# THESIS OF PhD DISSERTATION

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**HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES**

# UTILIZATION OF THE EFFLUENT WATER FROM AN INTENSIVE FISH FARM FOR IRRIGATION IN SHORT-ROTATION ENERGY WILLOW PLANTATIONS AND GRAIN SORGHUM CROPS

**THESIS OF PhD DISSERTATION**

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Classification by branch of science: Crop Production and Horticultural Science

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Signature of approval by the supervisor and the head of the doctoral school:

The candidate has fulfilled all the requirements of the Doctoral Regulations of the Hungarian University of Agriculture and Life Sciences, and has taken into account the comments and suggestions made during the home defence when revising the thesis, therefore the thesis may be submitted for the public defence procedure.

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# 1. BACKKGROUND AND OBJECTIVES OF THE WORK

There is a growing trend towards more efficient use of water resources, both in urban and rural environments. One of the main means of achieving greater efficiency is to recycle the types of water that were previously disposed of in natural receptors after use. The use of water for agricultural irrigation is often seen as a positive means of recycling water, due to the potential of using large amounts of water that can be used. Recycled water has the advantage of providing a permanent, reliable source of water and reducing the amount of surface or groundwater withdrawals.

With population growth and rapid urbanisation, the agricultural sector is under increasing pressure. Globally, the agricultural sector is responsible for 70% of water withdrawals, the use of organic-rich effluent water from aquaculture systems for crop production could reduce freshwater withdrawals. In addition, the macro- and micro-nutrient content of effluent water can increase soil fertility, improving crop success and reducing input material costs.

In Hungary, biomass is the most important renewable energy source, accounting for 65-80% of all renewable energy sources used. The use of biomass is mainly focused on the production of heat and electricity from woody biomass, but it can also be used for the production of bioethanol and biogas. The proportion of areas with unfavourable soil conditions is in excess of several hundred thousand hectares, where the establishment of short rotation woody energy crops is feasible. The production and use of biomass in these areas can contribute to a wider use of renewable energy sources, sustainable energy supply and diversification of agricultural activities.

Climate change will have a major impact on the viability of crop production. In our country, the last three growing years have shown the need to rethink the crop composition of rotations, going beyond the classic wheat-maize-corn-rapeseed-sunflower crop rotation. Priority may be given to the wider cultivation of crops that are already known but less widely grown in public production, or to the incorporation of new crop species into crop rotations. This will require improvements in the cropping system, in the agro-techniques used and in the cultivation technologies.

In view of this, the cultivation of sorghum proves to be an excellent choice especially for dairy farms, utilized as silage, the sowing of which can be effectively combined with corn. Sowing corn and sorghum together increases the energy content of the silage and the harvested green mass. This twin-row sowing practice is already used by many people in agriculture. On the other hand, grain sorghum is poorly digestible for ruminants, but due to its excellent amino acid and high protein content, it is a valuable feed source for poultry. The importance of its further cultivation is increased by the fact that its grain yield provides toxin-free feed, which is particularly beneficial in years such as the current one, when these parameters are of paramount importance. In addition, the most significant feature of sorghum is its stability, it tolerates drought and heat stress significantly better than corn. This makes sorghum an ideal choice in agricultural environments where weather conditions are variable and plants face higher biotic and abiotic stress.

In my research, I investigated the cultivability of short rotation energy willow and grain sorghum under field conditions in lysimeter and small plot conditions in the growing years 2015-2020, using effluent water from an intensive African catfish farm for irrigation with two different microirrigation technologies.

The irrigation experiment was designed to answer the following questions:

1. How do different water quality and water quantity affect the variation of physiological and phenological parameters (relative chlorophyll content, height) of energy willow and grain sorghum?
2. Is there a difference in macroelement content between surface and effluent water irrigated plant samples compared to non-irrigated controls?
3. How do different water quality and water dose affect biomass and yield?
4. Is the accumulation of sodium in effluent water reflected in the above-ground parts of the energy willow and in the grain yield of sorghum?
5. How does irrigation with effluent water affect the sodium content of the soil, and is there a difference between the cultivation of energy willow and grain sorghum?
6. How do irrigation and water quality affect the sugar content of the stem part of sorghum?
7. Is it suitable to use the effluent of the intensive fish farm for irrigation in the energy willow plantation and in the grain sorghum cultures?

# 2. MATERIAL AND METHODS

## 2.1. The conditions of the research work

The irrigation experiments were set up at the Lysimeter Station (46°51′49″ N 20°31′39″ E), covering 1 hectare at the Research Center for Irrigation and Water Management (ÖVKI) of Institute of Environmental Sciences (IES) of the Hungarian University of Agriculture and Life Sciences (MATE) in Szarvas. During the research period (2015-2020), the meteorological data was collected by the automatic meteorological station located at the MATE IES ÖVKI Lisimeter Station. In 2015, the measuring instrument registered a lower-than-average temperature value only in October. However, compared to 2019, May, August, October, December and January were colder in 2016 and 2017. The year 2015 proved to be drier, with only 400.6 mm of precipitation, until 2016 reached 633 mm. At the same time, the distribution was heterogeneous, characterized by a dry spring and a rainy early summer. In 2017, the amount of precipitation was close to the average.

*Characterization of the soil of the lysimeter energy willow experiment*

The soil in the experiment is of neutral pH. It is considered a moderately clayey meadow soil based on the Arany binding index. The total soluble salt content showed low values. Additionally, it exhibited a weakly calcareous state and low humus content. Prior to sowing, it was necessary to replenish the N nutrient element (40 kg/ha) as the soil's nutrient content showed low values during examination of KCl-soluble nitrate content. However, the quantity of P and K was adequate for the plants.

*Characterization of the Field Sorghum Experiment Soil*

Based on the examination results, the soil's pH was weakly alkaline at both depths. According to the Arany binding index, the physical soil type is loamy, clay loam. The total soluble salt content indicated low salinity levels. Based on the carbonate content, the soil exhibited weakly calcareous characteristics, with an organic matter content below 2%, classified as very low fertility. The soil's nitrogen availability was notably poor, as evidenced by the KCl-soluble nitrate content, requiring nitrogen supplementation during cultivation. The quantities of other macroelements, such as potassium (K) and phosphorus (P), were categorized as excessive.

## 2.2. The Presentations of the Experiments

*Lysimeter Experiments*

The short-rotation energy willow used in the lysimeter experiment is the 'Naperti,' a clone candidate from the Institute of Forestry Sciences at Sopron University. The plantation was established in 2014. This clone is known for its rapid growth and high wood yield.

Determining the minimum irrigation water requirement for the energy willows primarily involved considering available literature data alongside domestic climatic conditions. Zsembeli et al. (2013) provided 70-110 mm of irrigation water per treatment from June to September, in addition to natural rainfall, for willow individuals in the lysimeters. The number of irrigation rounds varied depending on weather conditions in the three study years. The 2015 study year was characterised by a more droughty winter and spring, resulting in a uniform application of 100 mm of irrigation water in April and May (Table 1).

Table 1. Amount of irrigation water applied per year and distribution of precipitation during the growing season studied

| | Irrigation water doses | The number of irrigations in the examined period | Amount of water applied by irrigation (mm) | Amount of precipitation in the examined period (mm) | Amount of water available for plants during the test period (mm) |
|---|---|---|---|---|---|
| 2015 | 15 mm | 15 * | 310 | 105 | 415 |
| | 30 mm | | 520 | | 625 |
| | 60 mm | | 940 | | 1045 |
| 2016 | 15 mm | 6 | 90 | 308 | 398 |
| | 30 mm | | 180 | | 488 |
| | 60 mm | | 360 | | 668 |
| 2017 | 15 mm | 9 | 135 | 184 | 319 |
| | 30 mm | | 270 | | 454 |
| | 60 mm | | 540 | | 724 |

* During the first irrigation, each treatment received an even 100 mm of Körös irrigation water.

