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EVALUATING KALE (*Brassica oleracea* var. *acephala*) GROWTH IN AN AQUAPONIC SYSTEM

Mirela CREȚU[1, 2], Ion VASILEAN[1], Săndița PLĂCINTĂ[2], Marian Tiberiu COADĂ[1, 2], Angelica DOCAN[2, 3], Lorena DEDIU[2, 3], Carmelia Mariana DRAGOMIR BĂLĂNICĂ[1]

[1]Cross-Border Faculty, "Dunărea de Jos" University of Galați, 47 Domnească Street, 800008, Galați, Romania
[2]Romanian Center for Modelling Recirculating Aquaculture Systems, "Dunărea de Jos" University of Galați, 47 Domnească Street, 800008, Galați, Romania
[3]Faculty of Food Science and Engineering, "Dunărea de Jos" University of Galaţi, 111 Domnească Street, 800008 Galaţi, Romania

Corresponding author email: ion.vasilean@ugal.ro

Abstract

This study explores the growth performance of kale (Brassica oleracea var. acephala) cultivated in an aquaponic system integrated with fish production. The experiment was conducted in a controlled environment using varying planting densities to assess their impact on plant development and overall system productivity. Four densities were evaluated: 14 plants/m², 21 plants/m², 28 plants/m², and 41 plants/m² respectively. Plant growth performance, including plant height, leaf number, and biomass, were evaluated across densities to determine the optimal conditions for kale growth while maintaining water quality parameters for the fish. Results showed significant differences in growth across the stocking densities, with 28 plants/m² achieving the highest productivity, marked by greater biomass and vigorous development. The findings highlight the potential of aquaponics as a sustainable cultivation method, effectively recycling fish-derived nutrients to support the growth of kale.

***Key words**: crop yield, nutrients, plant growth, water quality.*

INTRODUCTION

Aquaponics is an innovative, sustainable food-growing system that combines the cultivation of plants and fish (Timmons and Ebeling, 2013; David et al., 2022; Liu et al., 2025). In these systems, fish waste is a natural fertilizer for the plants, while the plants filter and purify the water, creating a closed-loop ecosystem with minimal environmental impact. Beneficial bacteria convert fish waste into essential nutrients, which the plants absorb, thus maintaining the system's balance (Al-Hafedh et al., 2008; Filep et al., 2016). The purified water is then returned to the fish tank, completing the cycle (Rakocy et al., 2004). Aquaponics is, therefore, an extremely efficient, resource-conserving food production technique. Its water use is lower than in traditional soil agriculture, given that water is cycled through the system instead of being lost through evaporation or runoff. Additionally, the absence of soil reduces the need for massive land use and environmental degradation linked with conventional farming practices (Ibrahim et al., 2023).

Therefore, aquaponics offers a resilient and climate-smart agricultural solution in the context of increasing global water disparity and the pressing challenges of climate change. While conserving water by dramatically reducing its use and negating nutrient runoff, aquaponic systems also help protect water resources and lower the carbon footprint of food production. As such, aquaponics' efficiency and adaptability afford this strategy prominence among those required to ensure sustainable food security against environmental change, particularly when climate change threatens traditional agriculture through severe weather or resource scarcity.

However, the management of aquaponic systems is also faced with several challenges. A key aspect of aquaponics is determining the specific nutrient requirements of each plant species based on the available nutrients in the system. Monitoring water quality and nutrient levels is crucial for maintaining a balanced and effective aquaponic system.

Kale (*Brassica oleracea* var. *acephala*), a member of the cruciferous vegetable family, has become a prominent staple in modern diets due to its exceptional nutritional profile and numerous health benefits (Šamec et al., 2019). Rich in vitamins A, C, and K and essential minerals like calcium and iron, kale is renowned for supporting immune health, promoting bone strength, and combating oxidative stress. In addition to its health advantages, kale is also a versatile crop in sustainable agricultural systems.

This study evaluates kale growth in an aquaponic system, exploring the plant's nutrient needs and performance within this sustainable farming approach.

