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## Efficiency of potassium sulphate application for growing *Clarias gariepinus* in an aquaponics system

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**Abstract.** The study aimed to determine the effect of adding potassium sulphate ( $K_2SO_4$ ) at a concentration of  $500 \text{ mg/dm}^3$  on the quality of the aquatic environment, growth of *Clarias gariepinus* and yield of lettuce in an aquaponics system. The experiment was conducted in two parallel lines: control (without  $K_2SO_4$ ) and experimental (with the addition of  $K_2SO_4$ ). The initial total weight of 19 fish in each line was 1330 g. In 57 days, the weight in the control line increased to 1995 g, and in the experimental – to 2888 g. The feed conversion was 2.5 in the control and 1.1 in the experiment. The specific growth rate (SGR) was 0.82%/day in the control and 1.74%/day in the experimental group. The potential yield of lettuce ( $4000 \text{ g/m}^2$ ) was realised by 51.1% in the control and 87.5% in the experiment. In the control line, the main limiting factor was potassium deficiency ( $21.6\text{--}28.3 \text{ mg/l}$ ), and in the experimental line, the pH increased to 8.3 due to insufficient nitrogen uptake at  $19.5^\circ\text{C}$  (below the optimum for nitrification). In both lines, a significant increase in the content of mineral compounds ( $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ,  $\text{SO}_4^{2-}$ ,  $\text{PO}_4^{3-}$ ) was recorded, but the water parameters remained within the range acceptable for aquaponics technologies. The results obtained indicate a positive effect of adding  $K_2SO_4$  at a given concentration, which ensures an increase in fish and plant productivity, although it requires the incorporation of the ratio of green crops to fish biomass and

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water temperature. The addition of  $K_2SO_4$  contributed to the increase in the biological efficiency of the aquaponic system while maintaining acceptable water quality

**Keywords:** lettuce; biomass growth; feed conversion; water quality; nitrate nitrogen; hydroponics module performance

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## Introduction

The African Clarius catfish (*Clarias gariepinus*) is an important aquaculture element due to its rapid growth, resistance to stressful conditions and ability to breathe atmospheric air, therefore resilient to high planting densities. In one cubic metre of water, 200-300 kg of adult fish can be grown, and under favourable conditions, catfish can reach a weight of 1.5-2 kg in six months (State Agency of Fisheries of Ukraine, 2021). B.Yu. Kovalenko *et al.* (2021) emphasised that catfish can adapt to different growing conditions, which is important for aquaponics systems, where effective management of the aquatic environment is critical for system stability. At the same time, N.M. Vdovenko *et al.* (2020) emphasised the importance of optimising feeding strategies to ensure high productivity and ecosystem stability.

A.M. Trofymchuk *et al.* (2021) provided a fish farming and technological rationale for recirculating aquaculture systems for African catfish, highlighting the importance of proper control of the aquatic environment to ensure optimal conditions for fish growth. This highlights the need for an integrated approach to managing aquaculture systems, where maintaining water stability and fish health are key factors for a successful system. Aquaponics, which combines aquaculture and hydroponics, is a sustainable system that allows for efficient use of resources and reduces the negative impact on the environment. Mineral elements are substantial in this system, in particular potassium, which is a key macronutrient for plant growth. Potassium sulphate ( $K_2SO_4$ ) is a popular source of potassium in agriculture because it does not contain chlorine, which can be harmful to some crops.

However, the impact of potassium sulphate on the health and productivity of aquatic organisms, in particular the Clarius catfish, has not been sufficiently studied. Research demonstrated that an increased concentration of potassium sulphate in the aquatic environment can affect the physiological parameters of aquatic organisms. For instance, I.S. Babarchuk & Yu.V. Babich (2022) studied the effect of potassium sulphate on the haematological parameters of the mollusc *Planorbarius corneus*, which indicates the potential impact of this fertiliser on aquatic life. The efficient use of mineral fertilisers in aquaponics systems, in particular potassium sulphate ( $K_2SO_4$ ), is an important aspect of research aimed at optimising these agroecological systems. According to H. Neerudu *et al.* (2023), potassium sulphate is a source of potassium, which is essential for normal plant growth and is also important for regulating water and salt balance in organisms, including aquacultured fish. Potassium is critical for chlorophyll synthesis, energy transfer and maintenance of cellular pressure, and therefore its deficiency or excess can have a significant impact on the performance of aquaponics systems.

Potassium is important not only for plant development but also for fish health, as evidenced by studies showing that potassium helps fish to better adapt to stressful conditions such as rising water temperatures and changes in water quality. The potential positive effect of potassium on fish is also supported by H. Nyadjeu *et al.* (2020) and L.C. Wenzel *et al.* (2021), studies on the African Clarius catfish, which demonstrated improved health and metabolism when added to feed. One of the most important areas of research is the study of the effect of potassium sulphate on

the physiological parameters of fish, particularly the African *Clarias gariepinus*. The study by A. Granal *et al.* (2024) demonstrated that potassium has a positive effect on the ability of fish to adapt to stressful conditions, including increased water temperature. However, at excessive concentrations of potassium sulphate, there is an increase in toxicity, which can lead to a decrease in fish activity and negatively affect their ability to grow. In addition, studies demonstrated a positive effect of potassium on improving fish metabolism improving the condition of their skin and reducing stress levels in the event of sudden changes in water parameters.

