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CONTENTS

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Research Article

Hibiscus cannabinus Biochar Enhances Crop Health and Soil Biochemical Functioning in Barley under Drought Stress

Ghulam Murtaza[1], Muhammad Usman[2], and Rashid Iqbal[3]

[1]School of Agriculture, Yunnan University, Kunming, Yunnan 650504, China
[2]School of Agriculture and Biology, Shanghai Jiao Tong University, Shanghai 200240, China
[3]Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan

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Abstract

Drought stress is a critical constraint to crop health, productivity, and soil functional stability in arid and semi-arid agroecosystems. This study evaluated the potential of *Hibiscus cannabinus*-derived biochar to enhance physiological resilience and soil biochemical functioning in barley (*Hordeum vulgare* L., cv. 'TJ-70') under water deficit conditions imposed at tillering and grain-filling stages. A controlled pot experiment was conducted with biochar incorporated at 30 and 40 g kg^{-1} soil prior to sowing. Water deficit markedly impaired crop health by reducing biomass accumulation, chlorophyll content, photosynthetic rate, and grain yield, while elevating oxidative stress and suppressing soil enzymatic activities and microbial-associated biochemical indicators. Biochar amendment significantly alleviated drought-induced damage by improving photosynthetic performance, chlorophyll retention, and antioxidant defense systems, including superoxide dismutase, catalase, and peroxidase activities, thereby minimizing oxidative injury. In parallel, biochar application enhanced soil biochemical attributes, reflecting improved microbial functionality and soil health under moisture-limited conditions. The higher application rate (40 g kg^{-1}) consistently produced greater improvements in both plant physiological performance and soil biochemical stability. Overall, these findings demonstrate that *H. cannabinus*-derived biochar effectively enhances crop health by integrating plant stress tolerance with soil functional restoration, highlighting its potential as a sustainable management strategy for drought-prone cropping systems.

Keywords: *Hibiscus cannabinus*-biochar, soil microbial activity, soil traits, soil biofilm, barley, water stress

1. Introduction

Barley, scientifically known as *Hordeum vulgare*, is a highly vigorous crop and the most crucial staple crop globally [1]. Furthermore, it assumes a crucial function in the economic dynamics of the agricultural industry [2]. Drought stress is a major abiotic stress that causes a substantial decrease in barley yield by adversely affecting seed germination, growth of seedlings, and physiological processes of crops [3]. The increased demand for water, coupled with diminished availability, intensifies drought susceptibility in some areas. Drought-induced stress constitutes a significant barrier to attaining sustainable barley output [4]. An increase in atmospheric carbon dioxide results in climate change, modifications in precipitation patterns, and seasonal drought stress [5]. The increasing severity of drought in response to shifting climatic events necessitates the use of appropriate crop production management strategies [6]. Drought stress can hinder the root development of barley plants during the initial growth stages. Insufficient hydraulic conductivity in the roots and leaves might impair the physiological and metabolic functions of the crop [7]. Food insecurity and global warming are compelling farmers to adopt strategies to increase agricultural productivity in the face of restricted water resources [8]. This work is exceedingly difficult due to persistent climate change. Water stress not only hinders nutrient absorption in plants but also interferes with fertilizer application, as many fertilizers become volatile and unavailable to plants in arid conditions. The processes of planting and crop management, which include all agricultural operations, might affect drought stress [9]. Efficient soil management, entailing the effective use of resources to sustain soil productivity, is essential in modern agriculture [10]. The widespread use of chemical fertilizers and insecticides in agriculture results in soil fertility reduction, adversely affecting the soil's physicochemical properties [11]. Microbial activities and the decomposition of different inorganic substances are detrimental as a result of the present use of pesticides [12]. The introduction of organic material for soil management is essential to maintain soil fertility [10]. Assessing soil quality in water-stressed conditions can identify critical regions for sustainable productivity and soil health, essential for increased crop yields [13]. Soil productivity pertains to the optimal conditions for plant development, characterized by an appropriate growth medium and nutrients [14].

The addition of organic supplements has been suggested to enhance soil properties, thus boosting productivity and mitigating the negative impacts of drought [15]. Recently, biochar, a carbonaceous product produced from the incineration of carbon-based resources, has garnered significant interest as an amendment to the soil and a protector under drought [16]. The biochar application in the soil was found to improve soil organic carbon levels, moisture content, and porosity. Furthermore, it enhances the cation exchange capacity and improves the retention of polyvalent cations. Kabir et al. [17] documented the impact of biochar application on improving soil texture stability and aggregate stability. In instances of low soil moisture, aggregate stability can significantly improve soil water retention [18]. Nevertheless, the water retention volume of soils altered with biochar may vary depending on soil type, feedstock type, and biochar addition rate, and the procedures used to produce the biochar [19].

Application of biochar is well recognized for enhancing soil characteristics in semiarid regions with restricted water resources [20]. The purpose of this work was to scrutinize the influence of *Hibiscus cannabinus*-biochar addition on chemical traits of soil and barley growth, as well as physiological and oxidative enzyme levels in drought-stressed environments. Published research has not analyzed the invasive species Hibiscus cannabinus-biochar for mitigating drought stress in barley. We utilized this biochar to enhance barley growth under drought conditions, aiming to provide insights for the future enhancement of this biomass biochar. We hypothesized that the addition of *Hibiscus cannabinus*-biochar to the soil would improve soil properties and barley growth due to improvement in biochemical and physiological parameters under drought conditions.

2. Materials and Methods

2.1. Study Site and Experimental Design

The study was performed at Islamia University of Bahawalpur, IUB, Punjab, Pakistan. The trial utilized the barley seed variety "TJ-70" from NIAB, Pakistan. Eight barley seeds were cultivated in each pot, each filled with 4 kg of soil. Before the experiment, analysis of the soil found the presence of 0.80% organic matter, 80 mg kg^{-1} available potassium, 30 mg kg^{-1} available phosphorus, EC 229 (µS/cm), TSS (0.49%), and 23%, 39%, and 38% clay, silt, and sand levels, respectively. The average humidity and temperature recorded throughout the experiment are provided in Table 1.

Table 1. Average humidity and temperature levels during the barley-growing phase.

Month	Temperature, °C	Humidity level
November	19	59
December	15	69
January	12	72
February	14	67
March	20	60
April	30	49

Biochar was applied as a soil supplement just 10 days before planting barley seeds. Biochar was made from *Hibiscus cannabinus* biomass (known as non-wood biomass). The experiment utilized biochar produced by the pyrolysis process at 550 °C. The applications of biochar varied in dose based on the treatments in pots: BC_0 (no biochar), BC_1 (30 g kg^{-1}), and BC_2 (40 g kg^{-1}). To induce water stress, irrigation was withheld at both the tillering phase (WS1) and grain-filling phase (WS_2) of barley growth. Fully irrigated (WS_0) plants were designated as the control group. Irrigation/watering was administered at crucial growth phases, and 4-inch containers were filled with water throughout irrigation. Properties of the *Hibiscus cannabinus*-biochar utilized in the trial are provided in Table 2. Totally, other components remained consistent with the recommended dose. A complete randomized (CRD) design with 4 replications was applied to settle the planting pots.

Table 2. Characteristics of the applied biochar.

Biochar traits	Values
pH	9.11
Ash level (%)	3.29
CEC ($cmol_c\ kg^{-1}$)	35.19
EC ($\mu S\ cm^{-1}$)	941
Total carbon (%)	70.1
Total Nitrogen (%)	0.70
SSA ($m^2\ g^{-1}$)	113.6
Water soluble C (%)	149
Water soluble N (%)	89.54
$Cr_2O_7^{2-}$ oxidizable organic carbon (%)	4.61
Carbonate level (%)	12.31

2.2. Plant Harvesting and Quantification of Biomass

Upon reaching physiological maturity, which occurs after 125 days of germination, the plant was collected and divided into roots, branches, and spikes. After washing with distilled water, the plant components were meticulously rinsed with tap water. Initially, the root samples were rinsed with 1% hydrochloric acid solution. Each sample was divided into several components, including height of plant, length of spike, number of spikelets per spike, per spike grain numbers, 1000-grain weight, and per plant grain yield. The samples were dried in an oven at 70 °C until grasped a consistent weight. Dry biomass of each component was then measured individually, crushed, and kept for further analysis.

2.3. Determination of Gas Exchange Parameters and Photosynthetic Pigments

After 70 days of sowing, chlorophyll levels and gas exchange-related parameters were assessed by removing one plant from each treatment. The chlorophyll level was quantified with a spectrophotometer (Shimadzu UV-1800) at wavelengths of 470 nm, 647 nm, and 664.5 nm once samples were extracted with 85% (v/v) acetone (CH_3COCH_3) in the absence of light at 4 °C for 24 hours, followed by centrifugation at 4000×g for 15 minutes [21]. Stomatal conductance (Gs), water use efficiency (WUE), transpiration rate (Tr), and photosynthetic rate (Pn) were measured with a non-dispersive infrared gas analyzer (LI-6800). These variables were recorded during the period from 10:30 - 11:30 a.m. while barley plants were totally functional.

2.4. Quantification of H_2O_2, Malondialdehyde, and Electrolyte Leakage Levels

After 70 days of planting, electrolyte leakage in shoots was measured through uprooting one plant from every treatment. Samples were sliced into small pieces and positioned vertically in tubes containing 10 mL of DI water. The solution's initial EC was measured after a 2-hour incubation period at 30 °C. The samples were subjected to another autoclaving process for 25 minutes at 120 °C. The solution's final EC was measured after cooling the sample to 27 °C. Then, the electrolyte leakage was calculated with the equation suggested by Cuesta et al. [22].

$$EC = (EC1/EC2) \times 100 \qquad (1)$$

The malondialdehyde concentration quantification was conducted with an approach outlined by Mendes et al. [23]. To a 0.5-gram fresh sample, 5 mL of a 0.1% solution of thiobarbituric acid (TBA) was mixed. After centrifuging the aliquot for ten minutes at 12,000×g at 4 °C, the supernatant was obtained. After adding 4 mL of a 20% trichloroacetic acid solution (including 0.5% thiobarbituric acid) to 1 mL of supernatant, the mixture was immersed in boiling water at 95 °C for 30 minutes. The solution was then rapidly cooled in an ice bath and centrifuged at 10,000×g for 10 minutes. Samples were measured for absorbance at 532 nm, and non-specific absorbance at 600nm was subtracted. MDA levels were then determined with an extinction coefficient of 155 $mM^{-1}\ cm^{-1}$.

To quantify hydrogen peroxide, a 3 mL phosphate buffer solution (50 mM) was mixed with 50 mg of leaf samples to create a uniform mixture. The mixture was then centrifuged at 6000×g for 25 minutes at 4 °C.

Subsequently, the extracted solution was combined with 1 mL of 0.1% TiO (SO_4) in 20% (v/v) sulfuric acid. The resulting mixture was subjected to centrifugation at 6000×g for 20 minutes at a consistent temperature of 4 °C. Supernatant absorption was quantified at a wavelength of 410 nm. An extinction value of 0.28 μmol^{-1} cm^{-1} was employed to measure the amount of hydrogen peroxide.

2.5. Quantification of Antioxidant Enzymes

APX, CAT, POD, and SOD activities were measured using spectrophotometric instruments. For this purpose, shoot samples were pulverized in liquid nitrogen with a pestle and mortar. Standardizing the samples with a 0.05 M phosphate buffer at a pH of 7.8, the solution was filtered and centrifuged for 15 minutes at 12,000×g at 4 °C. The resulting supernatant was gathered and used for analysis. Peroxidase (SOD) and peroxidase (POD) activity were measured using the Pan et al. [24] technique.

The activity of catalase (CAT) was evaluated using the Ge et al. [25] technique. In summary, a 3 mL test mixture was prepared by adding 100 µL of enzyme extract, 100 µL of 250 mM hydrogen peroxide, and 2.8 mL of 50 mM phosphate buffer with 2 mM of CA at a pH of 7. Absorbance reduction at 240 nm was quantified to determine catalase activity. A reaction mixture containing 100 µL of enzyme extract, 100 µL of ascorbate (7.5 mM), 100 µL of Hydrogen peroxide (300 mM), and 2.7 mL of 25 mM tribasic potassium phosphate buffer with 2 mM CA was used to determine the activity of APX. Ascorbate oxidation activity was quantified by detecting at 290 nm ($\varepsilon = 2.8\ mM^{-1}cm^{-1}$), following the Ge et al. [25] method.

2.6. Soil Analysis

Samples of soil were gathered from pots at various stages of barley growth and after that preserved in plastic bags before their transportation to the lab. Supplementary containers were already prepared to gather soil samples from each phase of growth that underwent identical treatments and growing conditions. Phonological sampling was conducted at two distinct periods of barley growth: the tillering stage and the grain-filling stage. To accomplish this, many containers were set up for soil samples during the tillering and grain-filling stages, while maintaining equal conditions. Once the soil samples were moved to the laboratory, they were sifted through a sieve with a mesh size of less than 1.5 mm and then examined for soil moisture level. Once sieved, the soil was kept at a temperature of 4 °C.

The values of SOC, Bray P, and exchangeable potassium were calculated using established techniques as proposed by Sparks et al. [26]. Measurement of the soil pH level was conducted in a suspension of water and soil. The determination of total nitrogen was conducted through steam distillation, as documented via Mulvaney [27]. The quantification of carbon (DOC) and dissolved organic nitrogen (DON) was conducted following the methodology introduced by Smolander and Kitunen [28]. The nitrogen mineralization (NMIN) rate was determined by analyzing the soil both before and after a 10-day incubation period at a temperature of 30 °C. N, C, and P levels in the soil microbial biomass were quantified via fumigation extraction techniques as stated by Vance et al. [29]. Soil respiration (SR) was measured following the method described by Cuesta et al. [22]. The soil enzyme activities, including acid phosphatase (AcP), β-glucosidase (βG), dehydrogenase (DH), and urease (UR), were measured using the Tabatabai method [30].

2.7. Statistical Analysis

An analysis of variance was performed on data with Fisher's test with fixed factors biochar treatment (unamended, 30 g kg^{-1}, and 40 g kg^{-1}) and moisture treatment (continually irrigated, water stress during the tillering stage, and grain-filling phase). The Least Significant Difference (LSD) test was employed to identify significant differences in the interaction between amendment and moisture treatment at 95% confidence level ($p \geq 0.05$) (Steel et al., 1997).

3. Results

3.1. Barley Growth and Yield Parameters

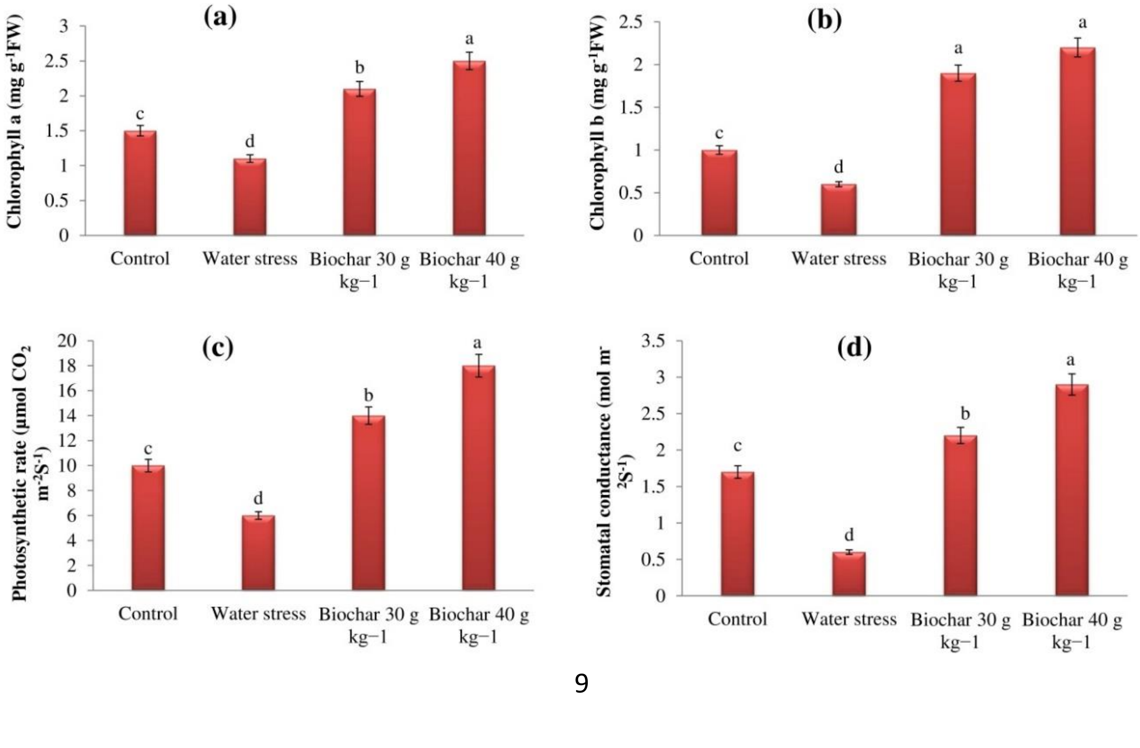
The drought stress had a significant impact on the barley growth indices and yield parameters. Additionally, it was detected that the addition of *Hibiscus cannabinus*-biochar had a notable effect in improving the barley growth as well as yield, as shown in Table 3. The best results were observed when biochar was applied at a dose of 40 g kg^{-1}, whereas the lower levels were obtained when no biochar was applied. The study revealed that the application of drought during the tillering stage resulted in the lowest spikelet numbers, spike length, and plant height. Conversely, the drought stress application during the grain-filling stage led to the lowest grain numbers, 1000-grain weight, as well as yield of grain. Similar patterns were observed in the results when the *Hibiscus cannabinus*-biochar was used in conjunction with drought stress.