MATERIALS AND METHODS

Experimental design. The experiment was conducted at the Romanian Centre for Modelling Recirculating Aquaculture Systems (MoRAS- www.moras.ugal.ro) of the Faculty of Food Science and Engineering, "Dunărea de Jos" University of Galați, Romania. The description and functioning of the aquaponic system were previously presented in our article (Crețu et al., 2022).

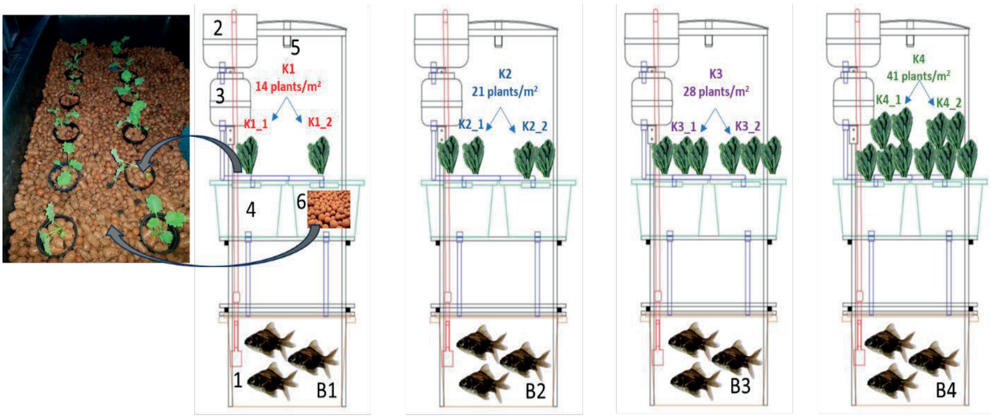

Figure 1. The scheme of the aquaponic system:
B1-B4 - fish rearing unit; 1- recirculation pump; 2- mechanical filter; 3- biological filter;
4- aquaponic units; 5- led lamp; 6- Lightweight Expanded Clay Aggregate (LECA) substrate

For this experiment, we used 33 fish per tank (B1-B4) (Figure 1) (*Carassius auratus* var. Black Moor), with an average size ± SEM of 12.67 ± 0.07 g. Fish were fed manually with extruded pellets (34% protein, 15% lipids, 1.4% crude fibre, 6.80% ash). The fish were fed daily at a rate of 5% of their total biomass, with the total feed amount distributed across three meals at 8:00 a.m., 12:00 p.m., and 6:00 p.m.

The kale seedlings (Figure 2) were obtained in our laboratory. Seedlings were irrigated with a nutritive solution (0.27% Fe, 0.07% Mn, 0.05% Zn, 0.04% B, 0.009% Cu, and 0.006% Mo) to support plant growth (2 mL solution/L water). After true leaves were developed (4-5 leaves), plants were transferred to the aquaponic system (after 25 days). The following experimental variants were created, in duplicate: K1 - 14 plants/m^2, K2 - 21 plants/m^2, K3 - 28 plants/m^2 and K3 - 41 plants/m^2.

Figure 2. Kale seedlings before transfer to the aquaponic system (Original photo)

All the plant units were filled with Lightweight Expanded Clay Aggregate (LECA). LECA is a porous, lightweight material used in aquaponic systems as a growing medium. It is chemically inert and durable and doesn't affect the system's pH or nutrient levels. It provides excellent aeration and drainage for plant roots while retaining sufficient water.

Water quality analysis, including temperature (°C), dissolved oxygen (mg L^{-1}), and pH, were monitored daily using a Pro1020 (YSI Incorporated, USA) and pH-meter (WTW InoLab pH 7110, Xylem Analytics, Germany). Nitrogen compounds (nitrates, nitrites, and ammonium) were measured twice weekly with Merck kits and a Merck Spectroquant Nova 400 spectrophotometer (Merck Chemicals GmbH, Germany). Water samples were taken at different points: after mechanical and biological filtration (M+B), from the plants growing units (P), and the fish basins (F). Luminous intensity (lx) was measured weekly with a TESTO 545 light meter (Testo Co., USA).