A total of eight lysimeter vessels were used per treatment. Two plants were planted in each lysimeter with a stem spacing of 50 cm and a row spacing of 100 cm. In order to reduce edge effects, additional willow clones were planted around the containers with the same stem and row spacing. The first cutting took place in December 2015, the second in January 2017, and the third harvest in January 2018.

Two different types of water and their combinations were used for the irrigation experiment of the energy willow clones. The untreated thermal water effluent of the intensive African catfish farm located in the city of Szarvas was collected directly from the outfall storage basin of the farm and irrigated with 15 mm (E15), 30 mm (E30) and 60 mm (E60) irrigation water doses in eight replicates and weekly during the growing season. Fresh water from the Körös oxbow lake was used as the irrigated control. Irrigation water was applied weekly in doses of 15 mm (K15), 30 mm (K30) and 60 mm (K60), in eight repetitions (Table 1). In addition, a non-irrigated control (C) treatment was also set up, also in eight replicates. In order to reduce the negative effects of high salinity, the effluent water was pretreated and after pretreatment it was used with a dose of 60 mm per week (D). Before irrigation, the effluent water was diluted in a ratio of 1:3 by adding water from the Körös surface water to reach the recommended upper limit of the total salinity of the irrigation water (500 mg/L). Additionally, gypsum (calcium sulfate) was added (312 mg/L) to reduce the percentage of sodium compared to the diluted treatment (Table 2). A micro-sprinkler irrigation system was used for all irrigation treatments. The amount of N, P, K and Na (kg/ha) applied by irrigation water per year is shown in Table 3.

Table 2. Average main quality parameters of the irrigation water used in the experiment

| | **EC** | **$NH4^{-}$N** | **N** | **P** | **K** | **Na** | **SAR** |
|---|---|---|---|---|---|---|---|
| | (µS/cm) | (mg/L) | (mg/L) | (mg/L) | (mg/L) | (mg/L) | |
| Effluent water | 1320 | 22,5 | 29,2 | 3,9 | 11,3 | 222 | 12,1 |
| Körös oxbow lake | 440 | 0,6 | 2,1 | 0,2 | 4,7 | 40,6 | 1,2 |
| Dilluted water | 1050 | 8,6 | 11,1 | 2 | 5,3 | 150 | 3,1 |

Table 3. Amount of N, P, K and Na (kg/ha) released by irrigation water in the case of the energy willow experiment

| Type of irrigation water | Year of irrigation | N (kg/ha) | | | P (kg/ha) | | | K (kg/ha) | | | Na (kg/ha) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 15 mm | 30 mm | 60 mm | 15 mm | 30 mm | 60 mm | 15 mm | 30 mm | 60 mm | 15 mm | 30 mm | 60 mm |
| Körös oxbow lake | 2015 | 4,4 | 8,8 | 17,6 | 0,4 | 0,8 | 1,7 | 9,9 | 19,7 | 39,5 | 85,3 | 170,5 | 341,0 |
| | 2016 | 1,9 | 3,8 | 7,6 | 0,2 | 0,4 | 0,7 | 4,2 | 8,5 | 16,9 | 36,5 | 73,1 | 146,2 |
| | 2017 | 2,8 | 5,7 | 11,3 | 0,3 | 0,5 | 1,1 | 6,3 | 12,7 | 25,4 | 54,8 | 109,6 | 219,2 |
| Effluent water | 2015 | 62,8 | 125,6 | 251,2 | 8,2 | 16,4 | 32,8 | 23,7 | 47,5 | 94,9 | 466,2 | 932,4 | 1864,8 |
| | 2016 | 26,9 | 53,8 | 107,6 | 3,5 | 7,0 | 14,0 | 10,2 | 20,3 | 40,7 | 199,8 | 399,6 | 799,2 |
| | 2017 | 40,4 | 80,7 | 161,5 | 5,3 | 10,5 | 21,1 | 15,3 | 30,5 | 61,0 | 299,7 | 599,4 | 1198,8 |
| Dilluted water | 2015 | 23,3 | 46,6 | 93,2 | 4,2 | 8,4 | 16,8 | 11,1 | 22,3 | 44,5 | 315,0 | 630,0 | 1260,0 |
| | 2016 | 10,0 | 20,0 | 40,0 | 1,8 | 3,6 | 7,2 | 4,8 | 9,5 | 19,1 | 135,0 | 270,0 | 540,0 |
| | 2017 | 15,0 | 30,0 | 59,9 | 2,7 | 5,4 | 10,8 | 7,2 | 14,3 | 28,6 | 202,5 | 405,0 | 810,0 |

*Field sorghum irrigation experiment*

During the small plot field irrigation experiment, the growth parameters of three state-approved grain sorghum hybrids ('Alföldi 1', 'Farmsugro 180', 'GK Emese') of the Gabonakutató Nonprofit Kft. (Szeged, Hungary) were investigated under different amounts and qualities of irrigation water. Each year, the sowing time was determined by the weather parameters and the average temperature of the soil. In all four experimental years, sowing took place at the end of April or beginning of May, when the soil temperature in the top 5 cm reached 12-13 °C. During sowing, the used row spacing was 70 cm, the stocking density was 190-230 thousand plants/hectare (114-138 plants per plot). Each plot had 4 rows (1 m), the measurements were made in each case in the middle two rows (in 6 repetitions). Accordingly, the size of a sample area was 3 m long and 2.1 m wide. The field experiment was set up with two factors, the "A" factor was irrigation (with 5 treatments), and the "B" factor (with 3 treatments) was the grain sorghum hybrids. From the technical and technological point of view of irrigation, we could only use a strip experimental arrangement. The area of the main plots (3 m x 2.8 m) was 8.4 $m^2$ per treatment, and the area of the sub-plots (1 m x 2.8 m) was 2.8 $m^2$. The two middle rows per subplot were taken as the sample area, so the measurements were performed in 6 repetitions per treatment. According to Sváb (1981), in the case of this type of strip experiment arrangement, the mathematical-statistical evaluation must be performed as a separate, one-factor experiment for each factor.

The irrigation experiment was also set up with two irrigation water doses (30 and 45 mm) on a weekly basis for the grain sorghum. Irrigation water was applied to the growing area by a drip system. Five treatments were set up, one non-irrigated control (C), two surface water irrigated treatments (K30 and K45) and two effluent water treatments (E30 and E45). For each treatment and hybrid, six replicates were used. For the first four weeks after sowing, the plants were irrigated with water from the Körös oxbow lake at different irrigation rates per year to supplement natural rainfall in each treatment in order to improve germination and initial growth. Differential irrigation was then applied (Table 4). The amounts of N, P, K and Na applied per year (kg/ha) with irrigation water are shown in Table 5.