Table 3. Evaluation of the impact of *Hibiscus cannabinus*-biochar on growth parameters and yield attributes of barley in conditions of drought-induced stress.

Application	Height of plant (cm)	Length of spike (cm)	Spikelet No. per-spike	Grains No. per-spike	1000-grain weight (g)	Grain yield per-plant (g)
WS_0	99 a (±0.889)	11.1 a (±0.139)	25.12 a (±0.119)	47 a (±0.349)	36 a (±0.360)	1.50 a (±0.008)
WS_1	88 c (±0.844)	8.77 c (±0.069)	23.07 b (±0.090)	39 b (±0.680)	33 b (±0.360)	0.89 b (±0.016)
WS_2	94 b (±0.399)	9.21 b (±0.159)	20.39 c (±0.040)	38 c (±0.909)	30 c (±0.160)	0.49 c (±0.030)
BC_0	89 c (±0.699)	10.09 c (±0.051)	22.31 c (±0.011)	38 c (±0.501)	31 c (±0.369)	1.19 c (±0.014)
BC_1	94 b (±0.398)	11.19 b (±0.090)	24.21 b (±0.020)	44 b (±0.909)	34 b (±0.401)	1.29 b (±0.020)
BC_2	98 a (±0.409)	12.11 a (±0.059)	26.39 a (±0.021)	48 a (±0.580)	37 a (±0.129)	1.50 a (±0.009)
WS_0BC_0	95.87 a (±1.041)	11.30 c (±0.069)	23.29 c (±0.039)	44 c (±0.399)	35 c (±0.140)	1.19 c (±0.010)
WS_0BC_1	97.41 b (±1.180)	12.19 b (±0.059)	25.30 b (±0.060)	47 b (±0.339)	37 b (±0.080)	1.29 c (±0.020)
WS_0BC_2	98.98 a (±0.932)	13.31 a (±0.260)	27.50 a (±0.089)	49 a (±0.380)	39 a (±0.109)	1.50 a (±0.010)
WS_1BC_0	85.40 h (±0.579)	8.19 h (±0.090)	20.10 f (±0.059)	40 f (±0.398)	29 f (±0.207)	0.90 f (±0.003)
WS_1BC_1	89.45 g (±1.159)	9.13 g (±0.180)	21.49 e (±0.129)	39 e (±0.180)	32 d (±0.030)	1.01 e (±0.008)
WS_1BC_2	89.61 f (±0.260)	10.14 f (±0.069)	22.39 d (±0.038)	40 d (±0.110)	34 e (±0.189)	1.09 d (±0.009)
WS_2BC_0	92.99 e (±0.388)	10.10 f (±0.049)	17.29 i (±0.029)	29 i (±0.359)	25 i (±0.090)	0.60 i (±0.006)
WS_2BC_1	94.32 d (±0.659)	10.99 d (±0.009)	18.19 h (±0.028)	34 h (±0.089)	27 h (±0.110)	0.70 h (±0.017)
WS_2BC_2	95.12 c (±0.630)	11.19 c (±0.169)	19.18 a (±0.008)	35 f (±0.409)	29 g (±0.079)	0.79 g (±0.010)

3.2. Analysis of Chlorophyll Levels and Gas-Exchange Characteristics

Quantification of chlorophyll a and b levels in barley showed a significant decline under drought stress (Figure 1). Both chlorophyll a and b showed a maximum reduction of around 40% in the presence of drought stress compared to the control group. The chlorophyll levels were significantly increased by biochar addition in comparison with the drought and control groups. 40 g kg^{-1} biochar treatment had the highest chlorophyll a and chlorophyll b levels, measuring around 81% and 72%, respectively, in comparison to the control. Water-induced stress reduced the values of WUE, Tr, Gs, and Pn in comparison to the control (Figure 1). The gas exchange-related parameters were significantly influenced by the biochar application in comparison to the comparable treatments without biochar. The highest increase in WUE, Tr, Gs, and Pn was recorded in 40 g kg^{-1} biochar, with values of approximately 55%, 89%, 49%, and 57% greater than the control samples, respectively.



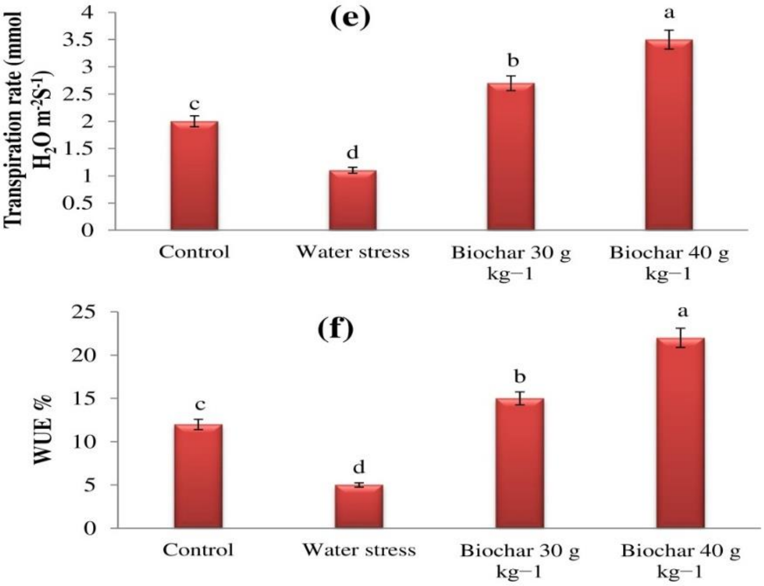
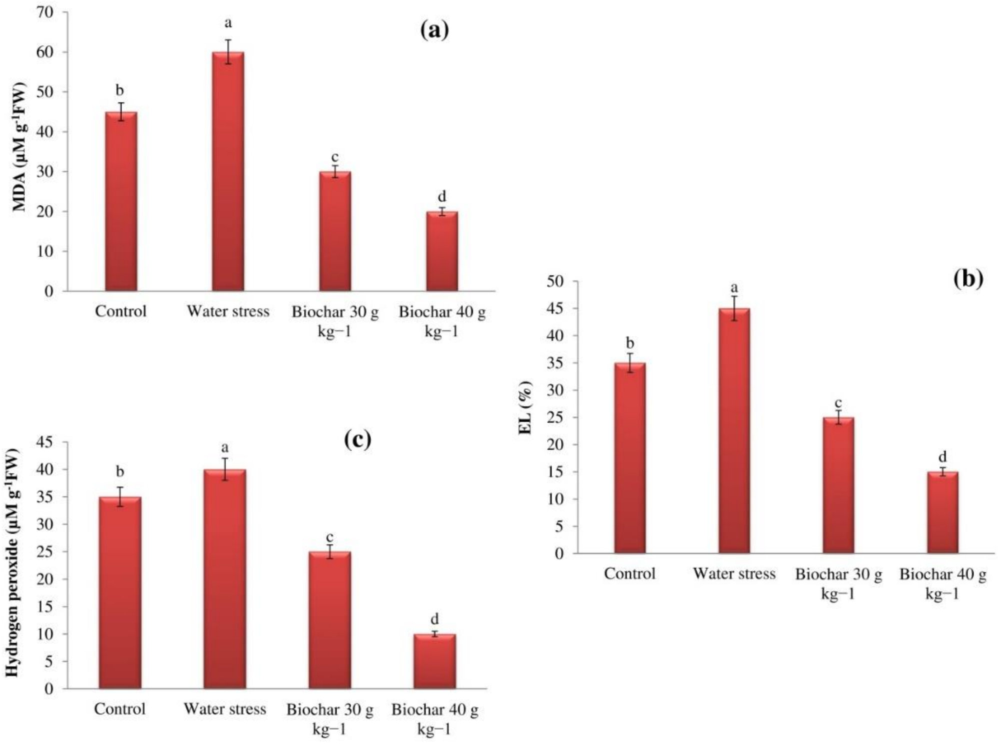


Figure 1. Evaluation of chlorophyll levels and gas exchange characteristics in barley cultivated under water stress, then subjected to escalating amounts of biochar. Values are means ± standard deviation (n = 4). Varying lowercase letters indicate a statistically significant difference among biochar treatments when the p-value is < 0.05.

3.3. Assessment of Oxidative Stress and Antioxidant Enzymes

Figure 2 depicts the data for oxidative stress, such as H_2O_2, EL, and MDA, as well as antioxidant enzymes, including CAT, POD, and SOD, in leaves. Drought stress resulted in elevated levels of H_2O_2, EL, and MDA in leaves compared to controls. Treatment with drought stress resulted in the highest increase in H_2O_2, EL, and MDA levels, with around 24%, 19%, and 29%, respectively to control. The biochar addition markedly decreased levels of H_2O_2, EL, and MDA compared to the similar drought application without biochar (Figure 2). The lowest levels of H_2O_2, EL, and MDA were detected in the 40 g kg^{-1} biochar. Reduced CAT and SOD activities and increased POD activity were observed during drought compared to the control. Application of biochar reduced POD activity and increased CAT and SOD activities in comparison to the drought application without biochar (Figure 2).



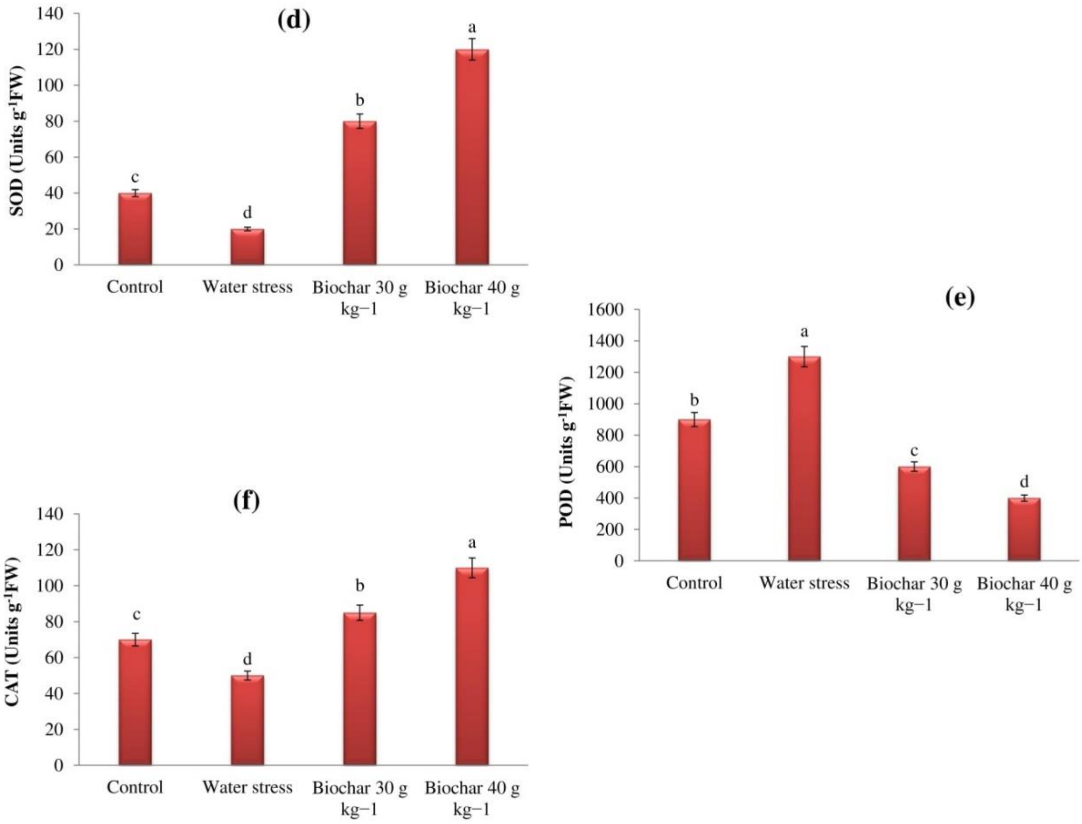


Figure 2. Evaluation of H_2O_2, EL, and MDA levels and antioxidant enzymes in barley cultivated under water stress, and then subjected to escalating amounts of biochar. Values are means ± standard deviation (n = 4). Varying lowercase letters indicate a statistically significant difference among biochar treatments when the p-value is < 0.05.

3.4. Soil Analysis

The soil pH level, total nitrogen, exchangeable potassium, as well as Bray phosphorus, recorded their maximum values in the soil under full irrigation with an elevated biochar treatment. Conversely, these values were lower when drought stress was applied at the grain-filling stage without biochar, as shown in Table 4. Under varying soil moisture circumstances (drought or full irrigation), higher doses of biochar resulted in high levels of various soil characteristics, whereas the lowest levels were observed in untreated soil. In general, both without and with biochar addition, these metrics were highest in the soil of plants that were completely irrigated but were lowest during the grain-filling phase under drought stress. No significant difference was observed in Bray phosphorus in biochar-added soil under drought during both the tillering and grain-filling stage.

Table 4. Impact of *Hibiscus cannabinus*-biochar on soil pH value, mineral nitrogen, phosphorus, and exchangeable potassium levels under water stress.

Treatments	pH of soil	Mineral nitrogen (mg kg^{-1})	Bray phosphorus	Exchangeable potassium
WS_0	7.10 a (±0.020)	84.60 a (±0.090)	7.79 a (±0.014)	169.49 a (±0.120)
WS_1	6.79 b (±0.090)	79.20 b (±0.050)	7.39 b (±0.017)	149.23 b (±0.069)
WS_2	6.80 c (±0.070)	75.50 c (±0.016)	6.89 c (±0.030)	139.34 c (±0.079)
BC_0	6.69 c (±0.059)	67.79 c (±0.040)	6.39 c (±0.210)	110.80 c (±6.321)
BC_1	6.90 b (±0.069)	85.49 b (±0.090)	7.19 b (±0.399)	180.99 b (±7.503)
BC_2	7.06 a (±0.080)	89.90 a (±0.050)	8.60 a (±0.130)	189. 21 a (±6.118)
WS_0BC_0	6.79 d (±0.012)	69.09 f (±0.088)	6.79 e (±0.015)	119.28 g (±0.088)
WS_0BC_1	7.02 b (±0.004)	90.29 b (±0.149)	7.79 c (±0.015)	197.00 b (±0.140)
WS_0BC_2	7.19 a (±0.020)	93.20 a (±0.079)	8.77 a (±0.015)	213.11 a (±0.131)
WS_1BC_0	6.69 e (±0.015)	66.23 g (±0.088)	6.39 f (±0.019)	99.63 h (±0.071)
WS_1BC_1	6.79 d (±0.008)	86.20 d (±0.089)	7.37 d (±0.007)	169. 20 e (±0.089)
WS_1BC_2	7.00 f (±0.011)	89.21 b (±0.099)	8.33 b (±0.019)	197.32 c (±0.059)
WS_2BC_0	6.59 e (±0.007)	64.09 h (±0.059)	6.09 f (±0.049)	98.31 i (±0.071)
WS_2BC_1	6.79 d (±0.006)	79.27 e (±0.058)	6.39 e (±0.015)	150.20 f (±0.086)
WS_2BC_2	6.89 c (±0.010)	87.16 c (±0.120)	8.39 b (±0.019)	179.45 d (±0.054)

Soil respiration, nitrogen mineralization, dissolved organic carbon, dissolved organic nitrogen, and soil organic carbon were greatest in the soil under full irrigation and the higher rates of biochar amendment. Contrariwise, these values were lowest in the absence of biochar addition at the grain-filling stage under drought stress, except for soil organic carbon, which was lowest under drought environments at the tillering phase at a biochar dose of 30 g kg^{-1} (as shown in Table 5). Both without and with biochar addition, these characteristics were highest in soil of completely watered plants and lowest at the grain-filling stage under drought stress, except for soil respiration, which exhibited no difference between the two water-stress conditions at a biochar dose of 30 g kg^{-1} and the low biochar level. No significant difference in soil respiration was observed between the two water-stress conditions when the biochar amount was reduced.

