants ( $A_{max}$ ) was measured at a light intensity of 1000  $\mu\text{mol m}^{-2} \text{s}^{-1}$  using a portable gas-exchange photosynthesis meter (LCPro, ADC Bioscientific, Hoddesdon, UK). The third fully developed leaf was used for the measurements. Basic fluorescence ( $F_0$ ), maximal fluorescence ( $F_m$ ), and variable fluorescence ( $F_v/F_m$ ) were measured using a Walz PAM-2500 fluorometer (Heinz Walz GmbH, Effeltrich, Germany). The fluorescence measurements were taken on the third fully developed leaf, after a 20 min dark adaption. The chlorophyll content of the leaves was measured at the end of the experiment using a MC-100 Chlorophyll meter (Apogee electronics, Santa Monica, CA, USA).

The relative humidity and temperature in the greenhouse chamber were measured using data loggers (HOBO U12, Onset Computer Corp., Bourne, MA, USA). The influx of natural irradiance to the greenhouse chamber was measured using a PAR sensor (Apogee electronics, Santa Monica, CA, USA) connected to a data logger (HOBO, Onset Computer Corp., Bourne, MA, USA). The daily light integral (DLI,  $\text{mol m}^{-2} \text{day}^{-1}$ ) was calculated as

$$\text{DLI} = (I \cdot t) / 1,000,000 \quad (1)$$

where  $I$  is light intensity (in  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and  $t$  is the time (in s).

After 22 days of cultivation in the NFT-system, the plants were harvested. Fresh weight as well as dry weight (after 96 h drying in 75 °C in a forced-air oven) were measured. The total content of mineral nutrients in the green plant parts was analyzed with results expressed as  $\text{mg} \cdot \text{kg dry matter (DM)}^{-1}$ . The analysis was performed by a commercial laboratory (LMI AB, Helsingborg, Sweden).

The analysis of plant secondary metabolites was performed in Experiment 1. Content measurements of vitamin C, vitamin K,  $\beta$ -carotene, lutein, and gluconapine were carried out using high-performance liquid chromatography (HPLC) [18–28].

## 2.2. Experiment 2: Increased NaCl

### 2.2.1. Experimental Setup

The experimental setup was the same as used for Experiment 1. The experiment was performed during November 2019.

### 2.2.2. Treatments

Four different treatments were included in Experiment 2 (Table 2) as follows: one control treatment based on mineral fertilizers (same as treatment MIN in Experiment 1); one treatment where NaCl was added to the mineral nutrient solution to reach a Cl concentration of 241 mg L<sup>-1</sup> ("MIN + NaCl"); one treatment with an organic solution based on liquid biogas digestate "ORG", similar to treatment ORG-2 in Experiment 1 but with some differences in the speciation of N; and, in the fourth treatment, the organic solution from treatment ORG was amended with NaCl solution to reach a Cl concentration of 241 mg Cl L<sup>-1</sup> ("ORG + NaCl"). When examining the organic solutions, we found that, on a molar base, the Cl concentration was higher than the Na concentration. This means that chloride contributed more to the solution EC than Cl. Since high EC is a very prominent problem in hydroponic production, we used the chloride concentration as the base for the treatments.

**Table 2.** Treatments and properties of the nutrient solutions used in Experiment 2.

Treatment	MIN	ORG	MIN + NaCl	ORG + NaCl
Type	Mineral	Organic	Mineral	Organic
Addition NaCl	No	No	Yes	Yes
EC (mS cm <sup>-1</sup> )	2	2	2.2	2.5
NO <sub>3</sub> -N (mg L <sup>-1</sup> )	210	190	210	190
NH <sub>4</sub> -N (mg L <sup>-1</sup> )	61	13	61	13
P (mg L <sup>-1</sup> )	38	4.1	38	4.1
K (mg L <sup>-1</sup> )	200	120	200	120
Ca (mg L <sup>-1</sup> )	190	59	190	59
Mg (mg L <sup>-1</sup> )	23	5.1	23	5.05
S (mg L <sup>-1</sup> )	48	19	48	19
Fe (mg L <sup>-1</sup> )	0.28	1.68	0.28	1.68
Zn (mg L <sup>-1</sup> )	0.72	0.098	0.72	0.098
Mn (mg L <sup>-1</sup> )	0.57	0.07	0.57	0.07
Mo (mg L <sup>-1</sup> )	0.04	0.01	0.04	0.01
Cu (mg L <sup>-1</sup> )	0.13	0.05	0.13	0.05
B (mg L <sup>-1</sup> )	0.24	0.05	0.24	0.05
Na (mg L <sup>-1</sup> )	16	64	172	121
Cl (mg L <sup>-1</sup> )	29	148	241	241

### 2.2.3. Sampling, Analysis, and Measurements

Samplings and analyses performed in Experiment 2 were the same as in experiment 1, except for the analyses of secondary metabolites.