Table 4. Sowing time of grain sorghum, the number of irrigations, the amount of precipitation and the amount of applied irrigation water in the four experimental years

| Sowing time | Irrigation water doses (mm) | Number of irrigations | Amount of water applied by irrigation (mm) | Precipitation during the growing season (mm) | Amount of supplementary irrigation (Körös) during germination (mm) | Total water input (mm) |
|---|---|---|---|---|---|---|
| 2016.05.04. | 30 | 5 | 150 | 296 | 120 | 566 |
| | 45 | | 225 | | | 641 |
| 2017.05.02. | 30 | 6 | 180 | 144 | 80 | 404 |
| | 45 | | 270 | | | 494 |
| 2019.05.07. | 30 | 8 | 240 | 208 | 40 | 488 |
| | 45 | | 360 | | | 608 |
| 2020.04.27. | 30 | 4 | 120 | 288 | 90 | 498 |
| | 45 | | 180 | | | 558 |

Table 5. Amount of N, P, K and Na (kg/ha) applied by irrigation water in the case of the grain sorghum experiment

| Type of irrigation water | Year of irrigation | N (kg/ha) | | P (kg/ha) | | K (kg/ha) | | Na (kg/ha) | |
|---|---|---|---|---|---|---|---|---|---|
| | | 30 mm | 45 mm | 30 mm | 45 mm | 30 mm | 45 mm | 30 mm | 45 mm |
| Körös oxbow lake | 2016 | 3.2 | 4.7 | 0.3 | 0.5 | 7.1 | 10.6 | 60.9 | 91.4 |
| | 2017 | 3.8 | 5.7 | 0.4 | 0.5 | 8.5 | 12.7 | 73.1 | 109.6 |
| | 2019 | 5.0 | 7.6 | 0.5 | 0.7 | 11.3 | 16.9 | 97.4 | 146.2 |
| | 2020 | 2.5 | 3.8 | 0.2 | 0.4 | 5.6 | 8.5 | 48.7 | 73.1 |
| Effluent water | 2016 | 44.9 | 67.3 | 5.9 | 8.8 | 17.0 | 25.4 | 333.0 | 499.5 |
| | 2017 | 53.8 | 80.7 | 7.0 | 10.5 | 20.3 | 30.5 | 399.6 | 599.4 |
| | 2019 | 71.8 | 107.6 | 9.4 | 14.0 | 27.1 | 40.7 | 532.8 | 799.2 |
| | 2020 | 35.9 | 53.8 | 4.7 | 7.0 | 13.6 | 20.3 | 266.4 | 399.6 |

## 2.3. Statistical analysis

The IBM SPSS Statistics 25.0 software was used for the statistical analyses. The one-factor analysis of variance (ANOVA) was used to determine the effect of the quality and quantity of irrigation water on the phenological parameters, macroelement and sodium content of willow clones and different sorghum hybrids per treatment and per plant part. Differences were considered significant if they reached the Tukey or Games-Howell test limits of $p \leq 0.05$ or $p \leq 0.01$. In the case of energy willow, we used the independent t-test for the 15 and 30 mm irrigated samples, and the ANOVA test for the 60 mm samples, for the statistical evaluation of the soil chemistry tests. The Pearson correlation was used to analyze the correlation.

# 3. RESULTS

## 3.1. Changes in the relative chlorophyll content

Both the energy willows and grain sorghum tests showed a difference between the applied irrigation water qualities, especially in the evaluation of the relative chlorophyll content. For energy willows, clones irrigated with effluent water had significantly higher chlorophyll values than individuals irrigated with water from the Körös surface water (47.5-52.1). The reason for this lies in the excess nutrient content of the effluent water. The higher nitrogen content of the effluent (29.2 mg/L) showed a positive correlation (r=0.579) to the chlorophyll content of the grain crop.

In the case of the 'Alföldi 1' hybrid, there was no significant difference between the treatments in the first two years. In the third and fourth year, SPAD values were significantly lower in the E30 (p=0.000), K30 (p=0.000) and C (p=0.001) treatments compared to the highest E45 treatment. In the 2020 crop year, when comparing the treatments, the chlorophyll content of the leaves was significantly lower compared to the E45 value in the E30 (p=0.001), K30 (p=0.002) and C (p=0.001) treatments.

For the 'Farmsugro 180' hybrid, the E45 treatment had the highest SPAD value in all cases except the first year, especially in 2017, where it reached 52.5. Among the four experimental years, the lowest average chlorophyll value was measured in 2019 (38.9–47.1), while the highest was measured in 2017 (49.8–52.5). During the statistical evaluation, there was no significant difference between the treatments in the first two years. In 2019 and 2020, the chlorophyll values of treatments E30 and K45 (p=0.000) were significantly lower than treatment E45 with the highest SPAD value.

For the 'GK Emese' sorghum hybrid, the lowest chlorophyll values of the four experimental years were measured in 2020 (38.8-45.5), while the highest were measured in the 2017 cultivation year (51.9-56.5). It was typical for the first two growing years that treatments irrigated with water from the Körös surface water had higher SPAD values, especially the K45 treatments (56.5 and 50.1). However, in 2019 and 2020, the plants measured in the K30 treatment (45.7 and 45.5) had the highest chlorophyll values. In this case, there was no significant difference between the treatments in the first two years of the statistical analysis. At the same time, among the data measured in 2019, the K45 (p=0.012) treatment had a significantly lower SPAD value than the highest values obtained in the K30 treatment. In 2020, the chlorophyll value was significantly lower for the E45 (p=0.003) and K45 (p=0.002) treatments compared to the highest K30 treatment.

## 3.2. Growth of test plants during the growing season

From the data measured on September 17, it can be established that at the last measurement, the highest energy willows were in the D treatment (428 cm), while the lowest were in the control plants (282 cm). In the examined period, when comparing the first and last measurements, the control plants grew 34 cm, while those in the E60 treatment grew 178 cm. In the analysis period of 2016, the control willows grew 75 cm larger, and the plants irrigated with 60 mm effluent water grew 176 cm larger. In the 2017 growing year, a slowdown in plant growth can be observed. The growth rate of the control willows was lower than that of the irrigated plants. At the last measurement, the height of the control plants was only 259 cm. In this case, the tallest plants were also observed in the E60 treatment (370 cm). All treatments of energy willow plants were found to be significantly higher (p=0.00) compared to control plants (n=6, Tukey test).

In the case of the 'Alföldi 1' hybrid, the significant difference between the treatments could only be detected in the first year of cultivation, where the other sorghum plants grew significantly smaller compared to the E45 treatment with the highest value ($p \leq 0.01$). In the case of the 'Farmsugro 180' hybrid, the plants of the other treatments grew significantly lower ($p \leq 0.05$) compared to the K45 treatment with the highest plant height value among the measurement data of the first year of cultivation. In subsequent cultivation years, we recorded lower plant height values for all treatments. A significant difference was observed when comparing the treatments in both the first and the second year of cultivation, typical of the 'GK Emese' hybrid. In 2016, the plants of the C (p=0.001) E30 (p= 0.008) and K30 (p=0.016) treatments grew significantly lower than those of the E45 treatment. In the second year, significantly lower values were detected in the C treatment (p=0.018) compared to the highest E30 treatment.

### 3.3. Nitrogen content of plant parts

In the case of energy willows, when comparing the treatments of the 2015 growing year, the N content of the leaf parts was the lowest in the case of the K60 (1.6 m/m%) treatment, while the highest in the E30 treatment (3.5 m/m %). Compared to the K60 treatment, leaves contained significantly more N in the E60 (p=0.015), E30 (p=0.000), K15 (p=0.005) and C (p=0.001) treatments. For leaf samples, less N was localized in the stem parts. The lowest N content was also measured in the K60 (1.6 m/m%) treatment, the samples irrigated with effluent water, the K15 and C treatments contained significantly more nitrogen ($p < 0.001$). At the same time, the highest N content was detected in the E60 (0.9 m/m%) treatment. When the treatments were compared, the N content of the leaves showed a decrease in the 2016 growing year. Treatment K60 (1.3 m/m%) had the lowest nitrogen value, while samples K15 (2.3 m/m%) had the highest. E15 (p=0.018), K15 (p=0.002) and C (p=0.029) leaf samples contained significantly more nitrogen than willows irrigated with K60 treatment. In the case of the stem, the values were in almost the same range in 2016 and 2017. The measurement results of both years exceeded the N content measured in 2015. In the third experimental year, in the case of samples irrigated with D, C, K30 and effluent water, it can be established that significantly (66%) more nitrogen was stored in the leaves of the willows than in the K60 treatment.

For the 'Alföldi 1' hybrid, among the values measured in 2016, the lowest nitrogen content was the K45 treatment (1.5 m/m%), and the highest value was the control samples (2.4 m/m%). The 2017 growing year was characterized by balanced N values during the comparison of the treatments. The measurement results obtained in the following two years show an almost identical course, where the values of the plants treated with C had the lowest nitrogen content, and the samples irrigated with effluent irrigation water had the highest values. In the first year of cultivation, we measured a verifiably significant difference between the treatments, where compared to the C and K30 treatments, the E45 sample (p= 0.005) had a significantly lower N content.