Table 5. Impact of *Hibiscus cannabinus*-biochar on soil respiration, nitrogen mineralization, dissolved organic N, soil organic carbon, and dissolved organic carbon in conditions of drought stress.

Treatments	SOC (g kg^{-1})	DOC (µg g^{-1})	DON (µg g^{-1})	Mineralization of nitrogen	Soil respiration
WS_0	1.29 a (±0.020)	139.75 a (±0.079)	22.12 a (±0.089)	78.77 a (±0.099)	24.17 a (±0.020)
WS_1	1.26 b (±0.0021)	136.52 b (±0.0080)	20.07 b (±0.080)	66.76 b (±0.080)	23.12 b (±0.219)
WS_2	1.24 c (±0.0007)	131.21 c (±0.130)	16.39 c (±0.080)	49.52 c (±0.089)	22.19 c (±0.006)
BC_0	0.89 c (±0.0060)	127.07 c (±1.214)	17.31 c (±1.801)	52.76 c (±5.591)	21.99 c (±0.401)
BC_1	1.50 b (±0.0181)	134.19 b (±2.175)	20.21 b (±1.806)	66.76 b (±7.989)	23.11 b (±0.843)
BC_2	1.49 a (±0.0180)	149.12 a (±3.680)	22.39 a (±1.811)	77.54 a (±7.997)	24.98 a (±0.711)
WS_0BC_0	98 d (±0.0013)	134.30 f (±0.059)	20.29 d (±0.079)	66.30 c (±0.119)	23.09 b (±0.021)
WS_0BC_1	1.49 b (±0.0020)	139.19 d (±0.089)	23.30 b (±0.078)	79.76 b (±0.089)	25.30 ab (±0.022)
WS_0BC_2	1.55 a (±0.0019)	160.31 a (±0.094)	25.50 a (±0.120)	88.89 a (±0.080)	26.20 a (±0.029)
WS_1BC_0	0.97 d (±0.0014)	129.19 f (±0.067)	18.10 f (±0.059)	49.76 e (±0.112)	22.29 cd (±0.009)
WS_1BC_1	1.51 d (±0.0025)	136.13 e (±0.099)	21.49 c (±0.070)	66.43 c (±0.069)	22.88 c (±0.711)
WS_1BC_2	1.51 ab (±0.0024)	149.14 b (±0.071)	23.39 b (±0.110)	79.09 b (±0.059)	25.12 b (±0.004)
WS_2BC_0	0.97 e (±0.0007)	130.10 g (±0.130)	14.29 h (±0.070)	46.21 f (±0.119)	21.21 e (±0.006)
WS_2BC_1	150 c (±0.0008)	133.99 f (±0.070)	17.19 g (±0.079)	49.43 e (±0.079)	22.15 d (±0.007)
WS_2BC_2	1.51 b (±0.0010)	147.19 c (±0.190)	19.18 a (±0.079)	59.19 d (±0.099)	23.41 c (±0.004)

Values in brackets are the standard error of the mean (n = 4).

Under full watering with the maximum biochar treatment (40g kg^{-1}), the soil exhibited the highest levels of microbial biomass C (MBC), microbial biomass N (MBN), and microbial biomass P (MBP). Conversely, when drought stress was introduced at grain-filling without biochar application, these values were the lowest (Figures 3 and 4). Across various soil moisture circumstances (drought or full irrigation), the soil indices exhibited the highest values when the biochar level was at its maximum, but the lowest values in untreated soil. In general, both without and with biochar addition, these metrics were highest in the soil of plants that were completely irrigated, but were lowest during the grain-filling stage under water stress.

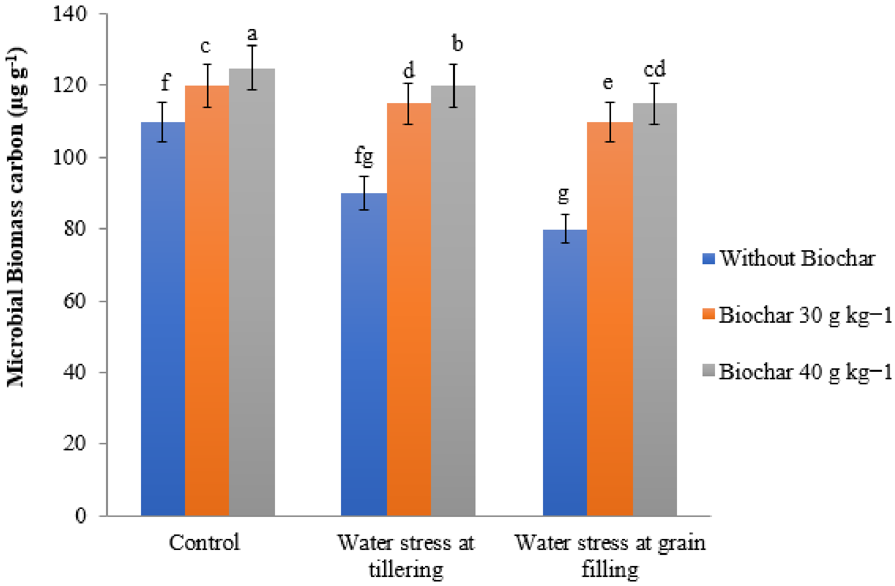


Figure 3. Impact of *Hibiscus cannabinus*-biochar on soil microbial biomass carbon under water stress conditions.

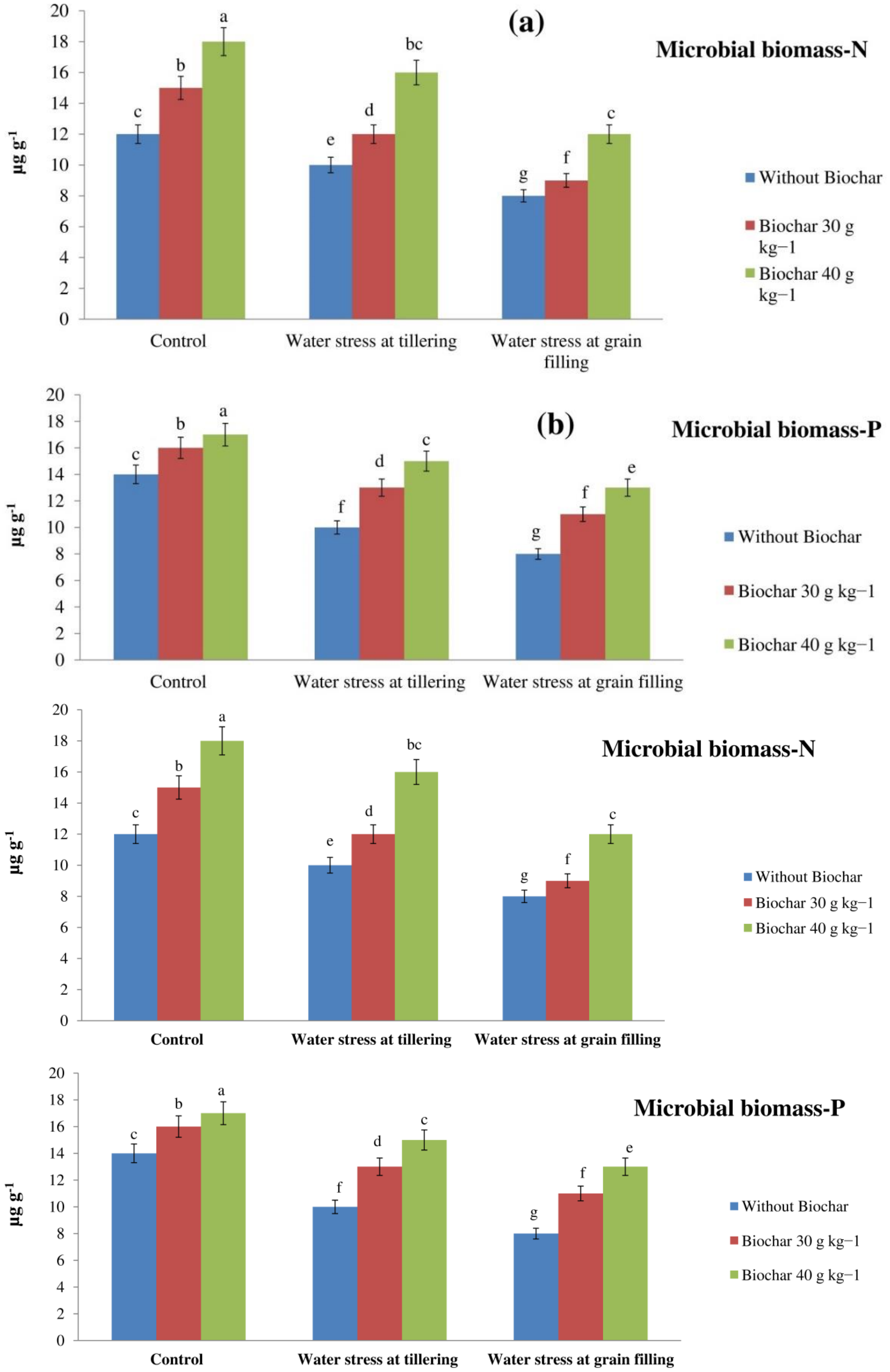


Figure 4. Impact of *Hibiscus cannabinus-biochar on microbial biomass* phosphorus and microbial biomass nitrogen and of the soil under water-stress conditions.

The data presented in Table 6 indicate that the soil β-glucosidase (βG), acid phosphatase (AcP), urease (UR), and dehydrogenase (DH) concentrations were highest in the absence of water stress, followed by drought at the grain-filling phase. Conversely, the lowest levels were observed when water stress was employed during the grain-filling stage. The biochar incorporation at a dose of 40 g kg^{-1} yielded the maximum soil enzymatic activity, followed by the biochar addition at a level of 30 g kg^{-1}. The treatment without biochar showed the lowest enzyme activities. A significant interaction was observed between the administration of *Hibiscus cannabinus*-biochar and water-stress treatments.

Table 6. Impact of Hibiscus cannabinus-biochar on soil β-glucosidase (βG), acid phosphatase (AcP), urease (UR), and dehydrogenase (DH) concentrations in conditions of drought stress.

Applications	DH (nmol TPF g^{-1} soil h^{-1})	UR (µmol NH_3-N g^{-1} h^{-1})	AcP (µmol *p*-Nitrophenol g^{-1} h^{-1})	βG (µmol *p*-Nitrophenol g^{-1} h^{-1})
WS_0	69 a (±0.799)	16.29 a (±0.280)	27.12 a (±0.250)	7.70 a (±0.059)
WS_1	34 c (±1.120)	10.28 c (±0.119)	18.07 c (±0.169)	3.39 c (±0.089)
WS_2	66 b (±0.897)	13.29 b (±0.110)	22.39 b (±0.139)	5.49 b (±0.070)
BC_0	66 c (±1.432)	17.09 c (±0.019)	25.31 c (±0.269)	6.76 c (±0.319)
BC_1	77 b (±1.112)	18.19 b (±0.090)	29.21 b (±0.240)	7.76 b (±0.240)
BC_2	83 a (±0.872)	22.12 a (±0.030)	33.39 a (±0.502)	8.54 a (±0.089)
WS_0BC_0	64 c (±0.872)	14.30 c (±0.089)	23.29 c (±0.109)	7.30 c (±0.091)
WS_0BC_1	69 b (±1.112)	17.19 b (±0.130)	28.30 b (±0.499)	7.76 b (±0.200)
WS_0BC_2	76 a (±0.873)	19.29 a (±0.260)	32.50 a (±0.229)	8.89 a (±0.407)
WS_1BC_0	29 h (±1.431)	5.39 g (±0.260)	15.10 g (±0.529)	3.76 h (±0.140)
WS_1BC_1	36 g (±0.699)	7.13 f (±0.070)	17.49 g (±0.470)	4.43 g (±0.050)
WS_1BC_2	40 g (±0.801)	9.13 e (±0.060)	18.39 f (±0.699)	4.09 f (±0.059)
WS_2BC_0	59 f (±0.439)	10.10 e (±0.099)	18.29 f (±0.601)	4.21 e (±0.070)
WS_2BC_1	66 e (±0.399)	12.99 d (±0.100)	20.19 e (±0.501)	5.43 d (±0.129)
WS_2BC_2	69 d (±0.857)	13.19 c (±0.169)	22.18d (±0.811)	5.87 d (±0.120)

4. Discussion

Current research shows that water-induced stress during the tillering stage and the grain-filling stage significantly reduced the soil pH level, while soil pH remained higher in continually watered soils. Similar findings were documented by Katohar et al. [31], Ashfaq et al. [32] observed a significant reduction in soil pH when exposed to drought stress, ascribed to insufficient phosphate solubilization. The parameters associated with the growth and yield of the barley plants are interconnected. An increased 1000-grain weight results in a greater grain yield per plant [33]. Seleiman et al. [34] found that drought stress, observed at any stage of growth, significantly impairs barley growth and production due to the key role of water in the development and growth of plants. Drought stress leads to reduced availability of nutrients from the soil and decreased synthesis of photosynthetic components in crops, resulting in reduced growth of plants. The biochar addition in the soil enhanced barley growth and plant biomass, except in the case of drought, when biochar was not effective. Enhancing the quantity of biochar incorporation showed an improvement in barley plant growth under conditions of water scarcity [35]. Furthermore, multiple studies have revealed the enhancement of growth-related parameters with biochar in the presence of water deficit conditions [36]. The positive impact of biochar on barley yield and biomass in stressed environments was attributed to the enhancement of soil physicochemical characteristics in response to drought stress [37].

Drought stress resulted in a reduction in chlorophyll levels and gas exchange characteristics. The reduction in chlorophyll content is attributable to chloroplast damage induced by reactive oxygen species. Drought stress induces the generation of reactive oxygen species (ROS), including O_2^- and H_2O_2, resulting in the degradation of chlorophyll [38]. Conversely, the application of biochar enhanced barley plant chlorophyll levels and gas exchange characteristics more than control and drought treatments (Figure 1). Several reasons are rooted in its distinctive characteristics and interaction with plants and soil. Biochar improves nutrient accessibility in the soil, facilitating the uptake of vital elements including nitrogen, potassium, and phosphate. These nutrients are essential for synthesizing chlorophyll, the primary photosynthetic pigment in crops [39]. Studies have shown that the use of biochar under drought stress leads to an increase in chlorophyll levels, Gs, and Pn in the leaves of different plants, including wheat, barley, maize, and potato [40]. Similarly, biochar application enhanced photosynthesis in crops experiencing drought stress [41]. Biochar serves as an effective technique for increasing photosynthesis in crops experiencing drought stress by promoting water retention, nutrient accessibility, soil structure, and overall plant vitality. It alleviates the detrimental impacts of drought, guaranteeing that plants possess the necessary resources to sustain effective photosynthesis, resulting in improved agricultural yields even in water-scarce conditions [42]. The enhancement of photosynthesis observed with biochar addition under drought stress may be attributed to the ultrastructural alteration of barley seedlings. This is because the stress induces significant damage to the chloroplasts [43].