Plants and fish growth parameters. The physical growth of kale was determined by measuring weight gain of plants (g) (WG = final biomass of plants-initial biomass of plants), leaf area surface (cm^2/plant), final roots weight (g), and the number of leaves. At the end of the experimental trial, fish growth parameters such as feed conversion ratio (FCR), specific growth rate (SGR), feed intake (FI), body weight gain (BWG), and survival (S%) were calculated as follows:

- FCR = FI/BWG;
- SGR = (ln (Final body weight) − ln (Initial body weight))/Number of days;
- BWG = Final body weight − Initial body weight;
- FI = amount of feed provided – amount of remaining feed;
- S = (Number of fish at the end of the study/Number of fish at the beginning of the experiment) × 100.

Plant analysis. Plants were dried in a ventilated oven (Jeiotech, Jeio Tech Co., Inc., Korea) at 60°C until a constant weight was achieved, allowing for the determination of dry weight in grams. This value was then used to calculate the dry matter (DM) percentage. Nitrite and nitrate levels in plants were determined by the Griess method (STAS 9065:2002).

The chlorophyll content was assessed by extracting chlorophylls from leaf tissues using ethanol, following the procedure outlined by Castle et al. (2011). Absorbance was measured at specific wavelengths corresponding to chlorophyll a, b, and total chlorophyll, specifically at 649 nm and 665 nm.

The phosphorus concentration was measured colorimetrically using the SANseries Automated Wet Chemistry Analyzers (SANseries Skalar Analytical B.V., The Netherlands). The phosphate determination method relies on the reaction between ammonium heptamolybdate and potassium antimony (III) oxide tartrate in an acidic solution, with phosphate ions forming an antimony-phosphomolybdate complex. This complex is subsequently reduced by L(+) ascorbic acid, resulting in a deep blue-colored complex, which is quantified spectrophotometrically at 660 nm.

Statistical analysys. The data collected were processed using IBM-SPSS statistical software and presented as Mean ± SEM. Prior to conducting analysis of variance (ANOVA), Levene's test was applied to assess homogeneity of variances. One-way and two-way ANOVA were then used to evaluate significant differences in the parameters measured. Differences between means were determined using the Duncan multiple range test with a significance level set at $\alpha = 0.05$.

RESULTS AND DISCUSSIONS

Water quality parameters. In the experiment, maintaining water quality within optimal ranges was crucial for the health and growth of kale plants and fish, ensuring the success of the aquaponic system. The water temperature was kept within the ideal range for kale growth (Table 1), aligning with the findings of Chowdhury et al. (2021) that suggest a preferred temperature range of 20°C to 23°C, with a broader tolerance of 18°C to 28°C in greenhouse environments (Catigday et al., 2023). Additionally, dissolved oxygen levels remained consistent, with no significant differences between fish tanks ($p > 0.05$), ensuring both fish and beneficial bacteria had adequate oxygen for respiration and nitrification. The water pH ranged from 7.24 to

7.55, which was optimal for fish and plants, promoting a stable environment for the essential nitrification process, supporting nutrient cycling in the system.

The nitrogen compounds ($N\text{-}NO_2^-$, $N\text{-}NH_4^+$, and $N\text{-}NO_3^-$) did not show significant differences between fish tanks ($p > 0.05$), but their levels decreased significantly after water evacuation from the plant units ($p < 0.05$). This decrease is attributed to the plant's ability to absorb and retain these nitrogen compounds, highlighting their critical role in the nitrogen cycle. By taking up ammonium and nitrate, plants help regulate nutrient levels, reducing the concentration of potentially harmful compounds in the water.