In the case of the 'Farmsugro 180' hybrid, when comparing the annual treatments of the first two growing years, we measured almost the same N content in the grain yield, during which treatment C had the highest concentration (1.7-1.8 m/m%). However, in 2019 and 2020, a decrease can be observed between the measurement data. Significant differences cannot be described, however, it can be observed that a higher N content can be measured in the irrigated treatments. During the statistical evaluation, a significant difference was verified in the first cultivation year, where a significantly lower N content was measured in the E45 treatment (p=0.035) compared to the C treatment.

In the first year of cultivation, the most nitrogen was localized in the grain yield of the 'GK Emese' hybrid. The lowest values were measured for the K30 sample (1.6 m/m), and the highest for the E45 treatment (2.1 m/m%). In the experimental year 2017, a small decrease in N was observed for all treatments. When comparing the annual treatments of the last two growing years, the values of N show the same trend. We measured a significant difference in 2016 and 2019, where in 2016 the K30 treatment (p=0.047) contained significantly less nitrogen compared to the highest value E 45 treatment. In 2019, compared to the samples with the lowest values K30 (p=0.005), C (p=0.018) and K45 (p=0.029), the plant sample of the treatment irrigated with 45 mm of effluent water was characterized by a significantly higher nitrogen content.

### 3.4. Phosphorus content of plant parts

The P content of the leaves of willow clones irrigated with effluent and diluted water in the 2015-2017 growing year ranged from 1990 to 3023 mg/kg dry matter (d.m.). When comparing the treatments in 2015, the control contained significantly more P than the E60 (p=0.004) and D (p=0.001) treatments. In the following year, among the treatments, samples from treatment D had the highest P content, but at the same time, the P level was significantly lower in the leaves of samples E30 (p=0.046) and C (p=0.043). In the first experimental year, compared to treatment D, the control samples had significantly less P content (p=0.033). From the P element content measured in the stem part of the energy willows in the three vegetation years, it can be concluded that the measured level was 813 and 2457 mg/kg d.m. formed between In the first year, compared to the control value, the P content was significantly lower in treatments D (p=0.000) and E30 (p=0.005). In the second year, the E30 (p=0.004), E60 (p=0.000) and control (p=0.000) treatments had significantly less P content in the stem part of the willows compared to the D treatment. When comparing the treatments in the 2017 growing year, the stem samples of the clones contained significantly less phosphorus, with the exception of treatment D.

The phosphorus content of the grain sorghum hybrid 'Alföldi 1' is 2797 and 3793 mg/kg d.m. between were formed in the four years of cultivation. In the first growing year, we measured the lowest P concentration in the grain yield of the K30 treatment, which was 3190 mg/kg d.m. was, and at the same time the highest values can be observed in the case of samples C (3793 mg/kg d.m.). In the second growing year, the lowest P values were measured in the E45 (3160 mg/kg d.m.) treatment, while the highest phosphorus concentration was measured in the C (3703 mg/kg d.m.) samples. In the experimental years 2019 and 2020, a minimal decrease in concentration can be observed when comparing the annual treatments. At the same time, in 2019, a 5-10% increase in phosphorus levels can be detected in samples irrigated with effluent water. In the case of the measurement data of the last cultivation year, the values of the non-irrigated control samples should be highlighted, where a significant decrease in P value of 27% (1000 mg/kg d.m.) can be observed compared to 2016. We measured significant differences between the treatments except for the last year. In 2016, treatments K30 (p=0.028) and E45 (p=0.046) contained significantly less phosphorus compared to treatment C with the highest value. In the second year of cultivation, we measured significantly lower values for samples E45 (p= 0.003), E30 (p=0.047) and K45 (p=0.049) compared to treatment C. In 2019, the phosphorus value of the E30 treatment proved to be the highest, with significantly lower values for sample C (p=0.045).

For the 'Farmsugro 180' hybrid, we measured lower phosphorus values in the first experimental year compared to the other years. The lowest value was achieved by treatment E45 (2430 mg/kg d.m.) and the highest by treatment C (2987 mg/kg d.m.). In the next two experimental years, the values show an upward trend. However, in 2020, a decrease in the P level can be observed again. With the exception of 2017, there were significant differences between the applied treatments. In 2016, compared to treatment C, we measured a significantly lower concentration in E45 (p=0.004) samples. In 2019, the K30 (p=0.043) sample contained a significantly higher phosphorus concentration compared to the other treatments. In the last growing year, the E30 treatment (p= 0.048) was characterized by a significantly lower phosphorus content compared to the highest value E45 sample.

The phosphorus value of the grain yield of the hybrid 'GK Emese' is 2540-3950 mg/kg d.m. formed between. In the first growing year, treatment E45 (3373 mg/kg d.m.) had the lowest concentration, while treatment C (3943 mg/kg d.m.)

had the highest concentration. The difference between the measured values exceeded 600 mg/kg d.m. content. The measurement data of 2017 were characterized by balanced values. In the last two experimental years, when comparing the annual treatments, we observed a decrease in phosphorus levels, where the K30 treatment had the lowest P concentration and the E45 treatment the highest concentration. In 2017 and 2020, we could not statistically prove the difference between the treatments. At the same time, in 2016, when comparing treatments, treatments E45 (p=0.015) and K30 (p=0.023) contained significantly less phosphorus compared to treatment C with the highest P level. In addition, among the 2019 measurement data, we measured significantly more phosphorus content in the samples irrigated with 45 mm of effluent water.

**3.5. Potassium content of plant parts**

During the macroelement analysis of the plant parts of the energy willow clones, most K was concentrated in the leaves. The comparison of the treatments in the given growing year shows that the lowest K content was measured in 2015 and the highest in 2017. In the case of the leaves, in the first year the K-value was 11.880 and 15.465 mg/kg d.m. ranged between, while in the second year the measured element content was 11.445–18.492 mg/kg d.m.. Furthermore, values between 18187 and 21627 mg/kg d.m. were detected in the last year of 2017. It should be emphasized that, among the measurement data of the last two years, an increase in K level can be observed in the leaf samples of the E15 treatment. Tukey's multiple comparisons showed no significant differences between treatments in 2015; however, in the second year of the study, compared to the values of the K60 treatment, E15 (p=0.000), E60 (p=0.023), D (p=0.034) and K15 (p=0.010) leaf samples had significantly higher K values. In addition, in 2017, E15 (p=0.013) had a significantly higher K level compared to the values of K30 samples. Similar to the leaf parts, this trend can also be observed in the case of the stem part. Among the data from 2016, the level of K in the stem parts was in a higher range, during which the E15 treatment reached 8640 mg/kg d.m. value. In the first and last year of irrigation, the K content of the stem parts of the energy willow clones was 4100 and 6400 mg/kg d.m. formed between. During the one-way analysis of variance, there was a significant difference between the 2015 measurement data. Compared to the D treatment, the K15 treatments (p=0.001) had a significantly higher K content. No significant difference was detected in the other two years.

The potassium level of the grain yield of the 'Alföldi 1' hybrid in the first year of cultivation is 4020-5000 mg/kg d.m. between, where the K30 treatment had the lowest value and the E45 sample had the highest value. In 2017, the potassium level decreased in all treatments, where E30 had the lowest and treatment C the highest K level. When comparing the annual treatments, the measurement data of the last two growing years show the same pattern, where we measured a 14% higher potassium level in the K30 treatment compared to the values measured in the 2016 and 2017 growing years. In the first two experimental years, there was a significant difference between the treatments. In 2016, treatment E45 (p=0.044) contained significantly more potassium than the others. In the second experimental year, compared to the treatment with the highest C value, E30 (p=0.016) had significantly less K content.