## 2.3. Experiment 3: Increased Nitrite Concentrations

### 2.3.1. Experimental Setup

Experiment 3 aimed at studying the effects of NO<sub>2</sub><sup>-</sup> (nitrite) on plants grown in hydroponic solutions. The methodology used in Experiment 3 was a Static Aerated Culture (SAT), with 2 L plastic containers (ø 140 mm). This methodology was chosen in order to have more replications than in Experiments 1 and 2. The solution in the containers was continuously aerated by 1 mm hoses supplied by air from a pump (Aqua-Forte V-30, SIBO B.V., Veghel, The Netherlands). The experiment was

placed in a greenhouse chamber at the same climatic conditions as for Experiment 1. Pak choi was used as model plant, as in Experiments 1 and 2. The seeds were sown in rockwool plugs ( $\varnothing$  23 mm, Rockwool BV, Roermond, The Netherlands). On 17 DAS, the plants were transferred to floating rafts made out of styropor and placed in the containers with different nutrient solutions, as described below (1.5 L per plant renewed 2 times during the trial). The mineral and organic nutrient solutions were the same as used for Experiment 2 (ORG). Five different treatments were used in the experiment (Table 3). Nitrite was added to the solutions as  $\text{KNO}_2$ . To avoid microbial oxidizing of nitrite during the trial, the solution was heated and kept at 65 °C for 1 h. In a pre-study, it was determined that the nitrite and nitrate concentrations remained stable in the heated solution for at least two weeks. The experiment was started in mid-May and ended in the beginning of June 2020.

**Table 3.** The different treatments used in Experiment 3. Mineral N, as  $\text{NO}_2\text{-N}$  or total mineral-N,  $\text{mg L}^{-1}$ .

Treatment	Type	Added $\text{NO}_2^-$	Total N
ORG-C	Organic	0	203
ORG- $\text{NO}_2$	Organic	100	303
MIN-C	Mineral	0	271
MIN- $\text{NO}_2$	Mineral	100	371
MIN- $\text{NO}_2\text{-N}$	Mineral	100	271

### 2.3.2. Sampling, Analysis, and Measurements

Samplings and analyses performed in Experiment 3 were the same as in Experiments 1 and 2, except that the relative humidity and temperature in the greenhouse chamber was measured using the climate computer (Priva Intégro v. 730) with Priva Office (Priva, de Lier, The Netherlands). The content of mineral nutrients in the plant tissue was analyzed at the end of the experiment, as described for Experiment 1. Analyzes were performed by LMI AB, Helsingborg, Sweden.

### 2.4. Treatment of Data

For Experiment 1 and 2, a completely randomized block designs with three blocks per treatment and five plants per treatment in each block was used. Data from the five plants within the block was averaged before further calculations. For Experiment 3, a complete randomized setup with six replicates per treatment was used. For analysis of secondary metabolites, three replicate samples per treatment were used. The treatments were evaluated using one-way ANOVA with Tukey's multiple comparison test, where  $p < 0.05$  was considered to be significant. The calculations were performed with the software Minitab v. 18 (Minitab Inc., State College, PA, USA).

## 3. Results

### 3.1. Experiment 1: Different Nutrient Concentrations

The average DLI was  $10.7 \text{ mol m}^{-2} \text{ d}^{-1}$  during the experiments. The average air temperature in the greenhouse chamber was  $22.5 \pm 2.4$  °C and the relative humidity was  $57.5 \pm 12.3\%$  (data not shown).