Table 1. The physicochemical parameters of water during the experimental trial

Parameter	Fish tanks				Alimentation of aquaponic units				Evacuation of aquaponic units			
	B1	B2	B3	B4	K1	K2	K3	K4	K1	K2	K3	K4
Temperature (°C)	20.8± 0.16	20.7± 0.21	21.06± 0.23	20.9± 0.31	21.02± 0.4	21.12± 0.24	20.9± 0.25	20.6± 0.18	21.0± 0.23	21.2± 0.24	21.1± 0.30	20.9± 0.18
Oxygen (mg/L)	7.16± 0.23	7.24± 0.21	7.32± 0.19	7.16± 0.13	-	-	-	-	-	-	-	-
pH (pH units)	7.55± 0.51	7.42± 0.49	7.34± 0.40	7.37± 0.40	7.43± 0.44	7.32± 0.28	7.31± 0.43	7.28± 0.54	7.25± 0.50	7.32± 0.47	7.24± 0.35	7.36± 0.37
$N\text{-}NO_2^-$ (mg/L)	0.04± 0.003	0.05± 0.002	0.04± 0.003	0.06± 0.002	0.05± 0.002	0.04± 0.002	0.03± 0.001	0.04± 0.002	0.02± 0.003	0.01± 0.004	0.02± 0.002	0.02± 0.001
$N\text{-}NH_4^+$ (mg/L)	1.33± 0.51	1.09± 0.46	1.66± 0.29	1.46± 0.29	1.27± 0.5	1.02± 0.48	1.08± 0.37	1.05± 0.29	0.71± 0.41	0.86± 0.52	0.76± 0.36	0.96± 0.29
$N\text{-}NO_3^-$ (mg/L)	39.74± 1.53	37.74± 1.77	37.88± 0.69	36.73± 0.38	37.05± 1.31	35.57± 1.01	32.12± 0.77	35.3± 2.17	28.46± 1.47	29.55± 1.35	28.06± 0.85	26.12± 0.73
$P\text{-}PO_4$ (mg/L)	5.77± 0.62	5.87± 0.87	5.76± 0.72	5.99± 0.62	5.71± 0.79	5.55± 0.40	4.78± 0.40	5.62± 0.34	4.12± 0.42	3.82± 0.40	4.03± 0.72	4.12± 0.25
Conductivity (µS/cm)	1921.2± 173.63	2004.4± 172.67	1956.8± 114.35	1937.75± 151.19	1942.5± 173.63	2004.75± 148.60	1943.01± 115.14	1902.12± 110.01	1829.60± 137.60	1976.25± 114.23	1896.04± 112.03	1896.12± 112.01

Note: Values are presented as Mean ± SEM (standard error of mean); B1- B4 – fish rearing units; K1-K4 – aquaponic units.

Electrical conductivity (EC), which ranged between 1829.60 and 2004.75 µS/cm, was within the optimal range for plants and fish. Lower EC values were recorded after water evacuation from the plant units, reflecting the plants' uptake of dissolved nutrients.

Maintaining proper EC levels is essential for plant nutrient uptake and preventing toxic concentrations of salts or minerals.

The balanced fish-to-plant stocking density and careful monitoring of water quality parameters contributed to the aquaponic system's efficient nutrient cycling and optimal performance.

This balance is essential for preventing nutrient deficiencies and excesses, ensuring the sustainability and productivity of the system. Careful monitoring and adjusting water quality and plant density are key to ensuring a successful and productive aquaponic system.

Plant Growth in an Aquaponic System. Table 2 present the plant growth parameters of kale in the aquaponic system at different stocking densities of plants.

The initial weight of kale registered no significant ($p>0.05$) differences between the four experimental variants (Figure 3).

After 50 days, kale's final weight was significantly higher at the density of 28 plants/m² (K3), while no differences were recorded between the densities of 14 plants/m², 21 plants/m², and 41 plants/m², respectively (Figure 4).