In the case of the 'Farmsugro 180' hybrid, it can also be described that the treatment samples were characterized by a higher K level in the first year. In the year of 2017, the potassium level was ranged between 3490-3580 mg/kg. The potassium content of the 2019 and 2020 samples had a verifiable significant difference per treatment. In the 2019 research year, the grain yields of the E30 (p=0.010) and E45 (p= .021) treatments contained significantly less K than the 4383 mg/kg d.m. value in K30 treatment. In the last cultivation year, E45 (p= 0.029) accumulated significantly less K compared to the treatment with the highest value K45 (4053 mg/kg d.m.).

As in the case of 'GK Emese', as in all years, higher levels of K were found in the samples in the first year of cultivation, ranging from 3843 to 4266 mg/kg d.m.. When comparing the treatments of 2017, a small decrease in the potassium content of the grains can be observed, where K45 (3403 mg/kg d.m.) had the lowest value, while C (3653 mg/kg d.m.) had the highest value treatment. The last two growing years were characterized by an uniform K level, with almost identical values, where the C treatment showed a reduced potassium content (3580 and 3560 mg/kg d.m.). The highest values were measured in the E45 treatment in both years. During the evaluation of the K level measured in the grain yield of the 'GK Emese' hybrid, no significant difference between the treatments could be detected in any of the examined cultivation years.

### 3.6. Sodium content of plant parts

In the case of energy willows, the measured Na content in the leaf parts of the examined plants ranged between 49-79 mg/kg in the first experimental year. The lowest value was measured for the D treatment, while the highest value was measured for the E30 sample. In the growing years of 2016 and 2017, the Na level in the leaf parts had a similar pattern, where the samples irrigated with water from the Körös surface water had the lower values, and the samples irrigated with effluent water had the higher Na content. In the second year, the statistical analysis of the leaf parts showed a significant difference between the K15 and K60 treatments (p=0.025). In the case of stem parts, with the exception of 2015, the lowest Na level was measured in the K15 treatment, while the highest value was measured in the E30 samples. When comparing the treatments, among the measurement data of the cultivation years, the Na content of the stem parts shows an increasing trend year by year, especially in the case of samples irrigated with effluent water. Furthermore, noteworthy are the values measured in 2017, where the Na content in the E60 samples reached 114 mg/kg d.m., marking a 137% increase compared to 2015. In the first study year, the E15, D and K15 treatments contained significantly less ($p<0.1$) Na compared to the values measured in the E30 treatment during the one-factor analysis of variance. In the second vegetation period, a significantly lower Na level was detected in the stem samples treated with K15 and K30. It was also observed in the 2017 growing year that the willow clones had significantly lower Na content in the stems of samples irrigated with water from the surface water (15, 30, 60 mm doses).

The sodium content measured in the grain yield of the 'Alföldi 1' hybrid can be observed to increase from year to year. In the first experimental year, the lowest nitrogen (N) values were observed, ranging between 29-34 mg/kg d.m. value. In the 2017 growing year, a minimal decrease (30 mg/kg d.m.) can be observed in the case of the E30 treatment, but even in this case it exceeds the value measured in the unirrigated control sample of the first year. In the experimental year of 2020, a significant amount of sodium was localized in the grain yield of sorghum in all treatments, where the Na content measured in the E45 and C treatments exceeded 50 mg/kg d.m. value. The effect of the treatments within the given growing year were compared, where thare was not experienced any significant differences that could be verified.

The sodium content of the grain yield was higher in the 'Farmsugro 180' hybrid than in the 'Alföldi 1' hybrid. In the first year of cultivation, treatment C had the lowest measured value (32 mg/kg d.m.), while it was the highest in treatments K45, E30 and E45 (56 mg/kg d.m.). The following year was characterized by an increase in concentration. The lowest Na value was 63 mg/kg b.a. in the K45 treatment and the highest in the unirrigated control samples (73 mg/kg d.m.). Compared to previous years, a more significant decrease in concentrations (41-49 mg/kg d.m.) was observed in the samples in 2019. In the 2020 growing year, Na values increased for all treatments (46 and 54 mg/kg d.m.), but did not exceed the concentrations measured in the previous two years. At the same time, no significant differences were found during the statistical evaluation.

The level of Na content measured in the grain yield was similar for the 'GK Emese' hybrid. In 2016, balanced sodium levels were measured for all treatments, with concentrations not exceeding 26 mg/kg d.m. value. In the second year of cultivation, samples irrigated with water from the Körös surface water had higher Na levels (43-52 mg/kg d.m.). In 2019, however, samples irrigated with effluent water showed higher values (53 and 57 mg/kg d.m.). In addition, the Na values measured in the E45 treatment in the last two growing years should be highlighted, which showed a 21% increase in concentration compared to the unirrigated control. In this case as well, during the statistical evaluation, any significant difference between the treatments can not be found.

### 3.7. Changes in the sugar content of grain sorghum

The sugar content of the 'Alföldi 1' sorghum hybrid was between 7-11.4 degrees Brix. Compared to the lowest K45 treatment, it was characterized by a significantly higher ($p=0.013$) sugar content in the K30 treatment. The sugar content of samples irrigated with effluent water gave almost the same value. With the exception of the K45 treatment, the sugar content of all treatments exceeded 7.1 Brix degrees.

The sugar content of the 'Farmsugro 180' hybrid was higher than that of the 'Alföldi 1' hybrid. The lowest sugar content was for the unirrigated control C treatment (9 Brix degrees), and the highest for the E30 treatment, where this value was around 13 Brix degrees. During the statistical evaluation, treatments K45 ($p=0.022$) and E30 ($p=0.007$) resulted in a significantly higher sugar content compared to treatment C.

The 'GK Emese' sorghum hybrid had the highest sugar values. The lowest Brix value of 10.7 was measured in the K30 treatment, while the highest was measured in the E45 treatment (14.1 degrees Brix). With the exception of the K30 treatment, the sugar content of all irrigated samples exceeded the value of the non-irrigated treatment. Although the statistical evaluation showed no significant difference between the treatments. In the samples irrigated with effluent water, we observed a minimally higher increase in sugar levels.

## 3.8. The effect of irrigation on the biomass yield of cultivated plants

During the cultivation of energy willows with a short cutting cycle, the measurement data of the year 2015 showed the highest biomass mass, where the K60 treatment reached a dry mass of 864 g/plant. In all three experimental years, the biomass product of the control plants was the lowest. Furthermore, the mass of harvested biomass shows a decreasing trend year by year. Considering the control values of the experimental years, this resulted in a 56% reduction in yield. This decrease was also caused by the physical limitations of the lysimeters. The volume of 1 m3 inhibited the root growth of the two- and three-year-old willows. Compared to the control values, there is also a tendency that irrigation had a positive effect on biomass. During the experiment, the plants treated with effluent water had a higher g/plant dry mass value on average. Our tests show a dry weight of 554-734 g/plant in 2015, 298-482 g/plant in 2016, and 313-447 g/plant in the last year. In the case of samples irrigated with water from the Körös surface water, the harvested dry mass had lower values. Examining the differences between the treatments in each experimental year, it can be established that significantly higher values ($p = 0.000$) occurred in all irrigated treatments compared to the biomass product of the control plants.

The weight change of the grain yield of the hybrid 'Alföldi 1' measured in the first and second year of cultivation shows the same trend. In both cases, treatment C had the lowest grain yield in the previous year, only 82 g/plant, and in the second year, we measured 104 g/plant. In the experimental period of 2019, we harvested the least amount of grain, the weight of which was between 67-91 g/plant. In the last year of cultivation, the amount of grain yield per plant increased, but at the same time it did not reach the level of the first two years. Of the four cultivation years, the highest grain yield values were measured in 2016, where the K45 treatment reached 128 g/plant and the E30 samples 138 g/plant weight ($p \leq 0.001$).