F.X. Presas-Basalo (2021) highlighted the importance of a balanced supply of macro- and micronutrients in aquaponic systems. The study highlighted that potassium in high concentrations can affect the levels of other macronutrients, such as calcium and magnesium, which are important for normal physiology in both plants and fish. Furthermore, the system should include well-configured filtration to prevent the accumulation of toxic levels of salts. Other studies, such as by V.C. John *et al.* (2021), demonstrated that properly configured aquaponics systems using potassium sulphate can provide sustainable and efficient production of both fish and plants. The researchers noted that for the successful integration of potassium sulphate, environmental factors such as water temperature and pH must be incorporated, as these parameters directly affect the efficiency of potassium in both components of the system. In general, studies conducted by S.F.P. Duarte & B.S. Cerozi (2024) demonstrated that properly balanced potassium levels in aquaponics systems have a positive effect on the productivity of both fish and plants. However, more research is needed to determine the optimal concentrations of this element depending on the type of plants and fish species grown.

Overall, numerous studies demonstrated that potassium sulphate is promising for aquaponics systems, but more research is needed to determine the optimal concentrations of this element

depending on the type of plants and fish species grown. Another important area is the development of new methods of water purification and monitoring of mineral levels, which can reduce the negative impact of high potassium concentrations on the environment. Thus, the relevance of this study lies in the need to study the effect of potassium sulphate on the cultivation of *Clarius catfish* in aquaponics systems.

The study aimed to evaluate the effectiveness of potassium sulphate in ensuring optimal conditions for the development of aquaponics organisms (*Clarius catfish* and lettuce). Study goals included:

- analysis and evaluation of changes in the state of the aquatic environment during 1 cycle of growing lettuce (57 days) without the addition of potassium sulphate and with the addition of potassium sulphate at a concentration of 0.50 g/dm<sup>3</sup>;
- analysis and evaluation of the development of *Clarius catfish* in the experimental line of the aquaponics system (with and without the addition of 0.50 g/dm<sup>3</sup> of potassium sulphate) by metrics: average fish weight, feed conversion rate, specific fish growth rate, assessment of the impact of potassium sulphate on fish physiological parameters.

The research relevance is determined by the novelty of the comprehensive study of the effect of potassium sulphate on the cultivation of *Clarius catfish* in aquaponics systems, which will increase the efficiency and sustainability of such systems.

## Materials and Methods

The experimental study was conducted at the National University of Water and Environmental Engineering in the educational and scientific laboratory of cyclic water of agroecosystems in 2024 and aimed to analyse the effect of adding potassium sulphate (K<sub>2</sub>SO<sub>4</sub>) to fresh water of an aquaponic system with *Clarias catfish* (aquaculture module) and lettuce (hydroponics module) at a concentration of 0.5 g/dm<sup>3</sup> on the chemical parameters of water and productivity of *Clarias*

*garipepinus* in an aquaponic system. The study was conducted based on the Convention on Biological Diversity (1992).

**Experiment.** Two parallel aquaponics systems were used in the experiment: a control system (without potassium sulphate) and an experimental system (with potassium sulphate). In the aquaculture module of each line (a 1 m<sup>3</sup> tank with a water level of 0.8 m<sup>3</sup>), 19 Clarus catfish with an average initial weight of 50 g/individual were grown, with a total fish biomass of 950 g/tank. In the hydroponics module, leaf lettuce was grown on a planting area of 1 m<sup>2</sup> with a planting density of 57 plants/m<sup>2</sup>.

**Water quality analysis.** Water quality was tested at the start of the experiment (13 November 2024) and at the end of the experiment (8 January 2025). To determine the content of macroelements in water, a Lasa agro 1900 spectrophotometer (manufacturer: STEP Systems GmbH, country of manufacture: Germany) was used, and to determine the pH of water and the concentration of potassium ions, an ion meter I-160 MI (manufacturer: NPF Tensor, country of manufacture: Russia) with appropriate selective electrodes. This equipment provided accurate measurements of the concentration of the main chemical elements affecting the state of the aquatic environment in the aquaponics system. In addition, the following methods were used to study water quality: measurement of nitrate ion concentration by the photocolometric method MM No. 081/12-0651-09 (2010); measurement of the mass concentration of ammonium ions by the photocolometric method with Nessler's reagent MM No. 081/12-0651-09 (2010), measurement of the mass concentration of sulphates by titrimetric method MM No. 081/12-0653-09 (2010).

Two important physiological indicators were calculated to assess the efficiency of fish feed assimilation and fish development: Specific Growth Rate (SGR) and Feed Conversion Ratio (FCR). FCR is an important indicator of the efficiency of fish farming in aquaponic systems (Nyadjeu *et al.*, 2020):

$$FCR = \frac{\text{Consumed feed mass (g)}}{\text{Biomass growth (g)}}. \quad (1)$$

The FCR determines the amount of feed required to produce a unit of biomass gain. The calculation of these metrics determines how efficiently fish use feed and how fast they grow in conditions where potassium sulphate is added compared to control conditions. SGR is another important indicator that can estimate the growth rate of fish over a certain period (Dos Santos, 2018):

$$SGR = \frac{(\ln W_t - \ln W_0) \cdot 100}{t}, \quad (2)$$

where  $W_t$  – fish mass at the end of the experiment, g;  $W_0$  – initial fish mass, g;  $t$  – experiment duration, days;  $\ln$  – natural logarithm.