Oxidative stress affects various cellular processes in crops by promoting lipid peroxidation and inducing structural damage to nucleic acids [44]. The generation of reactive oxygen species (ROS) in crops is counteracted by important antioxidant enzymes found in crops, including superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT). Sodium oxidase (SOD) transforms $O_2^{\bullet-}$ into hydrogen peroxide (H_2O_2), catalase (CAT) directly converts hydrogen peroxide to water and O_2, and peroxidase (POD) catalyzes the dissociation of hydrogen peroxide. Therefore, plants undergo ROS detoxification in this manner, and a proper balance is necessary between the generation and breakdown of ROS for crop functioning [45]. Nevertheless, in stressed conditions, plants are incapable of eliminating the reactive oxygen species, and so, oxidative stress increases in crops [46]. In this work, drought was found to elevate the levels of H_2O_2, MDA, and EL and suppress the POD activity in barley seedling leaves, while reducing activities of CAT and SOD compared to the control (Figure 2). Drought stress frequently results in an imbalance between reactive oxygen species (ROS) generation and the plant's capacity to neutralize them via antioxidant enzymes such as peroxidase (POD), hence diminishing its ability to detoxify hydrogen peroxide (H_2O_2) and other ROS [47]. The observed elevation in oxidative stress and decrease in CAT and SOD activity under drought stress have significantly impaired the plant's antioxidative system. Choudhury et al. (2022) revealed that drought stress leads to an elevation of APX, POD, and CAT activities while causing a decrease in SOD activity in Poaceae plants. The research findings indicate that drought stress leads to a rise in MDA levels and activities in POD and CAT in maize leaves under drought stress compared to the control [47]. Drought-induced oxidative stress increased MDA levels in Castor and Indian mustard, with the particular reaction varying bestowing to the species and development phase duration [48]. Ishfaq et al. [49] observed that drought stress induces a dose-additive rise in the CAT, POD, SOD, $O_2^{\bullet-}$, H_2O_2, and MDA activities in both the shoot and root of the Poaceae family compared to the control group. The application of Hibiscus cannabinus-biochar to barley plants under water-stress conditions can lead to improved physiological responses and antioxidant enzymatic activity. The biochar treatment can enhance the plant's antioxidant defense system, increasing the activity of enzymes such as superoxide dismutase, catalase, and peroxidase, which help mitigate oxidative stress caused by water stress. Additionally, kenaf-biochar can improve plant water status, reducing the negative impacts of drought on plant growth and physiology. The treatment can also modulate physiological responses, such as increasing stomatal conductance, photosynthetic rate, and chlorophyll content, ultimately leading to improved plant growth and resilience under water-stress conditions. By enhancing antioxidant enzymatic activity and physiological responses, kenaf-biochar can help barley plants better cope with water stress.

Biochar is a highly efficient soil supplement that enhances soil characteristics and effectively sustains soil production over a long period [50]. The application of biochar as a soil supplement has a beneficial impact on the plant’s growth and development [51]. As biochar can elevate soil organic carbon (SOC) and soil organic matter (SOM) levels, while also augmenting the activity of soil microbes that facilitate nutrient availability [52]. In conditions of low soil water content, including drought stress, the buildup of OM can lead to a decrease in soil pH by releasing H^+ ions [53]. Furthermore, increased polarity of deposited cations caused by soil drying can induce a decrease in the soil pH values [54]. Furthermore, Chanthini et al. [55] revealed that a reduction in soil pH under drought stress may suggest that moisture increases the relationship between phosphatase activities in soil.

Nevertheless, biochar addition improved water-induced reductions in soil pH levels, primarily because of its alkaline nature and buffering capacity, along with its ability to influence soil properties and microbial communities [56]. The increase in soil pH resulting from biochar addition has been ascribed to the release of intrinsic alkaline compounds [19], as well as potentially elevated levels of calcium carbonate equivalent and calcium carbonate [57]. Su et al. [58] stated that biochar alkalinity is a critical determinant of its liming ability. The biochar addition impact on soil pH shows a positive correlation with biochar dose application under various soil water treatments in the current study.

Exposure to drought stress greatly reduced the nutrient levels (total nitrogen, mineral nitrogen, bray phosphorus, and exchangeable potassium) in soil, as compared to soils that were consistently irrigated, due to several interconnected physical, chemical, and biological processes such as (a) reduced nutrient mineralization, (b) impaired nutrient solubility and mobility (c) soil Drying and nutrient leaching (d) soil compaction and root activity (e) reduced cation exchange capacity that occur in the soil under water-limited conditions [59]. Under drought stress, decreased soil water level impedes microbial activity, leading to diminished breakdown of organic waste, according to Doroski et al. [60]. Phosphorus pool and soil respiration were reduced in soil with a lower water level (-1.700 MPa) compared to soil with an optimal water level (-0.078 MPa). Dry soil has reduced microbial activity and phosphorus availability in comparison to soils that are consistently irrigated [61]. The presence of higher nutrient levels in soil continuously watered soils may indicate the influence of soil microorganisms on the breakdown of SOM, leading to nutrient mineralization [62].

Biochar enhanced nutrient levels (mineral nitrogen, total nitrogen, Bray phosphorus, and exchangeable potassium) in both drought-stressed and continuously irrigated soils compared to untreated soils. Biochar is an effective amendment that boosts soil nutrient levels, improving plant growth and resilience in both drought-stressed and continuously irrigated soils by increasing nutrient availability and preventing nutrient losses [63]. Comparable findings were noted in the study conducted by Luo et al. [64]. Bankole et al. [65] also confirmed that the use of biochar enhanced the retention of nitrogen and SOM in the soil, leading to enhanced soil WUE. The increased soil nutrient availability caused by biochar under consistent drought and watering-imposed treatments may be attributed to either the release of existing nutrients from char or the accelerated breakdown of soil organic matter, known as "soil priming" [66]. Furthermore, Priya et al. [67] revealed that biochar addition to the soil increased nutrient availability and improved soil fertility. Significant influence on the nutrient levels released into amended soil, attributed to the biochar production temperature as well as feedstock [63]. The application of Hibiscus cannabinus-biochar can positively impact microbial activity and nutrient cycling in soil. The biochar provides a habitat for beneficial microorganisms, increasing microbial abundance and diversity, which can enhance nutrient cycling and availability. Kenaf-biochar's porous structure and high surface area can also adsorb and retain nutrients, reducing leaching and making them available to microorganisms and plants. This can lead to improved soil fertility, structure, and overall ecosystem health. Additionally, the biochar can stimulate microbial processes, such as nitrogen fixation, decomposition, and solubilization of minerals, further enhancing nutrient cycling and availability for plant uptake. By promoting beneficial microbial activity and nutrient cycling, kenaf biochar can contribute to a more sustainable and resilient soil ecosystem

Drought stress reduces the size of macroaggregates in the soil organic carbon pool, which subsequently impacts soil stability [68]. Biological carbon metabolism is extremely responsive to soil moisture levels [69]. Dissolved organic carbon (DOC), soil organic carbon (SOC), and dissolved organic nitrogen (DON) are interconnected with soil moisture availability and are all diminished under drought stress. Conversely, Nazir et al. [70] concluded that drought stress led to a rise in dissolved organic carbon (DOC) generation from marshland. Bai et al. [71] found that biochar contains carbon, so its incorporation into the soil also improves the soil's organic carbon and DOC. Furthermore, biochar increases organic matter levels in soil and promotes microbial activity, therefore enhancing the dissolved organic nitrogen levels. Biochar facilitates habitats for microorganisms owing to its porous structure and by encouraging the development of stable soil micro-aggregates. Biochar functions as a source of carbon and nutrients. Biochar modifies the physical and chemical characteristics of soil, establishing optimal conditions for microbial diversity [72]. The influence of soil moisture availability on nitrogen mineralization was documented by Naorem [68]. These conditions lead to a surge in nitrogen loss because of increased synchronicity between nitrogen generated via mineralization and its uptake by plants. Any soil additives capable of augmenting soil OM have the potential to alleviate nitrogen loss. By enhancing SOM and reducing nitrogen loss, the use of biochar also promotes nitrogen mineralization in soil [72].

Therefore, soil respiration is crucial for the long-term development of plants, microbes, and soil fauna. This parameter quantifies the speed at which SOM breaks down and the activities of microbes [73]. In this work, soil respiration was reduced by 7.11% and 11.01% during the tillering and grain-filling stages, respectively, under drought stress. However, after biochar was utilized and then exposed to drought stress at similar stages, much greater soil respiration was observed. The findings of Raj et al. [74] demonstrated that reduced soil moisture leads to a decline in soil microbial activity. Therefore, a higher number of microbes and roots of plants allocate energy towards the synthesis of protective chemicals, which in turn reduce soil respiration.

The soil microbial biomass is crucial in the process of organic matter decomposition. Enhanced soil fertility and increased soil nutrient availability are facilitated by higher microbial biomass. Furthermore, it acts as an association between soil nutrient sources and sinks [75]. Prasad et al. [76] documented that drought stress induces osmotic stress, leading to microbial mortality and a decrease in microbial biomass. A significant reduction in organic matter decomposition was observed under drought stress. Numerous studies have documented that biochar addition has the potential to increase microbial activities, nutrient levels, and organic matter in soil. Thus, this leads to an enhancement in soil microbial biomass, hence promoting plant growth and soil fertility.

Research findings indicate that drought stress leads to a significant reduction in soil enzymatic activities. Furthermore, Chen et al. [77] observed a decline in enzymatic activity in soil due to a climatic gradient under conditions of limited drought stress. Insufficient soil water availability reduces soil microbial processes responsible for recycling different soil nutrients. Various levels of soil nutrient availability and plant growth requirements at various phases of barley growth of barley result in distinct impacts of water stress on soil enzymatic activity. A reduction in enzymatic activity is found when there is nitrogen availability during drought stress, as described by Muhammad et al. [78]. Consistent with previous studies, our results indicate that dehydrogenase and phosphate activities, β-glucosidase, and urease are positively associated with soil water availability [79]. The biochar addition also enhances organic carbon content, which can greatly benefit the improvement of soil microflora [80]. Microbial processes in soil also improve the organic matter and nutrient content of soil. Several studies have also documented that biochar addition in soil leads to an increase in organic matter, which in turn improves soil enzymatic activity and yields positive effects on plants [81]. Babur et al. [82] presented that biochar addition as a soil conditioner enhances the levels of soil organic matter, which improves soil quality and health.

5. Conclusion

The current study results indicated that the application of biochar soil effectively enhanced barley growth and yield while alleviating the impact of drought stress on the plants. Under conditions of drought stress, biochar addition reduced oxidative stress and increased the activity of antioxidant enzymes. In comparison to control and drought treatments, the chlorophyll levels and gas exchange characteristics were enhanced. The biochar addition was observed to have a significant impact on the soil biochemical characteristics. The majority of organic matter exhibited a significant increase with biochar application. The biochar application under drought-stress environments has the potential to enhance both plant growth and soil chemical characteristics. Under drought stress, biochar addition at a dose of 40 g kg^{-1} of soil is more beneficial compared to a rate of 30 g kg^{-1}. Therefore, it is advisable for farmers and researchers exploring crops to employ biochar, particularly under drought stress, to enhance plant growth and as an alternative technique for enhancing nutrient availability for plant growth.

Author Contributions

Conceptualization, G.M., and M.U.; methodology, software, validation, R.I.; formal analysis, G.M.; investigation, G.M. and M.U.; resources, G.M; data curation, writing-original draft preparation, R.I.; writing-review, editing, G.M., and R.I.; All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors stated that they had no interest that might be perceived as posing a conflict or bias.

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Review Article

Reproductive Migration of Fish and Their Transit Through Azerbaijan Waters

Gultaj Y. Seyidzade[1] and Vitaliy Bekh[2]

[1]Department of Natural Sciences, School of Advanced Technologies and Innovation Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan
[2]Department of Aquaculture, National University of Life and Environmental Sciences of Ukraine, Kyiv 03041, Ukraine

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Abstract

The article summarizes the concept of fish reproductive migration, its main types, and the biological and ecological characteristics of migratory fish. The main goal of the study is to analyze the reproductive migration of migratory fish, especially species belonging to the sturgeon and salmonid families, distributed in Azerbaijani waters, the factors affecting the decline of their natural resources, and the importance of artificial enrichment measures. The article shows that migratory fish ensure population sustainability by moving between marine and river environments at different stages of their life cycle. The construction of hydrotechnical facilities, water pollution, illegal hunting, and degradation of natural spawning grounds in the Kura and Araz basins have sharply weakened the reproductive capabilities of these fish. Artificial reproduction programs are of strategic importance for the protection and restoration of valuable species, especially sturgeon and Caspian salmon, as their stocks are declining. The article discusses the role of fish breeding facilities operating in Azerbaijan, the importance of the practice of artificial insemination and the release of fry into natural water bodies, as well as the genetic, technological, and ecological problems that arise during this process. As a result, it is justified that artificial breeding alone is not enough for the restoration of migratory fish, and that it must be implemented in conjunction with the protection of basin ecosystems, the restoration of migration routes, and scientific monitoring.

Keywords: reproductive migration, migratory fish, sturgeons, salmonids, artificial insemination

1. Introduction

Fish migration is a significant biological event in terms of the circulation of substances in aquatic ecosystems, population dynamics, and the maintenance of biodiversity. As a result of migration, fish choose the most favorable environments for feeding, wintering, and reproduction. This process is especially clearly observed in migratory fish. These species spend different stages of their life cycle in marine and freshwater environments, reproducing primarily in rivers. Consequently, they serve as valuable indicators of the ecological condition of both marine and freshwater ecosystems.

The water bodies of Azerbaijan, primarily the Caspian Sea and the Kura and its tributaries, have historically been one of the habitats for valuable migratory fish. Sturgeons and salmonids are of great importance not only biologically, but also economically. However, in recent decades, increasing anthropogenic pressures, the construction of dams and reservoirs on rivers, deterioration of water quality, and illegal hunting have seriously affected the stocks of these species.

For this reason, artificial reproduction measures are widely used to protect and restore natural populations of migratory fish [1]. Artificial reproduction includes not only the acquisition of juvenile fish and their release into water bodies, but also complex measures such as the formation of mother fish flocks, the preservation of the gene pool, and ensuring adaptive management. Therefore, this review aims to evaluate reproductive migration of migratory fishes occurring in Azerbaijani waters, with particular emphasis on sturgeons and salmonids, and to assess current artificial propagation strategies and future conservation priorities.

2. Reproductive Migration and Biological Characteristics of Migratory Fish

Migration is the regular and repetitive movement of organisms, including fish, from one habitat to another in order to meet certain biological needs. In fish, migration is often associated with feeding, reproduction, hibernation, and the provision of separate stages of ontogenesis. These movements act as a mechanism for adapting not only to spatial changes but also to factors such as temperature, salinity, flow rate, oxygen regime, and photoperiod.

Fish migration is classified according to various principles. Depending on the purpose, feeding, wintering, and breeding migrations are distinguished. Depending on the direction, horizontal and vertical migration are distinguished. In vertical migration, fish change places between water layers, while in horizontal migration, they cover large distances. Depending on the environments involved in the life cycle, marine, river, transient, and semi-transient migrations are noted.

Of particular importance is reproductive migration, during which sexually mature individuals move to areas most suitable for their embryonic and early postembryonic development for spawning. In such areas, the water is usually rich in oxygen, the flow is stable, the bottom is sandy and gravelly, and the temperature regime is favorable. Restricted access to natural breeding grounds has a direct negative impact on the population of migratory species.

In the scientific literature, two main groups of migratory fish are indicated: anadromous species feed in the sea and reproduce in rivers, and catadromous species, on the contrary, live in fresh waters and reproduce in the sea. In the Caspian basin, the most important from the point of view of economy and protection are anadromous, that is, fish that migrate from the sea to the river. Sturgeon and Caspian salmon, which are widespread in Azerbaijani waters, belong to this group.

Migratory fish are species that regularly move between bodies of water of different salinity to complete their life cycle. Their bodies have highly developed osmoregulation mechanisms. This feature allows them to regulate water-salt metabolism during the transition from the sea to the river or vice versa. Migration in migratory fish is not only a physiological phenomenon, but also a form of instinctive behavior.

The life cycle of these fish usually consists of several stages: ascending the river to spawn, initial development of the larvae that hatch from the eggs in the river, then the juveniles to the sea, intensive feeding and growth in the sea, and migration back to the river after reaching sexual maturity. Disruption of this sequence reduces the rate of population renewal and puts the species' survival at risk.

Migratory fish usually have high commercial value [2]. Sturgeons produce black caviar and high-quality meat, while salmonids are important both as a valuable food product and as a sport fishery. Therefore, intensive fishing in the past has put serious pressure on these species. Currently, many migratory fish species are listed as rare or endangered species.

There are two main approaches to protecting transient species: natural habitat restoration and artificial augmentation. The first approach requires maintaining the ecological flow of rivers, opening migration routes, and reducing pollution. The second approach is based on taking reproductive products from mother fish in a hatchery, raising juveniles through artificial insemination, and releasing them into natural reservoirs.

3. Reproductive Migration of Sturgeons and Salmonids in Azerbaijani Waters and Artificial Propagation Measures

The Caspian Sea is one of the basins where the world's most important sturgeon stocks are formed. According to official data, more than 100 fish species and subspecies live in the Caspian Sea, some of which are migratory and semi-migratory species; 6 species of sturgeon are noted to be widespread in this basin. This group has historically had high economic importance in Azerbaijani waters. The main feature of their breeding strategy is their migration to rivers after feeding at sea.

The main sturgeons found in Azerbaijani waters include sturgeon, longnose sturgeon, stellate sturgeon, and Russian sturgeon. The largest and slowest-maturing forms of these species are giant beluga-type sturgeons, while smaller forms are regional and other species. Sturgeons are particularly vulnerable to anthropogenic impacts because they are long-lived, reach sexual maturity late, and have a low natural recovery rate.