During the experiment, we measured the least grain yield per plant for the 'Farmsugro 180' hybrid. In 2016, the measured values were only between 70-87 g/plant weight. A minimal increase can be observed in the following two growing years, at which time the values of the treatments ranged from 81 to 105 g/plant. In the last experimental year of 2020, we detected the lowest grain yield, where the K45 treatment was only 57 g/plant. During the study, the highest value was measured in 2017 for the K45 (105 g/plant) treatment. There was no significant difference between treatments in any of the growing years.

Similar to the 'Alföldi 1' variety, we harvested a higher grain yield in the first two years of cultivation with 'GK Emese'. In the first year, the K30 treatment brought outstanding results, where the grain yield reached 140 g/plant weight. In the second year, we measured values of 98 and 112 g/plant. When comparing the annual treatments of the 2019 and 2020 cultivation years, the decreasing trend is typical, where the measured values were between 73 and 110 g/plant, however, the differences cannot be statistically supported.

### 3.9. Changes in soil parameters during the irrigation experiment

During the lysimeter energy willow experiment, the effect of the quality of the irrigation water on the exchangeable sodium content of the soil can be verified at all soil depths and irrigation water amounts (in addition to the fact that with the 15 mm treatment, a more significant difference was observed in the 40-60 cm soil layer). Due to the higher sodium concentration of the effluent water, the irrigated soil is characterized by an increasing sodium content, which is demonstrably dependent on the amount of irrigation water. Based on our measurement, the highest value in the surface layer was for the E60 treatment ΔESP2015–2017 (+6.85%). This observation is also true for the irrigation water of the Körös surface water, but in the case of the K60 treatment the change is already negative, which means that the exchangeable Na content of the soil decreased as a result of the irrigation. Examining the results measured in soil layers at different depths, we found that sodium accumulation accumulated in the deeper soil layers compared to the surface layers during irrigation with effluent water, however, this finding is only valid for the values of the E30 treatment 0–20 cm and 40–60 cm ($n=3$, $p=0.041$, independent t-test) can be verified in the case of soil layers. As a result of improving the irrigation water, it was possible to reduce the increase in the Na content of the soil at all soil depths. According to the nitrogen content of the effluent water, the absorbable nitrogen content of the soil was higher for all samples irrigated with effluent water compared to samples irrigated with water from the Körös surface water. The differences between the N values for treatments with 30 and 60 mm irrigation water were statistically verified. Comparing the diluted treatment (7.52 mg/kg) with the water of the

Körös surface water (2.96 mg/kg), higher absorbable nitrogen values were showed.

During the irrigation experiment of small-plot open field grain sorghum, the chemical parameters of the soil were examined in two soil layers (0-30 cm and 30-60 cm). Except for the sodium content in the deeper layers of the soil (30-60 cm), there was no significant difference between the different treatments. The properties of the upper soil layer changed for five parameters due to irrigation or irrigation water quality. The pH values were significantly higher in samples irrigated with effluent water than in the K30, K45 and control treatments. The highest EC values were measured in the control, where there was no significant difference between the treatments. Regarding the two macroelements, phosphorus and potassium, the highest concentrations were measured in treatment C, which was 2300 mg/kg for P and 509 mg/kg for K content. In addition, in the E30 and E45 treatments, the amount that could be taken up in the soil was less than in the samples irrigated with water from the Körös surface water. The AL-Na content was the lowest in the K45 treatment (86.8 mg/kg); for samples irrigated with effluent water in the E45 treatment (122.9 mg/kg), where the value was significantly higher than in the other treatments ($p<0.01$).

# 4. CONCLUSIONS AND SUGGESTIONS

*Short rotation energy willow*

The applicability of irrigation using effluent water from an intensive African catfish farming facility was investigated, on short rotation energy willow plants during the 2015–2017 growing seasons. Agricultural water use can provide an ideal solution for preserving water resources, as the nutrient-rich effluent water from freshwater aquaculture systems can be utilized in various crop cultures and plantations (Castro et al., 2006; Miranda et al., 2008). Moreover, the organic load in natural receptors and the doses of fertilizers applied during cultivation can be reduced (Al-Jaloud et al., 1993). Dhawan and Sehdev (1994) described in their research that irrigation experiments using effluent water from fish farms resulted in higher crop yields (Dhawan and Sehdev, 1994).

Chlorophyll content is one of the indicators that can provide information about the health status of plantations. Analyzing the chlorophyll content in the foliage of test plants gives a more accurate picture of changes caused by natural and anthropogenic stressors, as they affect the quantity of chlorophyll. Changes in the plant's nitrogen content also reflect in the leaf chlorophyll content. For this reason, a linear relationship can be observed between the chlorophyll and nitrogen content of the leaves (Carter, 1994; Yoder and Pettigrew-Crosby, 1995). During the experiment, the change in the nitrogen content of the energy willows ($r=0.351$, Pearson correlation) caused the change in the chlorophyll content of the foliage. In accordance with the research results of Peng and Gitelson (2011), my experiences also support the linear relationship between the SPAD value of the leaves and the nitrogen content. At the same time, it can be established that the quality of the irrigation water also influenced this value. The SPAD value of the plants irrigated with effluent water exceeded that of the samples irrigated with water from the Körös surface water. In the three years of irrigation, the leaves of willows irrigated with 60 mm of effluent water had the highest chlorophyll content.

The results of the experiment also show that the height of the willow trees has decreased year by year. At the same time, irrigation had a positive effect on plant growth, as higher values were measured in all irrigated treatments during the last measurement. In 2015, the plants of the D treatment reached 428 cm, in 2016 the plants of the D treatment also had the highest value (414 cm), and in the last growing year we measured the highest height data for the E60 treatment (370 cm). Comparing the average highest and lowest plant height data, the difference between the stands was 141 cm in 2015, 124 cm in 2016, and 120 cm in 2017, which was also reflected in the biomass product.

This tendency can also be observed in the N level of the leaves of the energy willow clones. Nitrogen deficiency and stress result in a decrease in chlorophyll content in leaves (Evans, 1989; Niinemets and Tenhunen, 1997). This finding also serves as a reliable result for woody plants (Chang and Robison, 2003; Pinkard et al., 2006). At the same time, during the research, a higher N-concentration was observed in the irrigated plant parts due to the excess nitrogen in the effluent water.

Effluent with a higher P content was negatively correlated (r= -0.579, Pearson correlation) with the P content of the plants. In willow plants, phosphorus accumulated mostly in the stem and to a lesser extent in the leaf part. The difference is most noticeable in the amount of irrigation water, where the P content of the examined plant parts decreased as the amount of irrigation water increased.

Potassium is the most abundant cation in plants. Plants accumulate a large amount of potassium and can absorb a significant amount even from a solution with a low concentration. It is found in larger quantities in the meristems of organs with active metabolism. The K content of older organs decreases. The K demand and K content of plants therefore change during the growing season (Gierth and Mäser, 2007). In the case of the K levels measured in the plant parts of the willow clones, an increasing trend can be observed from year to year. At the same time, leaf parts are characterized by a higher element content, the reason for which can be explained by the $Na^+/K^+$ ratio (Freitas et al., 2019).

Sodium does not specifically activate many enzymes, but it can be replaced by element K; then its effect can be considered specific (Nieves-Cordones et al., 2016). In $C_4$ plants, there is a requirement for sodium as a micronutrient, whereas in $C_3$ plants such as energy willow, there are no deficiency symptoms observed for sodium (Maathuis, 2014). Sodium is not essential even for extreme halophytes, $C_4$ and CAM type plants only require micronutrient intake. Sodium becomes toxic to glycophytons if it is translocated to the germ in a significant amount (Pethő, 2006: Kronzucker et al., 2013). I closely followed the development of the Na concentration of the plants, because during the irrigation with the effluent water of the intensive African catfish breeding farm, a larger amount of Na entered the irrigated area. In the case of willow clones irrigated with effluent water, the Na content was mostly localized in the stem parts, during which an increase was observed year after year. The Na value measured in the E60 treatment in the 2017 cultivation year (114 mg/kg d.m.) should be highlighted, which exceeded the values measured in the control by 50%. However, this amount was not found to be toxic to energy willows.