To determine statistically significant differences between the mean values of the two experimental variants, the least significant difference (LSD<sub>05</sub>) was calculated (Ushkarenko *et al.*, 2013). These calculations determined: number of degrees of freedom for variants, replicates, and error; total number of observations; correction factor; total sum of squares; sum of squares for replicates, variants, and error; variance for line and error; Fisher's test; and relative error.

## Results and Discussion

The results of the study of Clarus catfish development in the aquaponics system showed that at the end of the experiment (57 days), the total weight of fish in the control line reached 1995 g/basin, while in the experimental – 2888 g/basin (Table 1).

The increase in the total biomass of Clarie catfish during the study period in the control line was +665 g/basin, in the experimental line +1558 g/basin, which exceeded the control indicator by 134%, which indicates a very positive effect of adding potassium sulphate at a concentration of 0.50 g/dm<sup>3</sup> on the development of Clarus catfish. At the same time, the average weight of one Clarus catfish in the control line at the end of the experiment was 105 g/individual, and in the experimental line, 170 g/individual.

Dispersion analysis showed statistically significant differences between the average fish weights in the control and experimental lines.

The smallest significant difference ( $LSD_{05}$ ) was 21.6 g/individual, which indicates the reliability of the differences.

**Table 1.** Growth and feed conversion parameters in *Clarius catfish*

Metric	Controller	Experimental	$LSD_{05}$	Absolute increase relative to control	Relative increase, % to control
Average weight of fish at the beginning of the experiment, g/individual	70	70	-	0	0
Number of fish, individuals/pool	19	19	-	0	0
Total weight of feed consumed during the experiment, g/pool	1670	1670	-	0	0
Average fish weight at the end of the experiment, g/specimen	105	152	21.6 g/specimen	47	+44.8
Total fish weight at the start of the experiment, g/basin	1330	1330	-	0	0
Total fish weight at the end of the experiment, g/basin	1995	2886	-	893	+44.8
Increase in total fish weight during the experiment, g/basin	665	1558	-	893	+134
FCR (feed conversion ratio)	2.51	1.08	-	-1.44	-57.3
SGR (specific growth rate), %/day (for 57 days)	0.71	1.36	-	0.65	91.2

**Source:** compiled by the authors

The feed conversion ratio (FCR) in the control line was 2.51, while in the experimental line, the FCR decreased to 1.07. According to the scientist J. Breinballe (2010), the average optimal values of the feed conversion ratio of *Clarius catfish* range from 1.2 to 1.5. Thus, the obtained values of FCR indicate a low level of feed assimilation by fish of the control line and a very high level in fish of the experimental line. Thus, the addition of potassium sulphate to the water at a concentration of 0.50 g/dm<sup>3</sup> increased the efficiency of feed assimilation by *Clarius catfish* by 57.3%. The specific growth rate of fish (SGR) during the study period in the control line was 0.71 %/day, in the experimental line, 1.36%/day, respectively, which indicates an acceleration of growth of *Clarius catfish* under the influence of potassium sulphate (0.50 g/dm<sup>3</sup>) by 91.2%.

An important benchmark for the level of water pollution in an aquaponics system is the water quality standard. The search for relevant standards

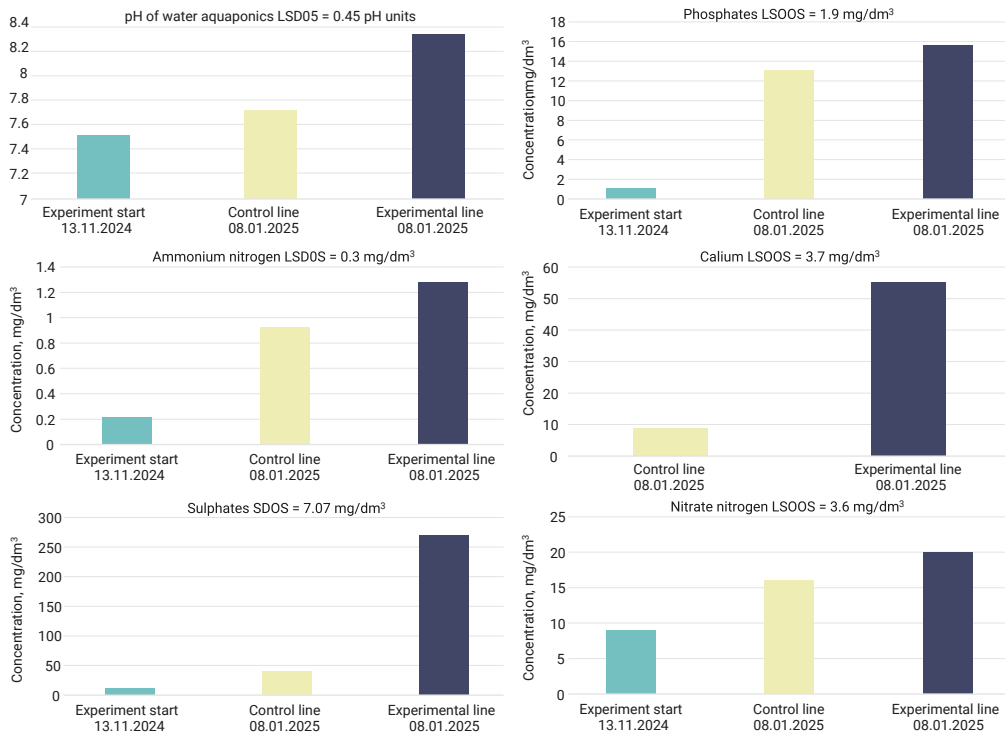
in Ukrainian and foreign regulatory documents demonstrated that in Ukraine, there are only fishery water quality standards for ponds, while EU countries also have relevant standards for surface water sources (Directive 2000/60/EC..., 2000; Order of the Ministry..., 2022). For aquaponics systems, no standards were found that would regulate the maximum permissible concentrations (MPC) of pollutants, but based on the study of various literature sources, some technological standards for water quality in recirculation plants for samarium were summarised in Table 2.