The most important migration route of the Sturgeons was connected to the Kura River [3]. In the past, these fish would migrate upstream along the river to spawn in areas with flowing, oxygenated, and gravelly bottoms. However, hydrotechnical structures, especially the Mingachevir reservoir and other regulatory facilities, have restricted the migration route. As a result, most of the natural spawning grounds have become inaccessible, and the natural reproduction of sturgeon has weakened.

The second major threat to sturgeon is illegal and uncontrolled fishing. The species has been intensively exploited for many years due to the high market value of its caviar and sturgeon meat. For this reason, a moratorium on commercial fishing was introduced in 2011 to protect sturgeon in the Caspian Sea. Although the moratorium is a significant conservation measure, it is not sufficient on its own to fully restore the population; artificial reproduction and habitat restoration are essential in parallel.

Hatcheries operate in Azerbaijan to restore sturgeon stocks. State and international sources state that millions of sturgeon fry are released into the Caspian Sea every year. At the same time, FAO data indicate that the Khilli sturgeon hatchery, located in the lower reaches of the Kura River, is carrying out artificial propagation of Acipenser persicus, Acipenser stellatus, Acipenser nudiventris, and Huso huso. The maintenance of broodstock, the procurement of reproductive products, and the raising of fry in these facilities constitute a key part of the sturgeon conservation strategy.

The most important place among migratory salmonids in Azerbaijani waters belongs to the Caspian salmon or Kura salmon. This fish is an anadromous form that feeds in the sea and enters rivers to reproduce. According to official data, there are two types of salmon in the Caspian [4]. Caspian salmon and white salmon. However, the main object of research in terms of reproductive migration is the Caspian salmon.

The biological characteristic of Caspian salmon is that after hatching, the juveniles develop in freshwater for a certain period of time, then descend to the sea and grow intensively [5]. Various sources indicate that this species has formed local populations associated with the Kura, Samur, Yalama, and other rivers. Clean, cold, oxygen-rich, and gravelly bottom areas are essential for their reproduction.

Historical data indicate that Caspian salmon was an important hunting target until the mid-20th century. However, the stock has declined sharply due to dam construction, changes in water regime, pollution, and destruction of spawning grounds in the Kura and Araz rivers. Disruption of the migration route is one of the most critical factors for this species, as salmon need to reach upstream to reproduce.

Special breeding facilities have been established in Azerbaijan to restore salmonids. According to the Ministry of Ecology and Natural Resources, approximately 200,000 salmon fry are released into natural water bodies each year. FAO data from 2021 shows that Kura salmon are being bred at the Azerbaijan Experimental Marine hatchery, and tens of thousands of 50-gram fry are released into the Caspian Sea every year. This fact shows the real practical importance of artificial breeding in restoring salmonid stocks.

However, for salmonids, simply releasing fry is not enough. The survival rate of the released individuals, their adaptation to the sea, protection from predators, the food base, and the ecological state of the rivers directly affect the final result. Therefore, the protection of salmonids should be based on the basin approach, and ecological measures should be taken in the upper reaches of the rivers.

Artificial breeding of migratory fish is a system of complex biotechnical measures applied in conditions of natural population decline or disruption of natural reproduction [6]. This system includes the capture or retention of parent fish, assessment of their maturity status, collection of reproductive products, artificial insemination, incubation, rearing of larvae and fry, and subsequent release into natural water bodies of appropriate size.

The main goal of artificial augmentation is not to artificially increase the natural resource, but to support the population's self-renewal potential. Therefore, preserving genetic diversity in breeding programs, using mother fish of different ages and origins, controlling diseases, and selecting the release time according to ecological conditions are important conditions. Otherwise, while a short-term increase in numbers may be observed, long-term recovery may not be achieved.

In Azerbaijan, this sector is being developed through both state and private enterprises [2]. According to official and FAO data, specialized fish breeding facilities operate in the country to restore stocks of migratory and other valuable fish species. The FAO indicates that three main hatcheries operate in the country, of which the Khilli Sturgeon Plant specializes in sturgeon, and the Azerbaijan Experimental Marine Hatchery specializes in Kura salmon.

FAO figures for 2019 indicate that 0.342 million sturgeon, 0.168 million Caspian (Kura) salmon, and a total of 3.927 million valuable fish fry were released into natural basins. Information from the Ministry of Ecology and Natural Resources shows that 7-9 million sturgeon juveniles and approximately 200,000 salmon fry are released annually [7]. The difference in figures may be due to different years and reporting approaches, but both sources confirm that artificial augmentation occupies an important place in the country's politics.

One of the most important stages in the artificial reproduction process is the correct selection of the place and time for the release of the fry. The fry should be released at a stage where they can adapt to the water temperature, salinity, food base, and hydrodynamic regime. The normal formation of landing behavior after release, especially in transient species, strongly influences subsequent survival rates. Therefore, fish breeding measures should be accompanied by continuous monitoring and tagging programs.

Despite artificial enrichment measures, the stable recovery of migratory fish stocks is hampered by a number of problems. The first problem is the limited stock of parent fish [8]. As natural populations decline, it becomes more difficult for factories to obtain mature, productive individuals. This increases the risk of reusing individuals with the same genotype and can lead to a decrease in genetic diversity.

The second important problem is technological and veterinary in nature. During the incubation and initial rearing stages, slight deviations in temperature, oxygen, water chemistry, and sanitation lead to high losses. Sturgeons and salmonids are particularly vulnerable during the larval stage. The spread of diseases, poor feed quality, or failure to carry out timely prophylaxis weaken the quality of the breeding material.

The third problem is ecological. After the factory-raised fry are released into the natural basin, most of them face unfavorable environmental factors. Disturbance of ecological flow in rivers, pollution, transformation of beds, and weakening of the food base in the sea reduce their survival rate. If the natural habitat is not restored, the effect of artificial reproduction remains limited.

The fourth problem is that migration routes are closed [9]. Even if fish are caught in a factory and released into the sea, there must be passageways in rivers to allow them to return to their natural breeding grounds once they reach sexual maturity. Dams and hydroelectric dams interrupt these routes, so the natural cycle is not completed. In this case, the population becomes permanently dependent on the plant, which is not an ecologically desirable model.

The fifth problem is that management and monitoring are not sufficiently integrated. An effective program requires the marking of released juveniles, registration of returning producers, genetic analyses, and monitoring of river and marine habitat indicators. Without this information, it is not fully determined which method is more effective, and which species cause the most losses at which stage.

4. Conclusion

While artificially increasing migratory fish populations is an important conservation tool, it must be complemented by an ecosystem approach. The main priorities in this area are the protection of the parent fish gene pool, the ecological restoration of water bodies, the prevention of illegal fishing, the implementation of fish passage devices, and the strengthening of the scientific observation system.

The analysis shows that reproductive migration of fish is one of the main biological mechanisms of their population sustainability. In migratory fish, this process provides interaction between marine and river ecosystems and is directly related to reproduction, which is the most sensitive stage of the life cycle.

Among the migratory fish in Azerbaijani waters, sturgeons and salmonids occupy a special place. These species are of great importance both in terms of biodiversity and economic value. However, their stocks have been seriously reduced as a result of the loss of natural spawning grounds, the closure of migration routes, pollution, and illegal hunting.

In the current situation, artificial propagation is an important tool for the conservation and restoration of these species. Specialized fish breeding facilities operating in Azerbaijan ensure that sturgeon and salmon fry are raised and released into natural reservoirs [10]. However, the effectiveness of artificial propagation directly depends on the condition of the natural habitat.

Therefore, future measures to protect migratory fish should be comprehensive. Artificial breeding programs should be coordinated with the restoration of river ecosystems, the opening of migration routes, genetic monitoring, the application of modern biotechnological methods, and management at the basin level. Only in this case will it be possible to achieve long-term restoration of migratory fish stocks in Azerbaijani waters.

Author Contributions

Y. Seyidzade prepared the manuscript, conducted the literature review, and wrote the original draft. N. Guliyeva supervised the study, provided scientific guidance, and critically revised the manuscript. Vitaliy Bekh reviewed the manuscript and contributed to its improvement through editing and constructive comments. All authors have read and approved the final manuscript.

Conflict of Interest

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Review Article

Analysis of the Current State of Economic Development of the Agricultural Sector and Research of Priority Directions

Rima Sh. Nasrullayeva[1] and Gulana M. Aliyeva[2]

[1]Department of Agribusiness and Management, Institute of Agrarian Problems, Ministry of Science and Education of the Republic of Azerbaijan, Ganja AZ2000, Azerbaijan

[2]Naftalan Oil and Surfactants Laboratory, Institute of Ecology and Natural Resources, Ministry of Science and Education of the Republic of Azerbaijan, Ganja AZ2000, Azerbaijan

Abstract

In modern times, the economic development of the agricultural sector constitutes one of the main pillars of the country's overall economic security and macroeconomic stability. The research analyzes the current state of agriculture and comprehensively examines the sector's share in gross domestic product and its growth dynamics. At the current stage, the application of innovative technologies to increase competitiveness in the agricultural sector is considered one of the most important priorities. Analyses show that increasing efficiency in the agricultural sector depends on the volume of direct investments and the optimization of state support mechanisms. The article assesses the changes in the structure of the agro-industrial complex and the level of development of the processing industry based on statistical indicators. Ensuring food security and supplying the domestic market with local products is the main objective of the research. In modern conditions, efficient use of water resources and preservation of soil fertility are crucial factors for the sustainable development of agriculture. The study shows that involving small and medium-sized farms in cooperative processes can significantly boost productivity. In order to expand the export potential of the agricultural sector, it is necessary to establish quality control systems in accordance with international standards. Improving logistics infrastructure and establishing a "field-to-fork" chain are of great importance in terms of preventing crop losses. The real economic effects of subsidies and tax breaks applied within the framework of the state's agrarian policy are explained in detail in the work. The application of digital agriculture and "smart village" concepts creates new opportunities in field management. The study examines the negative impacts of climate change on agriculture and ways to improve risk insurance mechanisms. Strengthening human resources potential in the agricultural sector and integrating scientific achievements into production are highlighted as priority areas. Analysis of the market situation shows that special attention should be paid to branding and marketing strategies in order to compete in the global market. The role of the agricultural sector in the socio-economic development of regions is assessed in the context of reducing unemployment and providing employment. As a result of the research, it is proposed to introduce modern management models and improve the investment climate for the development of the agricultural sector. Correctly identifying priority areas will create conditions for intensive development of agriculture in the future. Finally, the main points of the strategic roadmap for agricultural modernization and the expected economic dividends are summarized. This study can serve as a scientific source for the formulation of agrarian policy and the preparation of sectoral programs. In conclusion, it is noted that the development of the agrarian sector is a decisive factor in the diversification of the country's non-oil sector.

Keywords: agricultural economics, agro-industrial complex, sustainable development strategy, food security, innovative agricultural technologies

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1. Introduction

In the modern world economy, the agricultural sector is not only a sector that produces food products, but also has strategic importance as a guarantor of national security and social stability. In the context of globalization, the economic independence of countries is directly measured by the level of agricultural development and the degree to which the domestic market is supplied by local production. Geopolitical changes and disruptions in global supply chains in recent years have made the modernization of the agricultural sector an urgent issue for all countries. In the strategy for diversifying the non-oil sector of the Azerbaijani economy, the agricultural sector has been identified as one of the areas with the highest potential [1]. Our country's favorable climatic conditions, rich soil resources, and ancient agricultural traditions create a solid foundation for the intensive development of this sector.

The development of the agricultural sector is an important social factor that directly affects the increase in employment in rural areas and the regulation of urbanization processes. The main task facing the agricultural sector today is to completely abandon the extensive development model and transition to a science-intensive development path. The challenges of the modern era necessitate digital transformation in agriculture and the implementation of the concepts of "Smart Village" and "Smart Farm" [2]. The relevance of the research is also related to the need to develop new adaptation mechanisms to global problems such as water scarcity and soil erosion caused by climate change [3].

The priorities of the state's agrarian policy are aimed at supporting agricultural producers, increasing the efficiency of subsidies, and accelerating the flow of investment into the sector [4]. The development of the agricultural processing industry plays a crucial role in creating a value-added chain and transitioning from raw material exports to finished product exports [5]. In accordance with the requirements of a market economy, cooperation between farms and the expansion of the activities of agroparks serve to increase productivity. Improving insurance mechanisms in the agricultural sector is an important financial tool to protect producers from natural disasters and other risks.

In the modern stage of economic development, innovations applied in the agricultural sector aim not only to increase yields but also to produce environmentally friendly products. In order to remain competitive in the global market, the process of obtaining international quality certificates and branding of local products must be accelerated. The purpose of the research is to deeply analyze the current state of the agricultural sector, identify factors that hinder development, and suggest solutions. The dynamics of the sector's economic indicators allow us to objectively assess the results of the implementation of state programs.

Expanding scientific research in the agricultural sector and creating new varieties and breeds increases the quality of selection work. The availability of information and advisory services to farmers is one of the main factors accelerating the transfer of innovations to the field. Diversifying export markets reduces the foreign dependence of local products and stimulates foreign exchange inflows. The study also focuses on sources of financing for the agricultural sector, the role of soft loans, and the participation of the banking sector in this process.

Expanding the network of logistics centers and cold storage complexes prevents seasonal price fluctuations. The implementation of modern irrigation systems not only minimizes water loss but also increases the volume of produce obtained from a single area many times over. The development of the agricultural sector also means the renewal of rural infrastructure and an increase in the living standards of the population. This presented work proposes scientific and practical recommendations for the formation of a competitive structure of agriculture. This presented work proposes scientific and practical recommendations for the formation of a competitive structure of agriculture.

The issues raised in the introduction outline the future development model of the agricultural sector. A comprehensive examination of all these factors is of great importance for the full realization of the country's economic potential. In conclusion, it should be noted that the sustainable development of the agricultural sector is an integral part of the state's long-term economic strategy. This research paper presents a scientific view on the deepening of agrarian reforms against the backdrop of contemporary economic realities.

2. Relevance of the Topic

Rapid changes and global challenges in the modern world economy have made the development of the agricultural sector a strategic priority for every state. The issue of meeting the food needs of a growing world population further increases the relevance of agricultural development. Increasing agricultural productivity in the face of global climate change and limited natural resources requires new approaches. The issue of food security is currently considered an integral part of national security, and this topic remains relevant [6]. The disruptions in global supply chains amid the pandemic and regional conflicts have necessitated increased domestic production. The agricultural sector acts as one of the most important economic drivers in the development strategy of Azerbaijan's non-oil sector. The diversification of the country's export potential directly depends on the production of competitive agricultural products.

At the modern stage, the digitalization of agriculture and the application of "Smart Agriculture" technologies are among the main factors determining the scientific and practical relevance of the topic [2]. The efficient use of land and water resources is the basis of the research in terms of sustainable development principles. Expanding market access opportunities for small and medium-sized farms operating in the agricultural sector is still an urgent issue awaiting a solution. Increasing the role of the agricultural sector in the socio-economic development of regions is of great importance for increasing the employment level of the population. Optimizing state support and subsidy mechanisms is very relevant in terms of increasing the motivation of agricultural producers. Expanding the network of processing enterprises in the agro-industrial complex is important to prevent the loss of raw materials.

Improving the investment climate and attracting local and foreign investment to the sector is crucial for the success of agrarian reforms [4]. The tightening of international requirements for the quality and safety of agricultural products makes standardization issues in this area relevant. Risk management in the agricultural sector and the implementation of an agricultural insurance system are important factors in ensuring the financial stability of farmers. The integration of scientific achievements and innovations into the production process is necessary to overcome the technological backwardness of the sector. The weakness of cooperative relations in agriculture creates certain difficulties in establishing a unified production and sales chain. The lack of logistics infrastructure and cold storage systems negatively affects the cost and quality of the product.

Branding and promotion of the "Made in Azerbaijan" brand in global markets increases the foreign competitiveness of our agricultural products [5]. Attracting young specialists to the agricultural sector and modernizing the personnel training system remain urgent problems. Rebuilding irrigation systems based on modern technologies (drip and sprinkler) is the most effective way to combat the threat of water scarcity. The development of the agricultural sector also serves to improve the quality of life in rural areas and social infrastructure. Reducing import dependence and stimulating import-substituting production means strengthening economic sovereignty. A comprehensive examination of these issues in research forms the scientific basis for improving agrarian policy.

The increasing demand for ecologically clean and biological agricultural products in modern times is making changes in the production structure urgent. Statistical analysis of the development rates of the agricultural sector is necessary for the preparation of future forecasts and strategic planning. One of the main directions of the research is the assessment of the implementation status of state programs and their impact on sectoral development. Changing market conditions require the development of flexible decision-making mechanisms for farmers. Consequently, analyzing the current state of the agricultural sector and determining priorities is the most important factor ensuring the country's sustainable economic growth. This study aims to demonstrate scientific solutions to the listed pressing issues and provide practical recommendations.