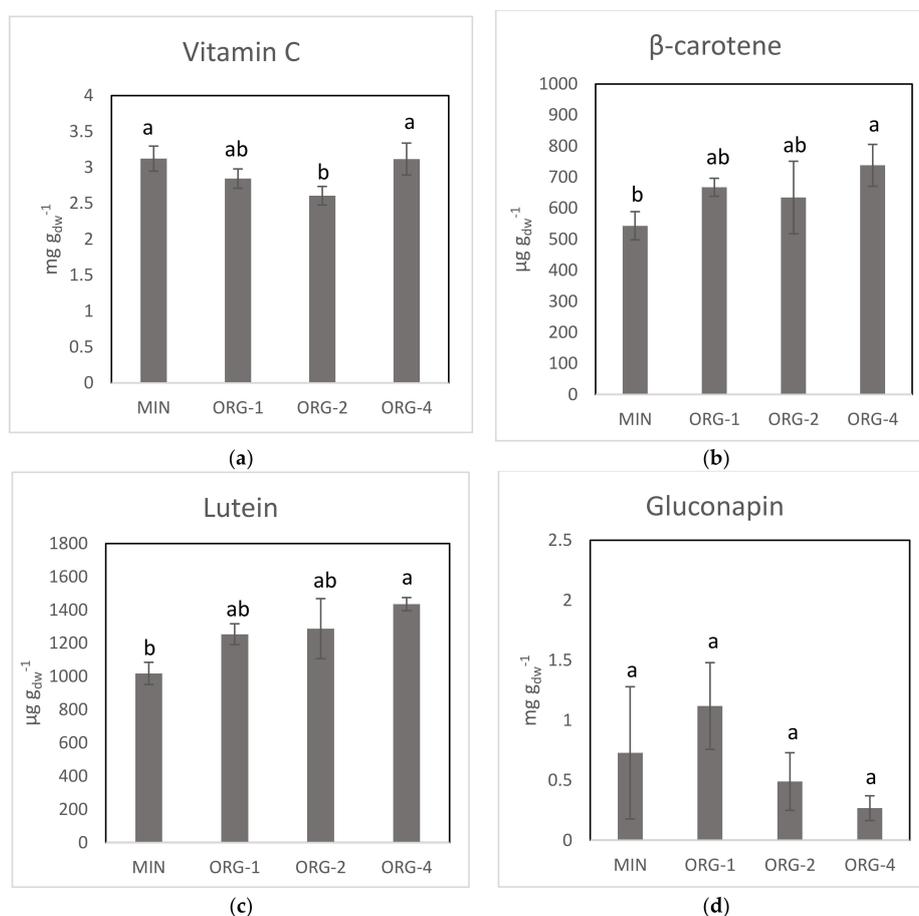
There were no significant differences between treatments with respect to photosynthetic capacity or chlorophyll fluorescence (data not shown). The fresh weight, as well as dry weight, were higher for the control with mineral nutrition, than for the treatments with organic nutrient solution (Table 4). However, the chlorophyll content was the highest in the treatment with the high-concentration organic nutrient solution, which was also visually darker in leaf color (Table 4). The leaf nitrogen content was also higher for this treatment. With respect to mineral uptake, the content of Na, Cl, and Si in the leaves was significantly higher in the treatments with organic nutrient solutions as compared with the control treatment with mineral solution. At the same time, the content of Mg was reduced in the organic treatments. The content of Ca in the green plant parts was the highest for the mineral control treatment and reduced with increasing strength of the organic solutions (data not shown).

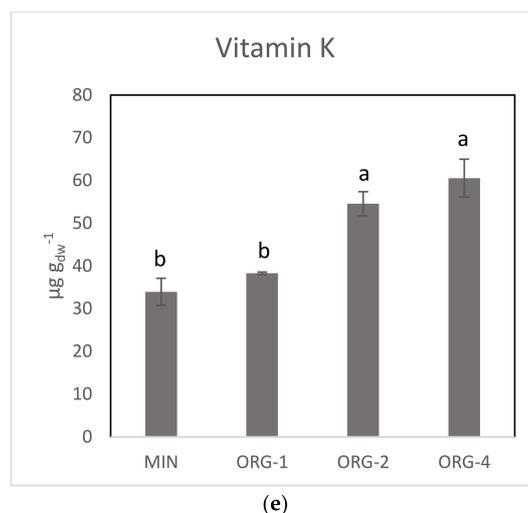
**Table 4.** Results from the biometric analyses of the plants in the three different experiments.

Experiment	Treatment	Chlorophyll Content	Fresh Weight	Dry Weight
		(rel)	(g)	(g)
Experiment 1	MIN	24.56 b	113.6 a	3.86 a
	ORG-1	26.42 b	60.43 b	2.22 b
	ORG-2	34.38 ab	50.62 b	2.04 b
	ORG-4	41.9 a	37.94 b	1.72 b
Experiment 2	MIN	17.1 a	87.4 a	3.0 a
	ORG	23.2 a	59.2 a	2.4 a
	MIN + NaCl	20.2 a	57.3 a	2.2 a
	ORG + NaCl	22.2 a	68.2 a	2.8 a
Experiment 3	ORG-C	30.92 a	158.6 ab	7.62 ab
	ORG-NO <sub>2</sub>	48.48 a	79.25 c	4.65 c
	MIN-C	29.6 a	185.9 a	8.25 a
	MIN-NO <sub>2</sub>	38.67 a	147.54 ab	7.76 ab
	MIN-NO <sub>2</sub> -N	43.18 a	125.94 b	6.15 bc

Figures within columns and experiments which do not share a letter are significantly separated ( $p \leq 0.05$ ). Values within column and experiment which do not share a letter are statistically separated at  $p < 0.05$ .