To determine the reasons for the acceleration of *Clarius catfish* development under the influence of potassium sulfate addition to water to set its concentration in the aquatic environment at 0.50 g/dm<sup>3</sup>, the main parameters of water quality were analysed at the beginning and end of the experiment in the control and experimental lines of the aquaponics system (Fig. 1) and a graph of the average daily water temperature dynamics (Fig. 2).

**Table 2. Consolidated technological standards for water quality of closed water supply systems for rearing juvenile *Claris catfish***

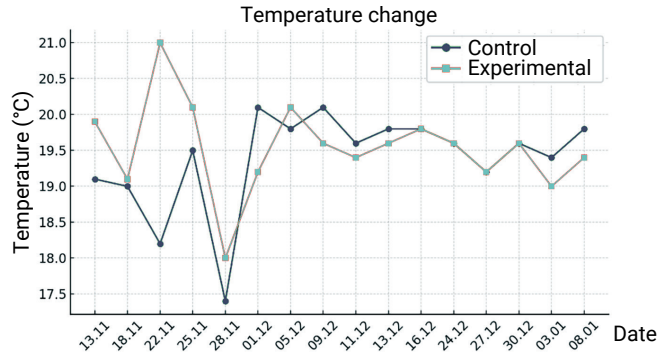
No.	Metric	Units of measurement	Technologically permissible fluctuation limits	Source of information on the value of the indicator's technological limits
1	pH	Unit, pH	6-8.5	A. Peteri <i>et al.</i> (2015)
2	Salt content	mg/dm <sup>3</sup>	10	A. Peteri <i>et al.</i> (2015)
			25-27	A. Peteri <i>et al.</i> (2015)
			>0.0	A. Peteri <i>et al.</i> (2015)
5	N-NH <sub>3</sub>	mg/dm <sup>3</sup>	<0.34	A. Peteri <i>et al.</i> (2015)
6	N-NH <sub>4</sub> <sup>+</sup>	mg/dm <sup>3</sup>	<80	A. Peteri <i>et al.</i> (2015)
7	NO <sub>2</sub> <sup>-</sup>	mg/dm <sup>3</sup>	<8.0	A. Peteri <i>et al.</i> (2015)
8	NO <sub>3</sub> <sup>-</sup>	mg/dm <sup>3</sup>	<100 for fish weighing up to 10 g, for fish weighing more than 10 g – not regulated	A. Peteri <i>et al.</i> (2015)
9	N- (NH <sub>4</sub> <sup>+</sup> + NO <sub>3</sub> <sup>-</sup> )	mg/dm <sup>3</sup>	<100	J. Breinballe (2010)
10	CO <sub>2</sub>	mg/dm <sup>3</sup>	<15	J. Breinballe (2010)
			<10	A. Peteri <i>et al.</i> (2015)
11	H <sub>2</sub> S	mg/dm <sup>3</sup>	<2.0	A. Peteri <i>et al.</i> (2015)
12	BSC	mg/dm <sup>3</sup>	<20	J. Breinballe (2010)
13	P-PO <sub>4</sub> <sup>3-</sup>	mg/dm <sup>3</sup>	<20	J. Breinballe (2010)

Source: compiled by the authors



**Figure 1. Comparison of the chemical composition of water at the beginning and end of the experiment**

Source: compiled by the authors



**Figure 2.** Dynamics of water temperatures during the experiment

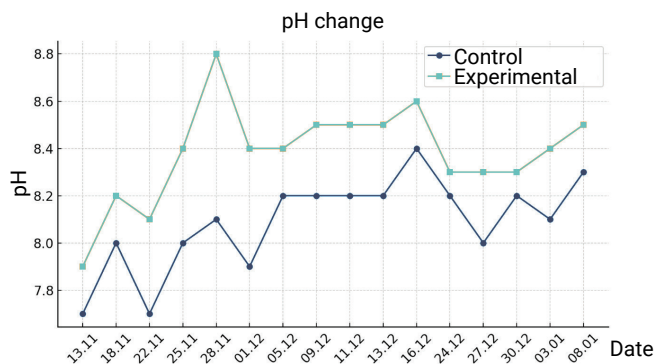
Source: compiled by the authors

The results of the analysis of changes in the redox conditions of the water environment (pH) of the control line during the experiment period (57 days) demonstrated an increase in pH from 7.5 to 7.7 pH units (+2.67% of the initial value), which is an insignificant increase, while in the experimental line the pH of the water increased to 8.3 pH units (+10.7% of the initial level). In the control line, the pH increased from 7.5 to 7.7, and in the experimental line, from 7.5 to 8.3. Such changes can be caused by several factors (Poloviy *et al.*, 2024):

➤ Ammonium nitrogen ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ) can increase the acidity of water, but their metabolic transformation, especially through nitrifying bacteria, can lead to a decrease in acidity. However, the addition of potassium sulphate can change the ion balance in the water, resulting in a slight increase in pH;

➤ Algae photosynthesis and bacterial processes can reduce  $\text{CO}_2$  concentrations in the system, leading to an increase in pH. This may also be the result of increased algae and bacterial activity under the influence of potassium, which reduces  $\text{CO}_2$  concentrations in aquaponics systems, as confirmed by other studies.