Purpose of the study: It consists of comprehensively analyzing the current state of economic development of the agricultural sector, identifying existing problems, and determining strategic priority areas on a scientific and practical basis to increase the competitiveness of the sector.

Research object: The agrarian sector of the Republic of Azerbaijan is a system of production and economic relations that determines the dynamics of economic development of economic entities operating in this field.

Research methods: The research process used methods such as systematic and comparative analysis, statistical grouping, economic-mathematical modeling, logical generalization, and correlation of quantitative indicators with qualitative changes.

3. Materials and Methods

The material base of the study is made up of official data of the State Statistical Committee of the Republic of Azerbaijan, reports of the Ministry of Agriculture, and reviews of international organizations related to the agrarian sector [3], [7]. When analyzing the statistical indicators of the last ten years, it is clear that the agricultural sector has maintained its share in non-oil GDP stably and has demonstrated a growth trend [7]. Analyses show that although the share of intensive technologies in the production of crop products is increasing, farms using extensive methods still dominate. During the discussions, it became clear that the agroparks and large farms established in the country significantly outperform small family farms in terms of productivity indicators [7]. However, the role of small farms in the country's overall food supply remains crucial, and this contrast proves the need for structural reforms in the sector.

Although subsidized fuel and fertilizer subsidies implemented by the state play an important role in reducing farmers' costs, the fact that subsidies are provided to the cultivated area rather than directly to the final product leads to inefficiency in some cases [4]. One of the important issues discussed is that the level of technical equipment in the agricultural sector does not meet modern requirements. An outdated fleet of tractors and combines causes serious losses during harvest, which reduces economic efficiency. Research materials confirm that the simplification of leasing mechanisms has increased the rate of renewal of agricultural machinery by 20% in recent years [7]. Discussions on irrigation water management show that it is impossible to solve the problem of water scarcity without abandoning traditional irrigation methods.

Productivity is 30–40% higher in areas where modern irrigation systems are applied, which shows that investments pay off in a short time [3]. The weak breeding work in the livestock sector and the low milk yield of local breeds are among the main topics of discussion. Adapting imported high-yielding breeds of animals to local conditions and establishing proper feed rations is still considered risky from an economic perspective. The level of development of the processing industry in the agricultural sector weakens the place of agricultural products in the value chain. Raw material exports bring 3–4 times less foreign exchange to the country than finished product exports, which requires a change in the economic priorities of the sector.

The poor development of logistics infrastructure, especially the "cold chain" system, leads to the fact that up to 25% of fruit and vegetable products spoil before reaching the consumer from the field. During the discussions, it was emphasized that there is still a great need for educational work in the field of implementing the agrarian insurance mechanism. Farmers' limited access to bank loans and onerous collateral requirements slow the flow of private capital into the sector. Although increasing the volume of state agricultural loans and lowering interest rates is a positive step, control over the intended use of these funds should be strengthened. Research materials show that the transition to organic agriculture promises great prospects for Azerbaijan's access to European markets [3].

However, excessive use of pesticides leads to soil degradation and product quality falling short of international standards. Another problem discussed is the lack of professional agronomists and veterinarians in rural areas. The mismatch between the practical knowledge of personnel trained by higher education institutions and production requirements is creating a personnel crisis in the field. Although the implementation of the Electronic Agricultural Information System (EAIS) has increased transparency in management, older generation farmers have difficulty using this system due to low digital literacy [2]. Branding and registration of local products under geographical indications is noted as a factor that increases their competitiveness in domestic and foreign markets [5].

Despite improvements in the legislation on cooperatives, farmers' reluctance to unite prevents them from fulfilling large-scale orders [4]. The discussions noted that the existence of monopoly elements in agricultural markets creates a sharp difference between the price of the product purchased from the producer and the retail price. This situation both reduces the producer's income and negatively affects the pocket of the end consumer. The efficiency of agroparks is assessed as a factor that directly affects the socio-economic development of the region in which they are located. In the face of climate change, the introduction of new drought-resistant plant varieties is a key task facing scientific research institutions [3].

Finally, the materials and discussions section confirms that the future of the agricultural sector depends on full digitalization and the integration of green technologies. Each discussed item provides a scientific basis for a more efficient development of the country's agrarian policy. The dynamics of statistical data show that with proper management, Azerbaijan can become the main agricultural center of the region in the next decade. The results of the study prove that infrastructure modernization and personnel training should be at the forefront in order to realize existing potential. All discussions come to a single conclusion: the agricultural sector is the backbone of Azerbaijan's non-oil economy. Each analysis in this section provides a solid foundation for determining future priorities.

The table below summarizes the main directions characterizing the modern state of economic development of the agricultural sector, the analysis of the current situation, and the development prospects.

Table 1. Economic development indicators and analysis of the agricultural sector.

Development Directions	Analysis of the Modern Situation	Current Problems	Priority Goals
Share in GDP and growth	Stable growth dynamics are observed in the non-oil sector.	Extensive methods are still widespread.	Increasing added value through intensive development.
Technological equipment	Introduction of new techniques by modern agroparks.	Deterioration and losses of small farmers' equipment.	Simplification of leasing terms and transfer of innovations.
Use of water resources	Starting the implementation of drip and sprinkler systems.	High water loss during traditional irrigation (up to 40%).	Full implementation of "smart irrigation" and cost-effective technologies.
State support and financing	Transparency of subsidies through ECTIS.	Banks' collateral requirements and the level of availability of loans.	Optimization of subsidies according to final product output.
Export potential	Leadership in the region in fruit and vegetable exports (tomatoes, hazelnuts, etc.).	Weakness in standardization and international certification (GlobalGAP).	Diversification of export markets and branding.
Processing industry	Raw material production exceeds processing capacity.	Lack of logistics centers and the "cold chain" system.	Transition to full processing of raw materials and export of finished products.
Personnel and science	Agrarian education reforms and stimulation of young specialists.	Discrepancy between theoretical knowledge and practical requirements.	Integration of scientific research into production and consulting services.
Cattle-breeding	State programs to increase the share of pedigree livestock.	Low productivity of local animal breeds.	Strengthening breeding work and improving the feed base.

As can be seen from the table, the current state of the agricultural sector necessitates a transition to a stage of digitalization and intensification. The implementation of priority areas is the main factor ensuring both the country's internal food security and foreign exchange inflow.

4. Results and Discussion

Conducted research and multidisciplinary analyses show that the agricultural sector is a strategic sector that plays a fundamental role in the sustainable development of Azerbaijan's non-oil economy. Against the backdrop of modern economic realities, the current state of agriculture simultaneously embodies both great potential and structural problems that need to be addressed. As a result of the study, it should be noted that the future development of the agricultural sector directly depends on the intensification and rapid integration of scientific and technological innovations into the production process. As a result of the agrarian reforms implemented in the country, management mechanisms have been improved, and the degree of transparency in the sector has increased significantly. The full implementation of the Electronic Agricultural Information System (EAIS) has become a key factor in ensuring the targeting of state support and the efficient distribution of subsidies [2]. However, statistical data proves that productivity in small farms is still below the world average.

One of the most important conclusions of the study is that the extensive development model should be completely abandoned, and the volume of output from a single area should be increased [3]. In an era of limited water resources, the application of modern irrigation technologies is no longer an option, but a necessity. To prevent soil salinization and erosion, land reclamation and irrigation systems must be radically rebuilt. Expanding the activities of agroparks creates conditions for the successful implementation of the clustering model in agriculture and increases the competitiveness of products. Economic analyses show that cooperation among agricultural producers is the most effective mechanism for facilitating their access to financial resources and sales markets [4].

To expand the export geography of the agricultural sector, the certification process in accordance with international standards (GlobalGAP, HACCP) should be accelerated [3], [5]. It has become known that products exported in raw form bring much less income to the country than finished products. For this reason, the development of the processing industry and the establishment of small and medium-sized processing enterprises in rural areas should be a priority [5]. The lack of logistics infrastructure, especially cold storage complexes, is a major factor in increasing crop losses, which directly reduces farmer profitability. Tax incentives applied within the framework of the state's agrarian policy are an important tool that stimulates investment in the sector. Further improvement of the agricultural insurance system will ensure farmers' resilience to risks arising from natural disasters [4].

To increase productivity in the livestock sector, the quality of artificial insemination and breeding work must be raised to a new level. Strengthening the feed base and efficient use of pastures can help reduce the cost of livestock products. The application of digitalization, drone technologies, and satellite monitoring systems in agriculture increases the accuracy of management decisions. The research results show that the network of agricultural advisory services should be expanded, and farmers should be provided with access to modern knowledge. Close cooperation between higher and vocational education institutions and agribusinesses can solve the problem of staff shortages. Protecting the domestic market and supporting import-substituting production are the main guarantees of food security.

The production of biological and organic agricultural products holds great promise for Azerbaijan in the context of a "green economy" [3]. Recycling agricultural waste both protects the environment and creates an additional source of income. The collateral conditions applied by the banking sector when providing loans to the agricultural sector should be made more accessible to farmers. Improving rural infrastructure within the framework of regional development programs is an important factor in preventing the flow from rural to urban areas. State procurement and financial support for scientific research in the field of breeding climate-resistant plant varieties should be increased [3]. The establishment of a fully closed "farm-to-table" chain serves to provide consumers with high-quality and safe food.

Properly establishing branding and marketing strategies in the agricultural sector will allow local products to take their place in the global market. The introduction of a "results-based" approach to the provision of subsidies will dramatically increase the efficiency of public funds. The conclusion of the study emphasizes that the development of the agrarian sector is not only economic, but also has a broad social significance. The attractiveness of the investment environment for the modernization of the sector must be constantly kept in focus. Adapting international experience in the field of agricultural innovation to the country's conditions will prevent waste of time.

Increasing the share of electronic platforms in the trade of agricultural products increases the direct income of farmers by reducing the number of intermediaries [2]. Optimizing the functioning of the land market will lead to more efficient use of land resources. Ensuring gender equality in the agricultural sector and involving women in agribusiness increases social inclusion. Measuring the economic efficiency of the digital transformation of the agricultural sector remains a relevant direction for future research.

5. Conclusion

In conclusion, it should be noted that Azerbaijan's agricultural sector has entered a new stage of its growth. Consistent implementation of the identified priority areas will both strengthen the country's food independence and lead to a significant increase in non-oil exports [6]. The coordinated activities of the triangle of state, science, and farmers are the key to sustainable progress in the agricultural sector. Research proves that a competitive agricultural sector will continue to be one of the key indicators of Azerbaijan's economic strength [1]. Every successful step in this area is an investment that serves the social well-being of the country and the security of future generations. Thus, an analysis of the current state of the agricultural sector once again confirms its irreplaceability for the country's economy.

The novelty of the research work: It consists of a comprehensive analysis of the development dynamics of the agricultural sector against the backdrop of climate change and digital transformation, and the substantiation of specific economic mechanisms and priority directions with new scientific approaches for the transition to an export-oriented intensive development model, along with the food security of the domestic market.

The applied significance of the research work: The scientific and practical recommendations put forward can be used in the preparation of state programs in the agricultural sector and in the development of strategic roadmaps to increase the economic efficiency of farms. At the same time, the results of the study are a favorable basis for application in the process of managing agricultural producers' risks and improving access mechanisms to export markets.

Economic efficiency of research work: It is characterized by increasing profitability from a single area by optimizing costs in the agricultural sector and minimizing crop losses. The application of advanced intensive development methods creates the basis for the formation of a value-added chain and a significant increase in export revenues by increasing the degree of processing of agricultural products. As a result, the implementation of these proposals directly contributes to both increasing farmer incomes and increasing tax revenues from the agricultural sector to the state budget.

Author Contributions

Both authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Review Article

Taxonomic Structure and Quantitative Indicators of Benthic Invertebrates of the Varvara Reservoir in the Kura Cascade

Ali I. Huseynov[1]

Department of Natural Sciences, School of Advanced Technologies and Innovation Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan

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Abstract

This review summarizes published information on the taxonomic structure and biomass distribution of macrozoobenthic communities in the Varvara Reservoir, Azerbaijan. This basin, the last link of the Kura cascade, is a unique ecosystem with an average shallow depth of 3–4 meters and an extensive Phytophilous vegetation cover of 89.9%. Modern literature emphasizes that macrozoobenthos are sensitive bioindicators in determining water quality and assessing ecosystem health, and that they respond rapidly to environmental stress factors. This review is based on published studies that reported systematic sampling of five major biotopes (lithophile, psammophile, pelophile, pelo-psammophile, and phytophile) within the Varvara Reservoir. According to the reviewed literature, 113 species and forms of invertebrates belonging to 22 systematic groups have been reported from the reservoir. Among these organisms, chironomid larvae constitute 38.1% of the species diversity with 43 species, providing absolute dominance in taxonomic terms. Mollusks constitute the dominant component of the benthic biomass and represent the principal biomass component of the ecosystem. In particular, Phytophilous biotopes cover a large part of the basin, forming both a safe shelter and an abundant food source for benthic organisms. Diurnal water level fluctuations and cold water flows associated with the operation of the Mingachevir HPP directly affect the stability and metabolic processes of benthic communities in the coastal zone. The species Paramysis lacustris and Pontogammarus robustoides introduced to the basin have successfully adapted to the ecosystem and qualitatively enriched the food base of important fish species. The results reveal the high biological potential of the reservoir. Collectively, the reviewed studies indicate the high biological potential of the reservoir and provide a scientific basis for sustainable water-resource management and fishery conservation. In addition, the impact of high population densities of Melanopsis mollusks on parasitological risks in the region was also assessed.

Keywords: Varvara Reservoir, macrozoobenthos biomass, bioindicator

1. Introduction

Macrozoobenthos communities are one of the most sensitive biological tools used to assess the health and water quality of river and reservoir ecosystems [1]. Due to their close association with bottom sediments and their limited mobility, macrozoobenthic organisms serve as valuable biological indicators, reflecting long-term physical and chemical changes in aquatic ecosystems and functioning as a "living archive" of environmental conditions. Modern scientific literature emphasizes that macrozoobenthos react very rapidly and significantly to environmental stress factors such as anthropogenic pollution and the construction of reservoirs [2], [3]. Therefore, it has become a global standard to determine the ecological status of a water body not just by instantaneous physical measurements, but by monitoring changes in the structure of macrozoobenthos communities. In particular, chironomid larvae, oligochaetes, and various mollusk species are considered the most reliable bioindicators of the degree of water pollution and oxygen regime.

The cascade of reservoirs constructed along the Kura River, Azerbaijan's largest and most important waterway, plays a strategic role in conserving the country's freshwater biodiversity and managing its water resources [4].

Historical studies on the hydrofauna of the Kura River have revealed that the species diversity, which was limited in the river environment before the construction of reservoirs, has been enriched with the transformation of ecosystems into lake environments [5]. The Varvara reservoir (Figure 1), one of the last and shallowest links of the cascade, has been systematically studied by Azerbaijani hydrobiologists since the 1950s [6]. The fundamental works of scientists such as Professor A.H. Gasimov and A.R. Khalilov have established the patterns of distribution of invertebrates in this basin on a scientific basis. Determining the biological potential of the Varvara reservoir is not just an academic interest, but is also important for protecting the food base of critically important fish in the basin [7].

Figure 1. Location map of the Varvara reservoir.

The main feature that distinguishes the Varvara reservoir from other water bodies in the Kura cascade is its unique hydrological regime, in which the water coming from the Mingachevir Hydroelectric Power Plant (HPP) is regulated on a daily basis. This operating mode creates a constant ecological stress on benthic organisms in the coastal zone, causing sudden and sharp fluctuations in water level every day. Although Varvara's shallow structure, averaging 3–4 meters, and dense phytophyte cover reaching 90% act as a refuge against such factors, it has not yet been fully clarified how this mechanism works by modern ecological criteria.

The aim of this review is to summarize and synthesize the available scientific literature on the taxonomic structure, species diversity, biomass distribution, and ecological significance of macrozoobenthic communities in the Varvara Reservoir. Particular attention is given to habitat-specific community composition, hydrological influences, and the importance of benthic organisms for fisheries and ecosystem management.