The concentration of vitamin K was significantly increased (by around 58%) in the plant tissue with increasing EC in the organic solution. With respect to vitamin C, however, there were significant differences between treatments, but no clear trend. For lutein as well as  $\beta$ -carotene, the contents were significantly higher (with increments of 10–14%) in the treatment with organic solution at EC 4.0 mS cm<sup>-1</sup> as compared with the MIN treatment (Figure 1).

**Figure 1.** Cont.



**Figure 1.** Contents of secondary metabolites in Pak Choi, cultivated in mineral or organic nutrient solutions; (a) Vitamin C, (b)  $\beta$ -carotene, (c): Lutein, (d) Gluconapin, and (e) Vitamin K. The different treatments were: MIN, mineral solution, EC 2.0 mS cm<sup>-1</sup>; ORG-1, organic solution, EC 1.0 mS cm<sup>-1</sup>; ORG-2, organic solution, EC 2.0 mS cm<sup>-1</sup>; and ORG-4, organic solution, EC 4.0 mS cm<sup>-1</sup>. Error bars represent standard deviation. For nutrient content see Table 1.

### 3.2. Results from Experiment 2

The addition of NaCl to the solutions did not render any significant differences among the treatments with respect to photosynthetic capacity, chlorophyll fluorescence (data not shown), chlorophyll content or fresh/dry weight (Table 4).

The average DLI was 5.1 mol m<sup>-2</sup> d<sup>-1</sup> during the experiments. The average air temperature in the greenhouse chamber was 21.8 ± 1.1 °C and the relative humidity was 57.5 ± 5.8%.

### 3.3. Results from Experiment 3

The addition of NO<sub>2</sub><sup>-</sup> generally negatively affected biomass production. The negative effect of NO<sub>2</sub><sup>-</sup> was more pronounced in the treatments with organic solution than in the treatments with mineral solution (Table 4). The chlorophyll content in the leaves was significantly higher for the treatments with added NO<sub>2</sub><sup>-</sup>. However, neither photosynthesis ( $A_{max}$ ) nor chlorophyll photosynthesis ( $F_0$ ,  $F_m$  or  $F_v/F_m$ ) was affected by the addition of NO<sub>2</sub><sup>-</sup> or by the composition of the nutrient solution (mineral/organic) (data not shown).

The content of mineral nutrients in the plant tissue was affected by the type of nutrient solution (mineral/organic), but not by the presence of NO<sub>2</sub><sup>-</sup>. Concentrations of N, K, and S were significantly higher in the plant tissue of the plants cultivated with the mineral nutrient solution as compared with organic solution, whereas for Ca, Cu, and Zn, concentrations were higher in the plants fed with organic solution. The content of Cd in the plant tissue was below detection level (0.2 mg \* kg DM<sup>-1</sup>) in all samples (data not shown).

The average DLI during the experiment was 30.6 mol m<sup>-2</sup> d<sup>-1</sup>. The average temperature was 23.1 ± 2.7 °C and the relative humidity was 48 ± 13% (data not shown).

## 4. Discussion

Market gardening, plant factories, and aquaponics are “novel” systems challenging traditional monoculture greenhouse or open field systems, which are commonly largely based on mined fossil resources [29,30]. This work was motivated by the idea of locating production facilities in the near vicinity of residential areas, within the city, in order to make use of wastes and supply the community with fresh produce, reducing transport. In order to close the nutrient loop completely, this implies the recirculation of human feces and urine. However, this is somewhat cumbersome in “short-loop

systems" as this would require advanced methods, such as struvite precipitation in order to eliminate the risk of pathogen transmission. In this study, therefore, we focused on using selected solid agricultural wastes treated in AD reactors as plant fertilizers. On the one hand, using organic nutrient solutions in hydroponic systems can compromise production in several ways as compared with using nutrient solutions composed of pure mineral salts as follows: (i) The nutrient composition might be unbalanced to fit the crop; (ii) the solution might contain unwanted substances such as NaCl,  $\text{NH}_4^+$ , or  $\text{NO}_2^-$ ; (iii) the organic solution might have high chemical or biological oxygen demand, causing depletion of oxygen in the root zone, and (iv) the organic substances in the solution might support undesirable microbial growth in the system. On the other hand, the organic solution might contain beneficial compounds and microorganisms stimulating plant growth in different ways, referred to as biostimulants and defined by Du Jardin [4].