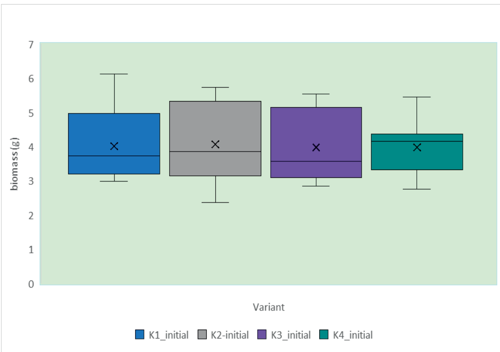

Figure 3. The distribution of the initial weight of kale

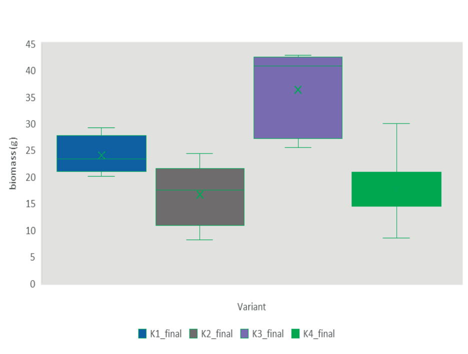

Figure 4. The distribution of the final weight of kale

The foliar surface area is a key indicator of a plant's ability to capture light and perform photosynthesis (Patil et al., 2018).
A larger leaf area allows for greater light interception, enhancing the plant's photosynthetic efficiency.
As a result, the foliar surface is closely linked to plant growth and biomass accumulation, providing valuable insight into the plant's developmental capacity and overall productivity.
At the initial stage of the experiment, the leaf area of kale plants was similar ($p>0.05$) across all four experimental variants (Figure 5).

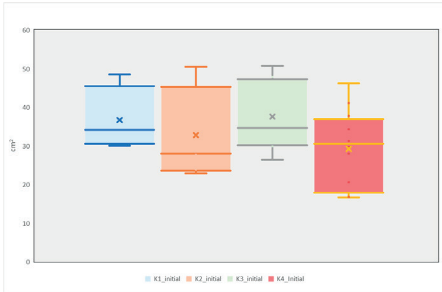

Figure 5. Leaf area of kale at the initial moment

However, at the end of the experiment, the leaf area values in the K3 variant (28 plants/m²) were significantly higher compared to the other planting densities (Figure 6).

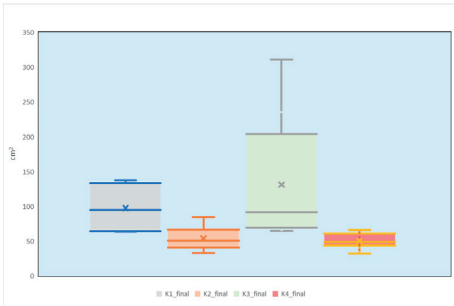

Figure 6. Leaf area of kale at the final moment

Table 2. Plant growth data from the aquaponic system

Parameter	K1 (14 plants/m^2)	K2 (21 plants/m^2)	K3 (28 plants/m^2)	K4 (41 plants/m^2)
Individual weight at initial moment (g)	4.01±0.61*	4.06±0.49*	3.98±0.35*	3,97±0.41*
Individual weight at final moment (g)	24.02±1.76*	16.64±1.56*	36.35±1.24**	17.67±2.45*
Initial biomass (g)	20.07±1.52	24.41±1.43	21.85±1.14	27.35±1.16
Final biomass (g)	96.08±3.52	99.84±2.43	290.86±2.23	212.06±3.35
Plant's weight gain (g)	76.00±2.54	75.44±2.40	269.01±2.35	184.72±2.27
Individual root weight at the final moment (g)	3.13±1.16*	7.92±1.14**	16.95±1.15***	3.5±1.09*
Number of leaves	15.63±2.16*	16.41±3.05*	23.93±1.01**	16.79±1.23*

Overall, the final plant biomass was higher in the K3 variant, followed by the K4 variant, where we have the highest plant stocking density. Regarding the number of leaves, a significantly higher number was reported in the K3 variant. The number of leaves on a plant is an important indicator of its growth, health, and productivity. A higher leaf count typically reflects strong vegetative growth, enhancing the plant's photosynthetic capacity and overall energy production.

In this study, stocking density significantly affected kale growth in an aquaponic system. The 28 plants/m² density (K3) resulted in the highest final plant weight, leaf area, and number of leaves, suggesting it is the optimal density for kale growth. At this density, plants had enough space to develop larger leaves, enhancing their photosynthetic efficiency and overall biomass accumulation. In contrast, higher densities, such as 41 plants/m² (K4), did not show significant improvements in biomass, likely due to increased competition for light and nutrients.

These findings highlight the importance of balancing stocking density to optimize plant growth and productivity in aquaponic systems. In the current scientific literature, there is a scarcity of studies that directly investigate the effect of different plant densities on kale growth in aquaponic systems, which limits the possibility of direct comparisons and highlights the need for further research in this area.