2. The Role of the Varvara Reservoir's Food Resources in Fisheries

The Varvara Reservoir is a specific link in the cascade on the Kura River, and the macrozoobenthos communities formed here play a necessary strategic role in the nutrition of fish of great importance, both in terms of quantity and quality. Studies reveal that mollusks, which make up the bulk of the biomass in the basin, play a crucial role in the diet of fish, but their heavy calcium-carbonate shells can make energy transfer somewhat difficult [8]. However, the massive development of 43 species of chironomid larvae and oligochaetes in muddy soils creates a high-calorie and easily digestible food environment, especially for young fish. The 1.00 g/m2 contribution to the annual biomass of successfully introduced mysids and semi-floating crustaceans, such as Pontogammarus robustoides, directly contributes to the diversification of the food base and the increase in fisheries productivity. The Phytophilous zone serves as a favorable source for the restoration of the reservoir's natural food resources. In order to use the food base more efficiently in the future and increase fishing potential, it is essential to manage the hydrological regime and biological resources of the reservoir on a scientific basis. At the same time, maintaining constant control over the parasitological situation that may arise due to the mass density of mollusks is a task of strategic importance in terms of protecting the health of fish populations [8].

3. Literature Sources

This review is based on published scientific literature concerning the macrozoobenthic communities of the Varvara Reservoir. Relevant information was compiled from peer-reviewed journal articles, monographs, regional hydrobiological reports, and other published sources describing the taxonomic composition, biomass, ecological characteristics, and habitat distribution of benthic invertebrates. Particular attention was given to studies reporting observations from the five principal biotopes of the reservoir (lithophile, psammophile, pelophile, pelo-psammophile, and phytophile).

Information regarding species composition, biomass, dominant taxonomic groups, hydrological conditions, and ecological characteristics was extracted, compared, and synthesized to provide an integrated overview of the current knowledge on the reservoir's macrozoobenthic fauna. Taxonomic nomenclature follows the terminology adopted in the cited literature [9].

4. Taxonomic Composition and Ecological Characteristics

Published studies have documented 113 species and forms of benthic invertebrates representing 22 systematic groups in the Varvara Reservoir. Collectively, these studies demonstrate that the transformation of the Kura River into a reservoir ecosystem has promoted the establishment of a diverse limnophilic macrozoobenthic community.

The reviewed literature consistently identifies chironomid larvae as the most species-rich group, comprising 43 species (38.1% of the recorded fauna). Their abundance in pelophilous habitats highlights their ecological importance as a major food resource for benthic-feeding fish.

Published biomass estimates indicate that mollusks constitute approximately 71–89% of the total benthic biomass within the reservoir. Several studies attribute this dominance to environmental conditions favorable for the development of bivalves and gastropods. Among these, *Melanopsis praerosa* has been reported to reach particularly high population densities.

According to previous studies, seasonal and hydrological factors strongly influence macrozoobenthic community composition. Higher abundances are generally observed during autumn and winter, whereas summer populations decline because of elevated temperatures and insect emergence [10], [11].

Overall, the reviewed literature indicates that species with greater tolerance to environmental disturbance tend to dominate under conditions of frequent hydrological fluctuations (Table 1).

Table 1. Summary of published information on species richness and biomass characteristics of macrozoobenthos in the principal biotopes of the Varvara Reservoir.

Biotope Name	Number of Species	Biomass Range (g/m²)	Dominant Taxonomic Groups
Phytophilous	63	1,298 – 10,650	Mollusks, Chironomid larvae
Lithophilous	25	3,530 – 36,920	Leeches, Caddisfly larvae
Psammophilous	24	0,870 – 35,533	Mollusks, Oligochaetes
Pelophilous	32	0,229 – 1,963	Chironomid larvae, Oligochaetes
Pelo-psammophilous	28	0,015 – 19,217	Bivalve mollusks

4. Conclusion

The available literature indicates that the Varvara Reservoir supports a diverse and productive macrozoobenthic community that plays an important ecological role in sustaining fish populations. Existing studies also highlight the influence of hydrological regulation on benthic community structure. Future investigations and long-term monitoring will further improve understanding of ecological changes within this reservoir.

In conclusion, the present findings indicate that the Varvara Reservoir currently supports abundant macrozoobenthic communities that constitute a significant food resource for fish. However, long-term monitoring is required to evaluate temporal stability and responses to hydrological regulation.

Author Contributions

Ali I. Huseynov conceived the study, conducted the literature review, performed the analysis, interpreted the findings, and prepared the original draft of the manuscript. Dr. Mahmud Humbatov supervised the research, provided scientific guidance throughout the study, critically reviewed and edited the manuscript, and approved the final version for publication.

Conflict of Interest

The authors declare no conflicts of interest.

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Review Article

CRISPR Technology in Agriculture: Applications, Challenges, and Bioethical Considerations

Khadija I. Aydamirova✉

Department of Natural Sciences, School of Advanced Technologies and Innovation Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan

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Abstract

The growing global food demand in agriculture, mitigating the effects of climate change, and creating sustainable production systems have necessitated the application of modern biotechnology. In recent years, CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology has been in the spotlight as one of the most promising approaches in the field of gene editing. This technology allows for highly precise changes in plant and animal genomes, thereby increasing productivity, quality, and potential uses in animal husbandry. In addition, bioethical issues arising from the application of the technology, possible impacts on ecological balance, protection of biodiversity, consumer acceptance, animal welfare, and current problems related to the regulation of genetically modified organisms are discussed.

Keywords: CRISPR, gene editing, agriculture, plant breeding, productivity, bioethics, animal welfare, biosafety

1. Introduction

One of the most significant steps in the application of the CRISPR/Cas system in plants is the efficient delivery of editing reagents into plant cells, resulting in the occurrence of genome editing events. The main editing reagents used for this purpose include DNA, RNA, and ribonucleoprotein complexes (RNP). These reagents can be introduced into plant cells by various methods. The most widely used methods are protoplast transfection, Agrobacterium-mediated T-DNA transformation, and particle bombardment (biolistic method). Protoplast transfection is mainly used for transient gene expression. In contrast, Agrobacterium-mediated transformation and particle bombardment are the primary and most widely used delivery methods for generating edited plants [1].

The most commonly used genetic material for plant genome editing is CRISPR/Cas DNA. Once introduced into a cell, the DNA cassette expressing the Cas protein and sgRNA can either be degraded and lost, or it can be randomly integrated into the plant genome. In the traditional DNA transformation approach, CRISPR/Cas DNA is introduced into recipient cells by Agrobacterium-mediated transformation or particle bombardment. This DNA is then integrated into the plant genome through the selection of marker genes and expressed, leading to genome editing. This strategy has been used in many types of plant genome editing. However, the permanent placement of CRISPR constructs and marker genes in the genome can have certain negative effects. In particular, this situation can lead to an increase in off-target changes, which may ultimately limit the commercial applications of the technology [1].

To avoid these problems, it is possible to obtain transgenic-free derivatives, which are mainly obtained through genetic segregation. As a result of self-pollination or crossing of plants, non-transgenic mutants are obtained by selecting progeny that do not carry the CRISPR construct. For example, Gao and colleagues have used a fluorescent marker cassette to monitor the presence of a CRISPR/Cas9 construct. Another interesting approach is to use suicide genes called CMS2 and BARNASE. These genes facilitate the selection of non-transgenic plants by eliminating transgene-bearing pollen and embryos produced in the T0 plant. However, the genetic segregation method is not suitable for vegetatively propagated plants. For example, this method cannot be used in plants such as potatoes, cassava (Manihot esculenta), and bananas (Musa species). In addition, there is a possibility that certain fragments of the DNA construct used may integrate into unknown regions of the genome [1].

Transient gene expression-based delivery of CRISPR reagents is considered an alternative approach to achieve transgene-free genome editing. This method does not involve classical selection steps using herbicides or antibiotics, and as a result, some regenerated plants are edited without any integration of foreign DNA into the genome. This method was first applied to wheat plants. In that study, the CRISPR/Cas9 plasmid was introduced into immature wheat embryos via particle bombardment, and the plants were then regenerated without the application of selection pressure. This approach reduced the regeneration time by approximately 3–4 weeks through tissue culture. The mutation rate was comparable to that of traditional DNA integration methods with selection. One of the necessary results is that 86.8 percent of T0 mutants did not contain transgenes [1].

In addition, DNA base editors have also been introduced into plants by transient delivery. These editors include cytidine base editors and adenine base editors, and have been used to achieve non-transgenic nucleotide substitutions. In addition to biolistic delivery, non-transgenic editing has also been achieved by other methods. For example, genome editing has been successfully achieved through protoplast transformation in tetraploid potato and tobacco protoplasts, as well as transient expression of the CRISPR/Cas system in tobacco via Agrobacterium. These approaches demonstrate that CRISPR technology has the potential to enable the development of safer and more efficient methods for plant genome editing [1].

The aim of this review is to evaluate the current and potential applications of CRISPR technology in agriculture, to explore its contribution to improving crop and livestock production, and to discuss bioethical and biosafety issues related to the application of the technology.

2. Improving Plant Quality and Productivity

CRISPR/Cas9 gene editing technology has become one of the most important tools in agriculture in recent years to improve the quality and productivity of plants. As a result of the development of this technology and the more accurate study of plant genome data, researchers have been able to change specific genes in plants with high precision. Compared to traditional breeding methods, CRISPR/Cas9 allows for faster and more effective results [2].

In modern times, CRISPR/Cas9 technology has opened up new possibilities in this field. Through this method, genes that have important functions in plants can be precisely edited. As a result, plant productivity is increased, quality is improved, and the selection process is carried out more efficiently. With the help of CRISPR/Cas9 technology, it is possible to improve the external and internal quality indicators of plants. External quality characteristics include the size, color, external structure, texture, and appearance of fruits and seeds. Internal quality characteristics include the amount of protein, carbohydrates, starch, fats, vitamins, and various bioactive substances [3]. For this reason, CRISPR/Cas9 technology is considered by many breeders as one of the most promising and widely applied strategies [2].

The studies conducted examined the achievements achieved as a result of the application of CRISPR/Cas9 technology in various plant species and analyzed the current status of this technology in improving the quality of plants. In addition, the shortcomings and difficulties encountered during the application of this method were also considered, and ideas and directions for future development prospects were put forward [2].

3. Regulation of Gene Expression and Editing of the Plant Genome

Recent studies show that most plant breeding work using CRISPR/Cas technology has focused primarily on the coding parts of genes. In contrast, relatively little research has been done on the regulatory regions that regulate gene expression and control gene activity. However, these regulatory regions are important elements that determine when and at what level genes are expressed and can have significant effects on plant traits [4].

Engineered nucleases were incorporated into a non-specific nuclease domain fused to a sequence-specific DNA binding domain. Such fused nucleases form a structure that can precisely cleave the target gene, and the breaks are repaired by NHEJ or HDR. This structure is called “genome editing”. Before the advent of CRISPR-Cas9 technology, genome editing used first-generation genome editing tools such as meganucleases, zinc finger nucleases (ZFNs), and TALENs [5]. However, these systems required complex, time-consuming, and tedious procedures to achieve high target specificity. CRISPR-Cas9, on the other hand, has created a new era in genome editing due to its easier design, high precision, and low cost. Therefore, genome editing is widely used in modern plant breeding, plant biology research, and also in animal systems [6]. Then, the importance of regulatory regions involved in the regulation of gene expression in plants was explained. In particular, in recent years, the application of mutations created in these regulatory regions using CRISPR/Cas technology in plant breeding and the results obtained have been in the spotlight [4].

In addition, promising directions for how genome editing technologies can be used in plant breeding in the future are presented. Overall, this approach may open up new research directions for plant improvement using genome editing methods and allow for the development of more effective breeding strategies [4].

4. Ethical Issues

4.1. Bioethical Issues

CRISPR-Cas9 is widely recognised as one of the most significant discoveries of the 21st century by the scientific community and associated industries. CRISPR-Cas9 technology is a complex field that raises ethical, social, and legal controversies beyond gene editing. The technology has rapidly gained acceptance in animals and the environment, but has also recently raised difficult questions, applications, concerns, and bioethical research in humans [7]. However, the rapid rise of CRISPR-Cas9 has led to new bioethical, social, and legal issues in medicine [8], agriculture, livestock, and the environment [7]. CRISPR-Cas9 is used to genetically modify human germ cells and embryos. This is called germline genome editing. Germline genome editing raises a series of bioethical issues, such as the occurrence of unwanted changes in the genome, who and how to obtain informed consent, and the breeding of the human species (eugenics). Also, the bioethical issues that CRISPR-Cas9 technology may raise in the environment, agriculture, and animal husbandry should not be forgotten. To this end, legislation should be developed worldwide, taking into account the views of both life and social scientists, policymakers, and all other stakeholders in the sectors, to ensure that CRISPR-Cas9 can be used safely in all areas and that potential problems are addressed, and CRISPR-Cas9 applications should be carried out in accordance with this legislation. However, these control measures should not restrict scientific freedom [7].

4.2. Ecological Imbalance

Nontarget effects should be thoroughly investigated in studies that employ RNA-targeted gene editing methods based on CRISPR-Cas9. Possible off-target mutations will continue to exist in each generation due to an ongoing process of gene transfer in a population. Furthermore, the frequency and impact of mutations may increase as generations advance. The potential for genes to transfer to other species in the environment is a further concern. Negative characteristics may be transferred to related organisms if regulated sequences are transferred to other species. The distribution of the properties of the entrained genes among the populations can make control very difficult [7].

4.3. Regulations for Consumers

It is extremely challenging to recognise and control genetically modified organisms (GMOs) once they leave the lab due to the use of CRISPR-Cas9 to achieve the required genetic alterations. Thus, regulatory agencies like the European Medicines Agency (EMA), the US Food and Drug Administration (FDA), and others should consider whether any GMOs are safe for consumers. However, it is not known exactly how to evaluate the possibilities of a growing market with CRISPR-Cas9 [7]. There are high prospects for making and taking up CRISPR-Cas9 technology for commercialization in many fields, including health, food, and biologics production. It is relevant for the commercialization of CRISPR technology given that it continues to experience regulatory, ethical, and market forces that are key to its future growth [9].

Patenting is one of the CRISPR-Cas9 issues that affects all of humanity. As is well known, certain human gene sequences for therapeutic applications as well as transgenic organisms used in industry have been patented. In the future, patent-related problems in many biotechnology fields will keep increasing as technologies like CRISPR continue to develop. Several cases of patenting still exist today. The patent rights case between Zhang, Doudna, and Charpentier about the therapeutic application of CRISPR-Cas9 in human cells is the most well-known. In the case concluded on 2 December 2016, it was decided to grant the patent to Caribou Biosciences, of which Doudna was the founder [7].

4.4. Generation of Chimeric Animals for Organ Transplantation

Organ transplantation is the process of replacing an organ that is no longer functioning in a person's body with a healthy organ from a living donor or dead body. The primary goal is to save the patient's life, who is at risk of dying from organ failure, as well as to extend their lifetime and improve their quality of life. The development of chimeric animals may prevent patients from spending precious time waiting for an appropriate donor [7]. Organ transplantation is the most promising cure for end–stage organ disease. Human-animal chimeras provide the ability to produce human organs in another species using autologous stem cells (e.g., induced pluripotent stem cells (iPSCs) or adult stem cells), which would be patient-specific and immune-matched for transplantation. However, organ shortage and substantial risk of rejection have limited the development of organ transplantation. Therefore, finding more resources for organ transplantation is urgently needed [10].

Chimaeras include human neurons and germ cells, which raises bioethical concerns. The two fundamental concerns can be summarised as defining the order of nature and the moral disorders induced by how the organism is handled, depending on whether it is classified as human or animal. This method has received a lot of attention because of the potential use of interspecies chimaeras in fundamental and translational research. Some people believe that chimeric embryos will have an impact on human dignity and identity because they have the ability to create organisms from human cells and tissues. Others argue that chimaera organisms containing human cells cannot transform into humans and hence do not threaten human dignity. They also argue that the human-like features imparted to chimeras will neither affect the biological environment nor the moral status of animals and will never reach human consciousness [10].

4.5. Animal Welfare and Dignity

Animal welfare is another bioethical dilemma raised by the use of genome editing technology on animals. Firstly, off-target mutations in the genome have the potential to cause illnesses or other negative consequences in animals. Such a situation will adversely affect animal welfare [7].

Another bioethical issue to be discussed could be the concerns about "animal dignity" and alterations in their natural environments and physiological needs. According to several studies, using animals as objects only for the benefit of humans is neither ethically nor morally acceptable, and such activities can lead to increased human control over animals. Some others say that animals are not bound by any moral law and hence there is no need for a discussion addressing animal dignity. Based on Schultz-Bergin (2017), the use of genome editing technology will have no negative impact on animal rights, welfare, or dignity. The existence of contrary opinions on this matter indicates that the mentioned bioethical issues will be on the agenda for a long time [7]. Crossing the species boundary between humans and animals is associated with additional ethical complexities that extend beyond traditional animal use. One of the main ethical concerns raised by human – animal chimeras is how to avoid stem cell contribution to the nervous or reproductive system. The possibility of inducing human cells into animal neural or reproductive systems has met particularly strong public resistance. For this reason, such research needs to be conducted cautiously, based on sufficient animal studies and under strict ethical review.