At the beginning of the experiment (one day after the addition of potassium sulphate in concentration and mixing of water in the system), the pH of the experimental line increased to 7.9 pH units (+0.4 pH units relative to the control line), at the end of the experiment, the pH of the experimental line exceeded the corresponding indicator of the control line by +0.6 pH units (+8.0%). During the study period, there were significant fluctuations in water pH in both the experimental and control lines (Fig. 3).



**Figure 3.** Water pH dynamics during the experiment

Source: compiled by the authors

In the control line, the temperature ranged from 17.4°C to 20.1°C, which is within the optimal range for *Clarius catfish* (18-28°C), as demonstrated in Figure 2. The drop in temperature to 17.4°C on 28 November was due to changes in external climatic conditions and the switching off lighting, which slowed the metabolic activity of the fish and reduced their ability to release ammonia. The temperature in the experimental line ranged from 18°C to 21°C, with sharper fluctuations.

Analysing the diagram of the course of average daily temperatures during the study period (Fig. 3), then on 28.11.2024, a clear inversely proportional relationship between temperature and pH is notable, in which a sharp decrease in water temperature causes a sharp increase in pH, especially in the experimental line (pH=8.8 units. pH), which is due to the deterioration of nitrifying bacteria, slowing down the development of lettuce plants and, as a result, the accumulation of ammonium nitrogen as a product of fish vital activity. In general, during the experiment, the pH of the water did not exceed the technological standards for *Clarius catfish* (Table 1), except for the date 28.11.2024, when the pH of the experimental line reached a maximum (8.8 pH units) due to a sharp decrease in water temperature to 18°C, which is normal for lettuce, but a factor inhibiting the development of *Clarius catfish* and especially nitrifying bacteria. After increasing the temperature from 18 to 20.1°C, the pH of the water in the experimental line decreased from 8.8 pH units to 8.4 pH units and came to the technological norm, not leaving it at the end of the experiment.

Monitoring the potassium and sulphate content in the water of the experimental and control lines and comparing them with the balance of sulphate ions and potassium ions added with potassium sulphate to the experimental line at a concentration of 0.50 g/dm<sup>3</sup>, the difference in potassium concentrations between the experimental and control lines is +46.3 mg/dm<sup>3</sup> in favour of the experimental line, and the difference in sulphate concentrations is 229 mg/dm<sup>3</sup> in favour of the experimental line is notable. The ratio of

the increase in potassium ion concentration to sulphate ion concentration in the experimental line relative to the control line is 4.95 times in favour of sulphate ion. At the same time, the ratio between potassium ions and sulphate ions in the water of the experimental line at the beginning of the experiment (at a potassium sulphate concentration of 0.50 g/dm<sup>3</sup>) was 1.23. Thus, a significant shift in this ratio at the end of the experiment (+302% of the initial value) is notable in favour of sulphate ions. To determine the reasons for this shift, it is necessary to analyse other water quality indicators, which will correlate with the processes of fish and plant development and water quality. It should be noted that the fish diet and feeding rates in both lines remained unchanged during the study period (30 g of feed per 19 fish per day), and the feed quality was also the same: Aller Aqua Classic, 4 mm fraction.

An important indicator of water quality is the content of ammonium nitrogen and nitrate nitrogen in water, which together is the sum of nitrogen from mineral compounds. These mineral nitrogen compounds in water occur as a result of the gradual conversion of organic nitrogen compounds (nitrogen amides, urea nitrogen) first to ammonium nitrogen, then to nitrate and nitrite nitrogen, and then to amino acid nitrogen in plant organisms and microorganisms living in water through assimilative denitrification (Nugraha *et al.*, 2020). But there is also another way of denitrification – dissimilatory denitrification, in which nitrates are reduced to gaseous nitrogen compounds (NO, N<sub>2</sub>O, N<sub>2</sub>), which indicates unproductive losses of nitrogen that could be used in the synthesis of organic compounds of the plant organism and effective microorganisms. The processes of transformation of nitrogen compounds in aquaponic systems are temperature-dependent: when the temperature rises to 25-30°C, the activity of nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*) increases, which contributes to more intensive oxidation of ammonium (NH<sub>4</sub><sup>+</sup>) to nitrite (NO<sub>2</sub><sup>-</sup>) and further conversion to nitrate (NO<sub>3</sub><sup>-</sup>), whereas at low temperatures (<15°C), the rate of

nitrification slows down significantly, which can lead to the accumulation of toxic forms of nitrogen in the aquatic environment.

In an aquaponic system, the main consumer of nitrogen compounds is plants, which consequently purify water from toxic nitrogen compounds. At the same time, nitrate nitrogen accounts for 75...95% of the total nitrogen consumption by plants, and ammonium nitrogen accounts for the rest. Therefore, an increase in the ratio between ammonium and nitrate nitrogen in favour of the former in aquaponics water indicates insufficient nitrogen consumption by plants in general, resulting in the accumulation of the ammonium form of nitrogen.