In accordance with literature data, we observed during our investigation that irrigation has a positive effect on the mass of energy willow biomass. In the case of both irrigation water qualities, the biomass product exceeded the value of non-irrigated control willow clones (Aasamaa et al., 2010; Jerbi et al., 2020). Under lysimeter conditions, biomass and irrigation water quality do not correlate with each other. However, a slight decrease in the biomass product can be observed from year to year. This decrease is also due to the limited living space, as the 1 $m^3$ vessel size of lysimeters has proven to be a limited size over the years (Oddiraju et al., 1994). The reduced living space and available amount of water (even with the higher irrigation water dose) resulted in a decrease in the mass of biomass. The biomass of irrigated energy willows is between 493-864 g/plant dry weight in the first year, 226-482 g/plant dry weight in the second year, and 268-553 g/plant dry weight in the third year. At the same time, these values are 170-250% higher than the yield average of non-irrigated control samples.

As we expected, the sodium content of the soil irrigated with effluent water increased with all three irrigation water quantities in all tested soil layers. Jahany and Rezapour (2020) made a similar finding, where the high concentration of sodium and bicarbonate in the effluent water caused the accumulation of sodium in exchangeable complexes. The combined effects of the increase in bicarbonate from irrigation and the evapotranspiration process promote the precipitation of $Ca^{2+}$ and $Mg^{2+}$ ions, while the more soluble sodium remains in solution, which resulted in the accumulation of exchangeable sodium and an increase in ESP values. In order to moderate the increase in sodium in the soil, the effluent water was diluted with water from the Körös surface water and improved with gypsum. According to the results, there was a lower sodium accumulation observed in the improved irrigation water quality compared to raw water. Consistent with our findings (Malash et al., 2005; Shilpi et al., 2018; Yu et al., 2011), water enhancement (using calcium-containing substances) can provide an effective solution for utilizing effluent water for irrigation purposes (Hopkins et al., 2007; Purves, 1985; Sheoran et al., 2021).

The N uptake in the soil was positively influenced by the use of effluent water for irrigation. In addition to the nitrogen concentration of water from the fish farm, the effect of irrigation on nitrogen mineralization can also cause an increase in mineral element content (Truu et al., 2009). All this promotes agricultural recycling, so irrigation supports water retention and conservation, and helps protect surface waters from nutrient loading. One of the reasons for the high N content observed in the control soil (compared to treatments irrigated with Körös surface water) may be the reduced nutrient uptake, during which the occurrence of water and willow roots was a limiting factor (Kun et al., 2018). The dilution of the effluent water also resulted in a significant increase in the nitrogen content of the soil.

*Grain sorghum*

The irrigation experiment of the grain sorghum varieties took place between 2016 and 2020. Our investigation showed that the irrigation with higher saline effluent water yielded similar results to Guimarães et al. (2016), where they described the successful cultivation of sorghum with significant saline effluent water irrigation.

Sixto et al. (2005) showed that as the salinity increases, vegetative development parameters decrease. In plants exposed to salt stress, shoot, stem and root development, fresh and dry stem and root mass, leaf area, leaf number, relative chlorophyll content and yield reduction can be observed (Chookhampaeng, 2011; Padilla et al., 2018; Sevengor et al. al., 2011; Shannon and Grieve, 1998). For all three hybrids, the average SPAD value of the leaves was lower in the last two years of cultivation. At the same time, the samples irrigated with 45 mm of effluent water had a significantly higher SPAD value. The conclusion can be drawn that the sorghum made good use of the excess nutrient content of the effluent water, and no salt stress condition developed. A positive correlation (r= 0.737, Pearson correlation) was observed between the nitrogen content of the grain yield and the chlorophyll value during the study.

In the case of plant height, it can be established that the tallest plants (149-236 cm) were measured in the first experimental year, which can be explained primarily by the maximum amount of water that can be absorbed (precipitation + irrigation). After that, there is a decrease in all three hybrids (133-181 cm) depending on the annual amount of water, since plant height is mainly influenced by precipitation and temperature. In the experiment, 'Farmsugro 180' reached its average height of 180-220 cm during the first year of cultivation, but a decrease of 18-25% occurred in the other years of the study. The height values of the 'Alföldi 1' (140-160 cm) and especially the hybrid 'GK Emese' (130-150 cm) showed a balance, which means that they were well adapted to the experimental stress conditions.

The increase in the nitrogen content of sorghum plants is directly proportional to the higher crude protein content, which can mean higher nutritional value for animals. The lower nitrogen content affects the physiology of the plant processes during which the macronutrient content of the grain changes, especially the uptake of Ca, Mg and S (Campos et al., 2021). In the first two years of cultivation, we measured a significantly higher nitrogen content for all three hybrids compared to the values of the other experimental years. In some years of the experiment, with the 'GK Emese' hybrid, we found that the higher N content of the effluent water was well utilized in the grain yield.

During the vegetation period, the demand for phosphorus in plants is significant, especially during the development of generative organs, although it is indispensable for the development of vegetative organs as well. Phosphorus is an essential macronutrient for crop production (Malhotra et al., 2018). Nitrogen and phosphorus are antagonists in terms of their physiological effects, where N stimulates the growth of vegetative organs, while phosphorus stimulates the appearance of generative organs and fruit ripening (Gordon and Whitney, 2000). Regarding phosphorus, there was no significant difference between the cultivars and the irrigated treatments. On the other hand, the sorghum hybrids 'Alföldi 1' and 'GK Emese' - especially in the last two growing years - were able to utilize the higher P content of the effluent water better.

Potassium is an essential element for growth and is one of the most abundant cations in plant organs. Unlike other elements such as nitrogen, phosphorus, magnesium, calcium, and sulfur, potassium is not incorporated into organic matter. Over time, the K content of older organs shows a decreasing trend (Marschner and Marschner, 2012). In the experiment, the grain yield of the sorghum plants was high, 3500 and 5000 mg/kg s.a. had a K level between

However, there was no significant difference between the breeds. The $Na^+/K^+$ ratio can be regarded as the basis of the salt tolerance of plants, this ratio increases in direct proportion with the increase in salinity (Chhipa and Lal, 1995). Ahman et al. (2002) and Iqbal et al. (2006) studies, irrigation with higher salinity effluent water did not reduce the accumulation of $K^+$ in plant organs.

High salinity in plants causes hyperionic and hyperosmotic stress effects and limited growth. Sodium is not essential even for extremely salt-tolerant plants, $C_4$ plants require only small amounts (Pethő, 2006; Rao, 2002; Rout and Shaw, 2001). Due to this fact, sorghum is able to maintain its photosynthetic activity and dry matter production under salt stress (Calone et al., 2020). The sodium content of grain yield was the lowest in the first year of cultivation. There was a difference between the sodium accumulation of the varieties, where a higher Na level was measured in the 'Farmsugro 180' hybrid, while a lower concentration was measured in the 'GK Emese' samples. Between the years, the Na level of the grain yield showed a rising trend, however, this was to a different extent in the case of the three sorghum hybrids. It should be emphasized that the 73 mg/kg s.a. measured in grain yield. The Na value had no toxic effect on the development of sorghum. In one growing season – in proportion to the amount of annual irrigation – 26-53 $g/m^2$ Na was applied to the experimental area with 30 mm effluent water irrigation, and 39-79 $g/m^2$ Na in the case of 45 mm effluent water.