From the present study, it can be concluded that using mineral solutions generally resulted in superior biomass production as compared with organic solutions. Increasing the strength of the organic solution reduced biomass production, indicating that the reduction in growth might be caused by substances present in the solution. Adding NaCl to the solution reduced biomass production, more markedly in a mineral solution than in organic solutions, indicating that something in the organic solution mitigates the adverse effects of the NaCl. It is speculated that this effect might be attributable to binding of NaCl to organic molecules in the solution, or to biostimulatory effects of compounds in the solution, increasing plant resilience to NaCl [31]. Thus, an elevated level of NaCl in organic solutions is not necessarily a significant problem at moderate concentrations. However, AD from municipal wastes could possibly contain NaCl concentrations above the levels applied in this study. When producing other crops than *Brassica* species, NaCl levels within the range used in this study might be problematic, as other plant species such as tomato are regarded as sensitive to salinity [32].

In general, it has been suggested that growing *Brassica* in hydroponic systems results in produce with high contents of minerals of interest to human health [33]. The production of the analyzed secondary metabolites in the plants seems, in general, to increase with increasing strength of the organic solutions. This could be interpreted as a stress reaction in the plants, even though no stress was detected when measuring chlorophyll fluorescence or photosynthetic capacity. Effects on production of carotenoids in kale (*Brassica oleracea*) have been demonstrated to be affected by mineral nutrition, especially the supply of S [34]. However, differences in S supply does not seem like a valid explanation for differences in production of lutein and  $\beta$ -carotene in this study. Dilution due to more vigorous growth in the treatments with lower strength of the organic nutrient solution cannot be ruled out as explanation. The concentrations of lutein and  $\beta$ -carotene in cabbage leaves, in this study, were within the same range as previously reported by Kopsell et al. [34].

During the nitrification, which is a biological process driven by certain bacterial species, instabilities may occur due to changes in abiotic factors such as temperature and pH which affect bacterial growth [35]. Accumulation of nitrite due to increased organic load or changes in pH have been reported [13,14]. Our results demonstrated higher toxicity of nitrite in an organic solution as compared with a mineral solution. Thus, to establish a well-functioning nitrification process is fundamental when using AD as nutrient solution in hydroponic systems.

The results obtained in the present study also demonstrate that care should be taken not to make direct translation of results obtained in studies based on pure mineral solutions. This applies to both the results discussed above considering risks with elevated levels of NaCl and nitrite and also to the fact that yields might be reduced in systems also using organic solutions as compared with mineral solutions of similar composition. The cause for such reductions will need further investigations. As plant tissue concentrations of N, K, and S were lower in plants cultivated with organic solutions, one explanation might be reduced uptake, and thus latent deficiency of either of these elements. The impaired uptake might be explained by competition from other ions, or damages to the roots caused by oxygen depletion or microbial attacks. Foliar sprays might be one strategy to cope with nutrient deficiencies caused by poor uptake [36]. The toxic effects of  $\text{NO}_2^-$  to plants are well known

and have been described previously [37–39]. However, it has been reported that concentrations up to 100 mg L<sup>-1</sup>, which was the maximum concentration applied in this study, did not affect growth adversely [40]. The occurrence of nitrite in the nutrient solution did not affect plant nitrogen status, even though uptake of nitrite in higher plants have been demonstrated [41].

## 5. Conclusions

It is clear from the present study that digestates from AD may be used as a sole nutrient source in hydroponic cultivation. It is evident that this use would provide benefits considering decreased use of mineral nutrients and increased food security in the cities. On the one hand, lower yields were obtained when using organic nutrient solutions as compared with control systems based on mineral nutrient supply, and on the other hand, the nutritional quality of produce, in some aspects, was increased when plants were cultivated with organic nutrient solutions. Thus, further optimization is important, and the present study suggests that impaired uptake of some mineral nutrients from the organic solution is the main cause for reductions in productivity when using AD as the sole nutrient source. Approaches to mitigate the adverse effects of imbalances in the organic nutrient solution should be addressed in future research, and also studies on the effects of NaCl concentrations exceeding the ones used in this study.

**Author Contributions:** K.-J.B. planned and performed experiments and wrote the manuscript; H.A. planned and performed the experiment and supported in writing the manuscript; M.H. acquired the funding for the project, planned the experiments, and supported in writing the manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by FORMAS, grant number 2018-01845.

**Acknowledgments:** We thank Karl-Erik Gustavsson for his support with the HPLC analysis and Karpalund Biogas Plant, with special thanks to Bengt Stuhre, for providing the certified digestate.

**Conflicts of Interest:** The authors declare no conflict of interest.

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