According to the results of studies of changes in the content of mineral nitrogen compounds in the water of the studied aquaponics system lines (Fig. 1), it is evident that at the beginning of the experiment, the total content of mineral nitrogen compounds in both lines was  $9.22 \text{ mg/dm}^3$ , with ammonium nitrogen accounting for 2.39% and nitrate nitrogen accounted for 97.6%. At the end of the experiment (58 days after the start of the experiment), the content of nitrogen in mineral compounds in the control line increased to  $16.9 \text{ mg/dm}^3$  (+7.71%), with the proportion of ammonium nitrogen increasing to 5.49% (+3.11%) and the proportion of nitrate decreasing accordingly. This indicates insufficient assimilation capacity of leaf lettuce plants per  $1 \text{ m}^2$  and the need to increase the area of lettuce plantings relative to the total fish biomass (1995 g) by approximately 17%. Overall, during the study period, the specific nitrogen concentration in water per 1 kg of live fish biomass changed from  $0.165 \text{ mg}/(\text{dm}^3 \cdot \text{kg})$  to  $0.466 \text{ mg}/(\text{dm}^3 \cdot \text{kg})$ , or +182% of the initial value. In the experimental line, during the study period, the increase in the specific nitrogen concentration in water per 1 kg of live fish biomass changed from  $0.165 \text{ mg}/(\text{dm}^3 \cdot \text{kg})$  to  $0.443 \text{ mg}/(\text{dm}^3 \cdot \text{kg})$ , or +168% compared to the initial value. This indicates nitrogen accumulation in both lines and an insufficient area of leaf lettuce plantings. These indicators also indicate

improved nitrogen assimilation of mineral compounds by plants of the experimental line by 14% under the influence of potassium sulphate at a concentration of  $0.50 \text{ g/dm}^3$ .

Considering the yield of green mass of leaf lettuce at  $2043 \text{ g/m}^2$  in the control line and  $3498 \text{ g/m}^2$  in the experimental line, respectively, it is possible to conclude that under the influence of potassium sulphate at a concentration of  $0.50 \text{ g/dm}^3$ , the lettuce yield increased by 71.2% with a 134% increase in fish biomass relative to the control line. Thus, the overall productivity of the aquaponics system increased in both the aquaculture module and the hydroponics module. The relative excess of the aquaculture module's productivity growth over the hydroponics module by 62.8% indicates the high potential for overall productivity growth of the aquaponics agroecosystem under the influence of potassium sulphate, which in this experiment was not fully realised, primarily due to insufficient planting area and insufficiently high water temperature, which did not contribute to the active life of nitrifying bacteria and increase the availability of total nitrogen for plants, which would have made it possible to increase the level of water purification from nitrogen compounds even with the available plant area of  $1 \text{ m}^2$ .

The phosphate content in the aquaponics system of both lines at the beginning of the experiment was  $1.04 \text{ mg/dm}^3$ . At the end of the experiment, the phosphate content in the control line increased to  $13.1 \text{ mg/dm}^3$  (+1160% compared to the initial value), while in the experimental line, this indicator increased to  $15.6 \text{ mg/dm}^3$  (+1400%). Such a catastrophic increase in phosphate content is the result of fish life and the high-water solubility of fish excrement in slightly alkaline water. According to J. Breinballe (2010), the technological standard for phosphorus content in water is less than  $20 \text{ mg/dm}^3$ , which is less than  $61 \text{ mg/dm}^3$  when converted to phosphates. Considering the average specific waste generation rates per 100 kg of feed consumed, which average 4.5-5 kg of nitrogen and 1.3-1.5 kg of phosphorus

(Babarchuk & Babich, 2022) under conditions of uniform consumption of both nutrients by plants, a maximum phosphate concentration of 9-10 mg/dm<sup>3</sup> in the experimental line and 5.5-6 mg/dm<sup>3</sup> in the control line would be expected. Therefore, it is possible to conclude that leaf lettuce does not cope with the task of uniform water purification in aquaponics systems and is not an ideal crop for this system. In the future, it will be necessary to seek additional ways to improve biological water purification in aquaponics systems, apart from the cultivation of leaf lettuce.

The most interesting indicator is the potassium content in the water of the control and experimental lines, since this study was designed to increase the intake of potassium as a macronutrient for plants. According to the hypothesis, the additional intake of potassium in the form of potassium sulphate (0.50 g/dm<sup>3</sup>) should have balanced the composition of the water in terms of the content of nutrients for leaf lettuce and increased the total nitrogen removal from the water, which would increase the level of water purification for fish and increase the lettuce yield (since the waste products of catfish, similarly to all other fish, have a low potassium concentration). According to research by T. Kleiber *et al.* (2013), the dry weight of leaf lettuce leaves contains 3.64-5.15% nitrogen, 8.13-9.11% potassium and 0.57-1.31% phosphorus. Therefore, when forming the yield of leaf lettuce per unit of nitrogen removed by the lettuce harvest, plants remove 1.8-2.2 units of potassium and 0.16-0.25 units of phosphorus.

Potassium, as a macronutrient, maintains the correct balance of ions in fish organisms and is involved in many metabolic processes. Its deficiency can cause slower growth and development of fish. Potassium is an important element for many physiological processes, including the regulation of metabolism, which can contribute to the faster growth of fish. Higher levels of potassium also improve cell membrane function and enzymatic activity, which has a positive effect on growth rates.