However, our findings align with previous research conducted in hydroponic systems. For example, Noboa et al. (2022), studying curly kale in a hydroponic NFT system, observed that reducing plant spacing increased overall yield per area; however, fewer plants per cell led to larger and more uniform leaves, highlighting a trade-off between maximizing yield and maintaining product quality. Although both studies emphasize the significance of density optimization, the aquaponic system in the present study revealed stronger limitations at higher densities, likely due to the compounded effects of light and nutrient competition inherent to integrated plant-fish systems. Similarly, in another aquaponic study (Afolabi, 2020) where kale was grown alongside Nile tilapia at a fixed density of 25 plants/m², researchers highlighted that system design and configuration (integrated aqua-vegeculture vs. deep-water culture) also play critical roles in determining plant and fish productivity, as well as water quality.

In Table 3 are presented the mean values of the dry matter content (%), Chlorophyll A and B, nitrite (mg/kg), nitrate (mg/kg), and phosphorus (mg/kg) content from kale plants at the end of the aquaponic trial. Dry matter content was slightly higher at K2, indicating slightly better biomass accumulation. Chlorophyll A levels were highest in K3, suggesting enhanced photosynthesis, while Chlorophyll B increased from K1 to K3, with K3 showing the highest concentration. Regarding nitrite, K3 had the lowest concentration, reflecting efficient conversion or uptake, while K1 and K2 had higher nitrite levels. Nitrate levels were highest in K2, suggesting greater nitrification but possibly reduced plant uptake. K3 had the lowest nitrate concentration.

Finally, phosphorus concentrations increased from K1 to K4, with K3 showing the highest values, suggesting better nutrient uptake and root development. Overall, K3 seems to support efficient nitrogen conversion and photosynthesis.

Table 3. Plant analysis at the end of the trial

Parameter	K1	K2	K3	K4
Dry matter (%)	8.55±0.99	8.88±0.78	7.78±0.54	8.29±0.87
Chlorophyll A ($\mu g \times g^{-1}$)	0.55±0.16	0.59±0.12	0.66±0.09	0.58±0.63
Chlorophyll B ($\mu g \times g^{-1}$)	0.40±0.09	0.74±0.07	0.81±0.08	0.68±0.05
Nitrite (mg/kg)	0.32±0.02	0.26±0.04	0.025±0.02	0.26±0.04
Nitrate (mg/kg)	3.12±0.17	4.23±0.18	2.63±4.36	3.63±2.19
Phosphorous (mg/kg)	2.06±0.56	2.36±0.42	2.49±1.02	2.21±1.16

Fish growth performance. At the end of the aquaponic experiment, the fish survival rates were very high, ranging from 96.97% to 100%, indicating a good water quality and system management (Table 4).

Table 4. Fish growth performance at the end of the experiment

Parameter	B1	B2	B3	B4
Initial number of fish	33	33	33	33
Initial biomass (g)	416	418	417	422
Initial fish weigh (g)	12.61	12.67	12.64	12.79
Final biomass (g)	648	687	689	643
Final fish weight (g)	20.25	20.82	20.88	19.48
Survival (%)	96.97	100	100	100

The final fish biomass increased in all groups, with the highest values recorded in B2 (687 g) and B3 (689 g).

These two variants also showed the highest individual final weights, reaching 20.82 g and 20.88 g respectively, suggesting that the stocking density of plants in these variants may have created favourable conditions for fish growth, likely through better nutrient cycling and system balance.

Despite a slightly lower final biomass in B4 (643 g), survival remained at 100%, indicating no lethal stress, though growth was slightly reduced, possibly due to competition or less optimal nutrient conditions caused by the higher plant density.

CONCLUSIONS

This study underscores the importance of carefully balancing plant stocking densities in aquaponic systems to optimize both plant growth and fish productivity.

The variant with 28 kale plants/m² emerged as the optimal density for kale growth, as it facilitated larger leaf area and better biomass accumulation.

Regarding the fish growth, the best growth performance was reported in the B3 basin (corresponding to the aquaponic units with 28 plant/m^2) and B2 (corresponding to the aquaponic units with 21 plant/m^2), likely due to the nutrient balance fostered by these plant densities.

The study emphasizes that higher plant densities beyond a certain threshold could lead to competition for light and nutrients, potentially limiting growth and productivity in both plants and fish.

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