In the case of all three hybrids, it can be shown that irrigation had a positive effect on the development of sugar content. Compared to non-irrigated samples, samples irrigated with surface water and effluent water had higher Brix values. The sugar content of the stem part of sorghum was significantly higher in the varieties 'Alföldi 1' and 'Farmsugro 180' irrigated with effluent water. In contrast, El-Kady et al. (2019) found in their research that the effluent water from the fish farm mainly helped the development of vegetative organs, but higher sugar values were measured when subsurface irrigation water was used.

Hussein et al. (2010) showed that higher Na concentration in irrigation water had a negative effect on the growth profile of sorghum. In 2017, the amount of irrigation water showed a positive correlation (r= 0.026, Pearson correlation) both in terms of green mass and grain yield, but at the same time, we measured lower biomass values in the last growing year. Sorghum is a moderately salt-tolerant plant (Ayers and Westcot, 1985), and yield reduction is not expected at 4.5 dS/m EC and 6.8 dS/m soil salinity. Based on the EC values measured in the soil, it has not been proven that the salinity is responsible for the decrease, therefore a more detailed analysis of the exchangeable sodium percentage of the soil is further justified. However, reductions occurred in all treatments and therefore cannot be linked with absolute certainty to water quality. For example, the sensitivity of 'Farmsugro 180' should be highlighted, during which the grain yield was only between 57-67 g/plant in the samples irrigated with water from the Körös surface water in the last growing year.

High concentrations of $Na^+$ and $HCO_3^-$ in irrigation water are known to be responsible for soil salinization. In saline soils, the ion exchange between $Na^+$ and

$H^+$ causes the dissociation of water in the soil solution, which leads to an increase in the concentration of NaOH, and the pH value of the soil can then rise above 10.5 (Sou/Dakouré et al., 2013; Wang et al., 2019). Another reason for the alkalinity of soils irrigated with effluent water could be the negative relationship between basic respiration and pH (Yang et al., 2020). There were no significant differences between treatments for total carbonate content, total organic carbon content and N values.

According to our results, in the non-irrigated treatment, the highest EC value was measured in the 0-30 cm layer of the soil. A close correlation can be founs between EC, P and K content measured in the surface layer of the soil (Pearson correlation coefficients 0.824 and 0.823, sig. <0.01), however, the values in the deeper soil layer were not correlated. According to our assumption, the EC deviations in the 0-30 cm depth of the soil occurred due to the absorbable higher concentration of nutrients (P, K).

The effect of irrigation and water quality on the absorbable phosphorus content of the soil was verified in the surface soil layer, where the lowest average P content was measured in the E30 and E45 treatments. According to our assumption, the breakdown of soil aggregates occurs due to soil salinization, during which the released colloidal clay particles played a significant role in P-fixation. At the same time, further tests are required to prove our assumption. Arienzo et al. (2009) showed in their study that the availability of potassium is strongly influenced by the pH level of the recycled water and the pH of the receiving soil. Optimally, potassium availability can be maintained for most plants in neutral or slightly acidic soil. In our research, the pH level of soil irrigated with water from the Körös surface water was significantly lower than in samples irrigated with effluent water.

The acidic extractant, ammonium lactate (AL, pH=3.7) solution, Egner et al. (1960) introduced, which is generally used in Europe. If the soil is treated with an AL extraction solution, the soluble material enters the solution partly by dissolution and partly by ion exchange, and the AL extraction solution can also break down the carbonates. A higher sodium concentration in soils irrigated with effluent water indicates the onset of salinization processes.

# 5. NEW SCIENTIFIC RESULTS

The primary goal of my research was the irrigation utilization of thermal water-derived effluent water from an intensive African catfish breeding farm located in Szarvas. Effluent water was used for irrigation in two cultures of different economic importance, during which the changes in the physiological and phenological parameters of the plants, as well as the evaluation of the biomass and grain macroelement content that also occurs in commercial cultivation, as well as the possible serious accumulation were monitored. Along the lines of the parameters listed above and the changes in the chemical composition of the soil, a proposal for the efficient use of effluent water was made. The basis of the comparison was the effluent water of the Körös surface water, with the same irrigation water dose as the effluent, in the case of both energy willow and grain sorghum, and an unirrigated control setting.

Based on these, I formulated the following new scientific results:

1. A short rotation energy willow irrigation experiment demonstrated that irrigating with 60 mm of effluent water per week resulted in a 13% higher relative chlorophyll content in the willow clones plant parts compared to samples irrigated with water from the Körös surface water. This was attributed to the willows effectively utilizing and incorporating the effluent water, which had higher nutrient content, into the plant tissues.
2. I confirmed that effluent water irrigation did not hinder the growth in plant height for both energy willow and grain sorghum. Especially in its last year of cultivation, where individuals irrigated with a weekly effluent rate of 60 mm (∑ 540 mm) increased their total height, which exceeded the value of non-irrigated control samples by 43%.
3. I proved that in the case of both plant cultures, the plants irrigated with effluent water (by 10-25%) accumulated more nitrogen in their plant parts and tissues than the samples irrigated with the surface water of the Körös surface water. In the case of energy willow, the nitrogen content of the leaves and parts of the treatments irrigated with 30 mm of effluent water per week exceeded the value of the surface irrigated samples by 25%. Among the tested grain sorghum hybrids, 'GK Emese', irrigated with 45 mm of effluent water per week, localized 10% more nitrogen in its grain yield than the surface irrigated treatments.
4. During the cultivation of energy willows, I proved that the phosphorus content of the stem parts shows a decreasing trend as the amount of irrigation water decreases. Compared to the weekly 30 mm irrigation, the weekly 60 mm treatment reduced the phosphorus content of the stem parts by 13% in the first growing year, by 18% in the second year, and by 12% in the third year.
5. I verified that in grain sorghum varieties, Na applied with effluent water (30 mm per week: 26-53 $g/m^2$, 45 mm per week: 39-79 $g/m^2$) did not

cause a decrease in the potassium level in the grain yield. I also proved that the energy willow accumulates an increasing amount of potassium in its plant parts every year (on average 36% for the leaf part and 42% for the stem part).

6. In the case of both cultures, I verified that during one vegetation period the amount of Na applied with effluent water (15 mm: 19-46 g/ $m^2$, 30 mm: 26-53 g/ $m^2$, 45 mm: 39-79 g/ $m^2$, 60 mm: 79-186 g/ $m^2$), an increase in the elemental content of plant samples can be observed. In the case of energy willow, the stem part localized more sodium, the value of which was 114 mg/kg d.m., which exceeded the non-irrigated control values by 50%. An accumulation of Na in the grain yield can also be observed in grain sorghum varieties, especially in the hybrid 'Farmsugro 180', which reacted more sensitively to water with higher salinity, where the Na value of the grain yield reached 68 mg/kg d.m., which is similar to the water of the Körös surface water resulted in a 7% increase compared to irrigated samples.
7. Based on the tests of the last growing year, I proved that irrigation increased the sugar content of the stem part of the sorghum in the case of the 'Alföldi1' and 'Farmsugro 180' hybrids compared to non-irrigated treatments. In addition, for the 'Farmsugro180' hybrid, samples irrigated with effluent water had the highest Brix (13%) value.
8. I found that effluent water irrigation has a positive effect on the amount of energy willow biomass. The thermal water-derived effluent water with higher sodium content (222 mg/L) did not cause yield depression. It proved to be as effective as treatments irrigated with water from the Körös surface water, showing no significant difference compared to the non-irrigated control values. Specifically, in the case of samples irrigated with 60 mm of effluent water, the biomass product exceeded the control willow clones by an average of 230%, resulting in an additional 253 g of dry biomass weight per plant.
9. I found that compared to the non-irrigated and the treatments irrigated with water from the Körös surface water, minimal Na accumulation (36 mg/kg AL-Na excess on average) can be observed in the case of effluent water irrigation, however, may lead to salinization of the soil in the long term. In the future, this will justify the monitoring of physical, chemical and biological changes in the soil.

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# 7. PUBLICATIONS RELATED TO THE TOPIC OF THE THESIS


## *Scientific papers*

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