Analysis of potassium content in the control line water (without potassium sulphate addition)

at the end of the experiment showed that the potassium content was 8.89 mg/dm<sup>3</sup>, while in the experimental line (with potassium sulphate added), the potassium content was 55.2 mg/dm<sup>3</sup> (+46.3 mg/dm<sup>3</sup> or +521% compared to the control). Comparing the relative increase in potassium content to the control (+521%), the relative increase in nitrogen content of mineral compounds to the control (+26%), and the relative increase in sulphate ions to the control (+567%) in the water of the experimental line at the end of the study period, it is possible to conclude that the area of leaf lettuce (1 m<sup>2</sup> per total fish biomass of 2.88 kg/m<sup>2</sup>) is insufficient to ensure a high degree of water purification from nitrogen compounds. In the control line water, the potassium to nitrogen ratio is 0.53, in the experimental line water it is 2.59, while in lettuce plants it is within the range of 1.8-2.2. Thus, there is a large potassium deficiency in the control line, and it is this deficiency that is the main limiting factor for yield, which explains the low level of lettuce leaf yield in the control (2.43 kg/m<sup>2</sup>). There is no potassium deficiency in the experimental line, and the maximum yield potential of leaf lettuce is only % realised. The increase in lettuce yield in the experimental line did not reach its potential level. The water in the experimental line contains 26% more nitrogen in mineral compounds, combined with high concentrations of potassium and phosphorus, which do not limit yield. Despite the optimal ratio of nitrate and ammonium nitrogen for the plant, leaf lettuce does not consume the available nitrate form of nitrogen. There is only one explanation for this: at pH >7.5 (as in the experimental line), the assimilation of nitrogen compounds by plants drops sharply. At pH > 7.5, the activity of nitrifying microorganisms gradually decreases, and after the threshold level of pH= 8.6, it drops sharply, which significantly complicates the processes of water purification and nitrogen consumption by plants.

Given the experimental data analysed above and revisiting the cause of the imbalance between the sulphate ion to potassium ion ratio in the

experimental line water at 4.54 and the control line water at 4.88 in favour of sulphate ion (+7.43% to the control), it is possible to unequivocally explain this increase in the ratios in both lines by the uneven removal of potassium and sulphur by lettuce plants in favour of potassium and the gradual accumulation of sulphates caused by the decomposition of fish waste products. Considering that the increase in sulphate content in the water of the experimental line during the experiment was  $+258 \text{ mg/dm}^3$ , while in the control line the corresponding increase was only  $+28.8 \text{ mg/dm}^3$  (where no potassium sulphate was added), it is possible to conclude that the addition of potassium sulphate causes a significant increase in the sulphate content in water. However, the total concentration of sulphates increased in both lines, indicating a significant accumulation of sulphates due to the biochemical transformation of fish waste products. At the same time, there are no technological standards for the sulphate content in the water of aquaponics systems. Taking into account the fact that when potassium sulphate was added to a concentration of  $0.50 \text{ g/dm}^3$  in the water of the experimental line, assuming the same formation of waste products as in the experimental line (since the same amount of feed was fed in both lines), the predicted increase in sulphate content was expected to be  $+316 \text{ mg/dm}^3$  compared to the actual ( $+258 \text{ mg/dm}^3$ ), which is 22.5% higher than the actual value, it can be concluded that due to the intake of potassium in the form of potassium sulphate, sulphates are consumed more intensively. However, excessive accumulation of sulphates can be dangerous for fish. Therefore, it is necessary to conclude that it is advisable to add potassium sulphate and to establish the maximum permissible concentration of this salt that is not harmful to fish. In addition, potassium chloride should be considered as an additional source of potassium in aquaponics systems. However, this issue also requires further research, as chlorides in excessive concentrations can harm plants and fish.

A. Bittsanszky *et al.* (2016) determined that the source of potassium had a significant effect on the growth rate of lettuce, photosynthetic activity and the efficiency of macronutrient uptake in closed aquaponic systems. In particular, the addition of potassium sulphate ( $\text{K}_2\text{SO}_4$ ) improved the absorption of calcium, magnesium and nitrates, and increased the overall yield of green crops due to a better ionic balance in the root nutrition zone. As noted by Q. Du *et al.* (2019), potassium stimulates chlorophyll synthesis and accelerates photosynthesis in plants, which can increase crop productivity in aquaponic systems. In particular, optimal concentrations of potassium improve the growth of leafy crops such as lettuce and spinach and can also improve plant resistance to pests and diseases. However, excessive concentrations of potassium in water can cause salinity, excessive levels of which can be toxic primarily to plants, but also to fish, which can lead to poor fish development. Other studies, such as the work of V. Kumar & P. Singh (2023), also highlight the importance of potassium in regulating the immune system of fish and their overall health in aquaponics systems, which affects the overall productivity of these ecosystems.

Thus, the research demonstrated that the use of potassium salts, in particular potassium sulphate, in aquaponics systems was a reasonable agrotechnological technique for increasing plant yields, improving fish growth and stabilising the quality of the water environment. The greatest effect was observed when potassium nutrition was combined with adequate temperature conditions and effective biofiltration. The use of such approaches helps to create optimal conditions for the development of both plants and fish, which increases the overall efficiency of the aquaponic system. In addition, this approach minimises the use of chemical fertilisers, which reduces the negative impact on the environment. As a result, potassium nutrition is becoming an important tool in achieving sustainable and efficient production in aquaponics systems. These results

indicate the feasibility of integrating potassium salts into aquaponics processes to achieve high productivity and environmental sustainability.

### Conclusions

Under optimal conditions of water temperature in the aquaponics system and light intensity in the hydroponics module at 2500 Lx/m<sup>2</sup> during 57 days of the experiment, the biomass increase of 19 individuals of Clarie catfish in the control line of the system was +1195 g, in the experimental line, under the influence of potassium sulphate addition until its concentration in water reached 500 mg/L, the total biomass increase of Clarie catfish during the experiment was +2886 g (+44.6% compared to the control), which indicates the high efficiency of potassium sulphate addition to the system water in stimulating the development of Clarie catfish.

The high stimulating effect of adding potassium sulphate (500 mg/dm<sup>3</sup>) to the water of the aquaponics system on the feed conversion efficiency of Clarian catfish was confirmed, which is estimated at 57.0% lower feed conversion ratio compared to the control (without potassium sulphate addition) and 91.5% higher growth rate of Clarie catfish relative to the control. The addition of potassium sulphate (500 mg/dm<sup>3</sup>) to the aquaponics system water increased the productivity of the hydroponics module with a planting area of 1 m<sup>2</sup>, also ensuring an increase in the green mass of leaf lettuce to 3498 g/m<sup>2</sup> in the experimental line compared to the control line (2043 g/m<sup>2</sup>) or +71.2% compared to the control. The potential yield of leaf lettuce (4000 g/m<sup>2</sup>) was realised in the control line by 51.1% and in the experimental line by 87.5%. Analysis of water quality in terms of pH, nitrogen content of mineral compounds, phosphates, sulphates and potassium showed that the main limiting factor for lettuce yield and fish productivity was a potassium deficiency in the system at a level of 21.61-28.3 mg/L, while in the experimental line of the system, the main limiting factor was an increase in pH to 8.3, which prevented the assimilation

of nitrogen compounds by lettuce plants. The reason for this was the insufficiently high average water temperature (19.5°C compared to the optimum temperature for microorganisms of the nitrification cycle of 25°C), which slowed down the processes of nitrification and assimilation of nitrogen compounds by plants.

Overall, the water quality in the control line of the aquaponics system during the 57-day experiment was within the technological standards but deteriorated due to an increase in ammonium nitrogen content by 323%, nitrate nitrogen by 77.8%, sulphates by 248%, phosphates by 1160%, at a pH level of 7.7. The water quality in the experimental aquaponics system (with the addition of 500 mg/dm<sup>3</sup> of potassium sulphate) during the same period of the experiment deteriorated due to an increase in ammonium nitrogen content by 482%, nitrate nitrogen by 122%, sulphates by 2223%, and phosphates by 1400% at a pH level of 8.3. The main factors contributing to the deterioration of water quality in the experimental line compared to the control line were an increase in pH to 8.3 units. This was due to insufficient planting area for leaf lettuce (1 m<sup>2</sup> per 2886 g of total biomass of 19 individuals of Clarian catfish) and insufficiently high-water temperature (19.5°C compared to the optimal 25°C).

Further research could optimise the area of lettuce plants, modelling nitrogen conversion processes with changing water temperatures, optimising potassium sulphate doses and finding additional ways to purify water from water-soluble phosphates to ensure maximum development of Clarius catfish and maximum yields of lettuce. The impact of increased potassium concentrations on long-term effects on fish health, as well as the optimal aquaponics conditions for achieving high productivity at different planting density levels, should be addressed.

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## Conflict of Interest

None.

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## Ефективність застосування сульфату калію для вирощування *Clarias gariepinus* в системі аквапоніки

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**Анотація.** Метою дослідження було визначення впливу додавання сульфату калію ( $K_2SO_4$ ) у концентрації  $500 \text{ мг/дм}^3$  на якість водного середовища, ріст сома кларієвого (*Clarias gariepinus*) та врожайність листового салату в умовах аквапонічної системи. Дослід проводили у двох паралельних лініях: контрольній (без  $K_2SO_4$ ) та експериментальній (з додаванням  $K_2SO_4$ ). Початкова загальна маса 19 особин риб у кожній лінії становила 1330 г. За 57 діб маса в контрольній лінії зросла до 1995 г, а в дослідній – до 2888 г. Конверсія корму склала 2,5 у контролі та 1,1 у досліді. Питома швидкість росту (SGR) була на рівні 0,82 %/день у контролі та 1,74 %/день у дослідній групі. Потенціал врожайності салату ( $4000 \text{ г/м}^2$ ) реалізовано на 51,1 % у контролі та на 87,5 % у досліді. У контрольній лінії головним лімітуючим фактором був дефіцит калію (21,6–28,3 мг/л), а в дослідній – зростання рН до 8,3 через недостатнє засвоєння азоту при температурі  $19,5 \text{ }^\circ\text{C}$  (нижче оптимуму для нітрифікації). В обох лініях зафіксовано істотне зростання вмісту мінеральних сполук ( $NO_3^-$ ,  $NH_4^+$ ,  $SO_4^{2-}$ ,  $PO_4^{3-}$ ), однак водні параметри залишалися в межах прийнятних для технологій аквапоніки. Отримані результати свідчать про позитивний ефект від додавання  $K_2SO_4$  у заданій концентрації, що забезпечує зростання продуктивності риб і рослин, хоча потребує врахування співвідношення площі зелених культур до біомаси риби та температурного режиму води. Додавання  $K_2SO_4$  сприяло підвищенню біологічної ефективності аквапонічної системи за одночасного збереження прийнятної якості води

**Ключові слова:** салат листовий; приріст біомаси; конверсія корму; якість води; азот нітратний; продуктивність модуля гідропоніки