5. Conclusion

CRISPR technology is an innovative gene editing tool with high potential for improving plant and animal breeding systems in modern agriculture. This technology demonstrates significant advantages in areas such as increasing productivity, improving product quality, and strengthening resistance to biotic and abiotic stresses. In addition, the application of CRISPR raises a number of bioethical and biosafety issues, such as ecological balance, biodiversity conservation, consumer acceptance, animal welfare, and regulatory frameworks. It is necessary to expand scientific research and improve international regulatory mechanisms for safer and more effective application of this technology in the future. The application areas of this revolutionary technology are quite wide, and in the agricultural sector, it has already become possible to increase the tolerance of plant species to various pathogens, pests, as well as negative environmental stress factors such as drought and salinity through CRISPR.

Author Contributions

The author solely conceived and designed the study, conducted the literature review and analysis, interpreted the findings, drafted the manuscript, critically revised the content, and approved the final version of the manuscript for publication.

Conflict of Interest

The author declares no conflicts of interest.

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Review Article

Hydrobiology of the Mingachevir Reservoir and Ecological Analysis of Zooplankton Communities

Marina R. Mustafayeva

Department of Natural Sciences, School of Advanced Technologies and Innovation Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan

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Abstract

This review summarizes the hydrobiological characteristics of the Mingachevir Reservoir, with particular emphasis on the ecological analysis of its zooplankton communities. In this review, the hydrological, biological, and ecological characteristics of the reservoir, as well as the species composition and dynamics of zooplankton communities, are analyzed on the basis of long-term data. The results of the studies carried out from 1960 to 2023 are compared, and changes in zooplankton communities are assessed. It is significant that a considerable number of species found in the works of Likhodeyeva (1963) and Ahmadov (1971) survived until now, and this suggests the relatively stable state of the ecosystem. However, the appearance of new species in the Mingachevir reservoir in 2021–2023 proves the growth of hydrobiological diversity. The relationships between zooplankton species diversity, dominant species succession, and environmental factors are discussed. Comparison with the Varvara reservoir made it possible to formulate necessary conclusions about similarities and differences of zooplankton communities in the cascade reservoirs.

Keywords: zooplankton, Mingachevir reservoir, hydrobiological characteristics, species diversity, ecological assessment

1. Introduction

The Mingachevir Reservoir is known as the first large reservoir built on the Kura River in Azerbaijan. The construction of the facility was completed in 1953 and has been operated for multiple purposes since its commissioning. The reservoir is located at approximately 40°55′30.1″ N latitude and 46°47′44.3″ E longitude and is the largest artificial lake formed in the middle reaches of the Kura River, which crosses the Samukh Valley. The main indicators of the reservoir are quite large: its length is 75 km, maximum width is 20 km (average width is 8.3 km), and the deepest point reaches 75 meters in the section near the dam. The average depth is considered to be 27 meters. The reservoir covers approximately 62,000 ha and has a total storage capacity of water. The dam that creates the reservoir is 1,550 meters long and 80 meters high. The Mingachevir Hydroelectric Power Station, with a total capacity of approximately 402 kW, operates on this dam. Two main irrigation canals, Upper Karabakh (172 km) and Upper Shirvan (128 km), also branch off from the reservoir. Both canals have been in operation since 1958 and have played a significant role in the development of the irrigation system in the region [1].

2. Hydrobiological Characteristics of Mingachevir Reservoir

In addition to being a necessary strategic facility in terms of energy, irrigation, and transportation, the Mingachevir Reservoir is also widely used in the city's drinking water supply, recreation, and tourism sectors. Fishing is also one of the main activities here. Fishing has been conducted in the reservoir area since 1955, and the productivity has been determined to vary between 0.6–4.1 kg per hectare. Scientific studies show that this figure can increase to 7 kg/ha. Under current circumstances, real productivity is likely to be higher than statistical figures. The reservoir is fed by the Kura, Ganikh, Gabyrri, and Ganja rivers. Although the reservoir can be classified as a riverbed type due to its hydrological characteristics, it is characterized as a lake-type reservoir due to the fact that the hydraulic residence time is approximately one year and a considerable proportion of suspended sediments is deposited within the reservoir [1]. As a result of the creation of the reservoir, ancient forests along the Kura, Ganikh, and Gabyrri rivers, as well as part of the Samukh forests located in the Samukh depression, were submerged [2].

These forests were dominated by valuable tree species such as oak, elm, willow, mulberry, and alder. Today, in the upper reaches of the reservoir, it is possible to find the dry remains of those trees, stumps jutting out of the water like "tombstones."

3. Phytoplankton Species Composition and Dynamics

Phytoplankton of the Mingachevir reservoir was first studied by S. Rzayeva in the 1950s–1960s. As a result of the research, a total of 232 algae species were recorded in the reservoir, approximately 150 of which were characterized as typical plankton forms. In terms of species diversity, green algae dominate (94 species), followed by diatoms (88 species) and blue-green algae (29 species). During the initial formation of the reservoir, the density of phytoplankton was quite high. Thus, an average of 9,050 cells were recorded per cubic meter of a 55-meter water column, and the total biomass was 11.9 g/m³. Among the species, Chlorella vulgaris, Coelastrum microporum, and Oocystis borgei are particularly widespread and dominant. However, the development of higher aquatic plants is observed at a relatively weak level.

Phytoplankton constitute the primary producers in the reservoir ecosystem and form the basis of the aquatic food web. Such organisms, which produce the largest share of organic matter via photosynthesis, are the foundation of primary production. Organic matter produced in this way serves as the major nutritional base for zooplankton, fish larvae, and benthic organisms. Mesotrophic-eutrophic features of the Mingachevir Reservoir provide high productivity of phytoplankton that positively impacts the development of higher trophic levels.

Another function of phytoplankton in aquatic ecosystems is the regulation of oxygen content in water. Photosynthesis performed in the daylight period enriches water with oxygen, thus creating the necessary conditions for the existence of fish, zoobenthos, and aerobic microorganisms. Research shows that the maximum activity of photosynthesis is provided mainly in the spring-summer period, when the content of dissolved oxygen in the water significantly increases. Species composition and abundance of phytoplankton serve as a significant bioindicator of the ecological state of the water body. Massive development of phytoplankton is often connected with the increased nutrient content of the water, in particular, nitrogen and phosphorus compounds, suspended particles carried to the water by rivers, and anthropogenic factors. For instance, the intensive development of blue-green algae (Cyanophyta) serves as a necessary indicator of the beginning of the eutrophication process. The excessive growth of phytoplankton leads to alters the physical and chemical characteristics of the water. At this point, the transparency of the water decreases, its color changes, and the light transmission is reduced. Thus, the temperature regimen of the reservoir and light penetration into the lower layers are changed, which influences the life of benthos. The role of phytoplankton in the development of fish populations is also enormous.

Phytoplankton is the first link in the food chain web, and the amount of phytoplankton affects the development of zooplankton, fish larvae, and productivity of fish. The reaction of zooplankton groups, Cladocera and Copepoda in particular, to phytoplankton amount is very sensitive, and a large amount provides the proper conditions for fishing. Moreover, the activity of phytoplankton in self-cleaning of the water body should be noted. They can absorb ammonia, nitrate, phosphate, and some heavy metals and organic substances, also stimulating microbiological degradation processes.

The above-listed characteristics make it possible to describe phytoplankton as a significant component of the biological water filtration system.

In this connection, phytoplankton in the Mingachevir reservoir serves not only as a source of the food chain, but also as one of the basic elements that ensure the stability, productivity, and ecological equilibrium of the aquatic ecosystem.

The roles of phytoplankton in the Mingachevir reservoir can be formulated as follows:

- ensures the normal functioning of the ecosystem;
- serves as a basis of the trophic chain;

- regulates the oxygen regime of the water;
- serves as an indicator of water pollution;
- is an essential factor in creating fish stocks.

Therefore, the analysis of phytoplankton's structure, quantity, and seasonal changes plays an important role in determining the ecological state of the reservoir.

4. Species Composition and Dynamics of Zooplankton

Zooplankton is one of the key biocomponents performing extremely significant roles in the Mingachevir Reservoir ecosystem. Organisms belonging to the primary consumers in the aquatic food web mainly consume phytoplankton and play a predominant role in energy and matter flow transfer processes in the aquatic environment. Since zooplankton serves as a natural link between phytoplankton and fish, the formation of fish populations in a reservoir is entirely dependent on their presence and activities. One more role of zooplankton is controlling water quality and regulating phytoplankton biomass through grazing. Otherwise, the overgrowth of the phytoplankton population will increase water turbidity and affect the oxygen regime negatively, thus creating adverse conditions for living organisms in the aquatic environment. Thus, zooplankton can be considered as a natural regulating system in the ecosystem. Zooplankton is also one of the main food sources for fish and other aquatic organisms. Young fish mainly feed on zooplankton. Therefore, the number of zooplankton organisms is extremely important for the survival of the fish population. The role of these creatures is not only limited to being consumers and contribute to natural water purification processes. Zooplankton aids in increasing water clarity and general sanitation through consumption of organic debris, bacteria, and phytoplankton in excess amounts. Thus, the number and diversity of zooplankton can be considered good indicators of the ecological state of the watershed. Systematic studies of the zooplankton of the Mingachevir Reservoir started in the 1960s, and the infusorians became the focus of research in the 1970s. Infusorians of the reservoir were first systematically investigated by I. Alakbarov (1977). As a result of his study, 50 types of planktonic infusorians were found in the reservoir, including the novel genus Astrostama and its species A. mobilis. In the course of his research from 1977 to 2005, I. Alakbarov described numerous new families, genera, and over 100 types of infusorians.

Although at the beginning of studies on the mesoplankton community of the reservoir there were 22 species discovered, in recent years the number of species has fluctuated between 32 and 38. Rotifers (15 species) and cnidarians are dominant in terms of diversity of species, but copepods lead in terms of numbers and biomass. Zooplankton biomass is in the range of 1.28–3.6 g/m^3, and 93–99.6% of biomass is represented by crustaceans [3].

The first research on the faunistic complex of zoobenthos goes back to the 1950s and 1960s. At the beginning of the research, 66 species were registered, and according to some data, there were almost 100 species. In the process of the research, the species composition of the benthos has changed: despite the fact that some rheophilic species which were present in abundance at the first stages of the research have disappeared, the fauna became richer due to the appearance of limnophilic and pelophilic species.

After the successive construction of the Shamkir reservoir (1982) and Yenikend reservoir (2000) on the Kura River in the upper reaches of Mingachevir, changes in water flow have had a significant impact on both the number and biomass of benthos in the Mingachevir reservoir. Currently, the mass of benthos varies in the range of 4.4–16.2 g/m^2, which is a significant decrease compared to previous periods.

In general, zooplankton and zoobenthos are components that play a key role in the formation of the food chain and biological balance of the Mingachevir reservoir ecosystem, and their changes are one of the most sensitive indicators of the ecological state of the reservoir.

5. Ichthyofauna

It has been continuously studied since the 1950s to the present day. 34 species and subspecies and 2 hybrid fish have been recorded in the Mingachevir reservoir. Among them, 9 species are of national importance. Among the fish inhabiting this area are kulma, cheki, chapaq, Khramulya, usach, sif, nakha, hasham, and shemaya. In recent years, 4 more species of valuable freshwater fish (salmon, agamur, and garasol) have been recorded in the reservoir. The biomass and number of zooplankton in the Mingachevir reservoir vary seasonally [3]. In recent years (2000–2008), the amount of fish caught from the Mingachevir reservoir has decreased significantly - from 39.2 tons (2002) to 94.9 tons (2005). On the one hand, this is due to the improper use of the biological justification prepared for the reservoir, and on the other hand, it is due to illegal fishing, the concealment of a large part of the fish caught, and the failure to record some of them (in statistics).

The metazoan plankton of the Mingachevir reservoir was first studied by Likhodeyeva (1963), and 21 zooplankton species were recorded [4]. Later, Ahmadov (1971) identified 38 species [5]. Both authors noted that A. priodonta, P. vulgaris, D. brachyurum, D. longispina, D. hyalina, B. longirostris, L. kindtii, S. sarsi, A. acutilobatus, M. fuscus, and T. dybowskii are the most widespread and permanent species of the Mingachevir reservoir. Studies conducted by Alekperov in the 1970s on the protozooplankton community (ciliate fauna) of the Mingachevir Reservoir documented 50 species of free-living ciliates (Alekperov, 1987; Alekperov & Tapdygova, 2022) [6]. Subsequent investigations carried out after the commissioning of the Yenikend Reservoir revealed that the species richness of metazooplankton within the reservoir cascade ranged from 26 to 31 species during the period 2001–2005 (Ahmadov, 2003, 2006).

A comparative analysis of zooplankton indicators obtained in the Mingachevir reservoir in 2021–2023 with data from the 1960s revealed that 16 of the 21 species recorded by Likhodeyeva (1964) and 25 of the 38 species recorded by Ahmadov (1971) have maintained their existence for 55–60 years [4], [5]. L. luna, B. bennini, B. falcatus, A. affinis, C. strennus, M. viridis, M. leucarti, and A. crassa, recorded in 2021–2023, are new species for the reservoir.

T. dybowskii, listed as the permanent species by both researchers, maintains its dominance today. In all seasons of 2021–2023, B. longirostris, Ch. sphaericus, and A. acutulobatus dominated the zooplankton complex.

6. Comparative Analysis of the Kura River Cascade Reservoirs

As it moves westward from the Central Lowland zone of Azerbaijan, the cascade of reservoirs of the Kura River begins with Varvara and ends with the Shamkir Reservoir. For the purpose of comparative analysis of zooplankton of cascade reservoirs, the Varvara reservoir was studied in 2019–2021, and 41 metazooplankton species were recorded: 19 species of rotifers, 12 species of cladocera, and 10 species of copepods (Alekperov and Tapdykova 2021) [6].

When comparing with the Sorensen similarity coefficient (1948), it was determined that [7]:

- 1 rotifer species, 4 cladoceran species, and 4 copepod species recorded in the Mingachevir reservoir were not found in the Varvara reservoir.
- 7 rotifer species, 4 cladoceran species, and 3 copepod species recorded in the Varvara reservoir were not detected in Mingachevir.

Similarity coefficients:

- Rotifera: K = 75%
- Cladocera: K = 66.7%
- Copepoda: K = 66.7%

Thus, the highest similarity between the Mingachevir and Varvara reservoirs is observed in rotifers, and lower in cladocerans and copepods. As a result of research conducted after an interval of approximately 60 years, new information has been obtained on the species composition, quantitative parameters, distribution across biotopes, and seasonal development dynamics of multicellular zooplankton (metazooplankton) communities of the Mingachevir reservoir [8]. It was determined that the metazooplankton of the reservoir consists of 36 species belonging to 3 taxonomic groups. Rotifera (36.1%) dominates in terms of species diversity. The most common types in all seasons of the year are:

- Polyarthra vulgaris
- Asplanchna priodonta
- D. longispina
- D. hyalina
- Ch. sphaericus
- Bosmina longirostris

- acutulobatus
- T. dybowskii

These species played a leading role in shaping the structure of zooplankton.

7. Conclusion

Studies confirm that the zooplankton diversity of the Mingachevir reservoir demonstrates both stability and renewal characteristics over time. The fact that a significant portion of zooplankton species recorded in the 1950s–1970s still exist today indicates the long-term sustainability of the ecosystem. However, the discovery of new species in 2021–2023 indicates that the hydrobiological dynamics and ecological conditions of the reservoir are changing. The maintenance of dominance in zooplankton communities by species such as B. Longirostris, Ch. Sphaericus, A. Acutulobatus, and T. Dybowskii ensures the functional stability of the ecosystem. Comparative studies with the Varvara reservoir have shown that there are differences in species diversity in cascade reservoirs and that these differences are formed depending on hydrology, nutrients, and anthropogenic impacts. In conclusion, contemporary ecological studies of zooplankton communities are the scientific foundation that can ensure the sustainability of biological productivity and the food chain, provides a scientific basis for the sustainable management of biological productivity, food-web integrity, and fishery resources.

Author Contributions

The author was responsible for the conceptualization of the study, literature review, data collection and analysis, interpretation of the results, and preparation of the manuscript. Dr. Naila Guliyeva supervised the research, provided scientific guidance throughout the study, critically reviewed the manuscript, and approved the final version for publication.

Conflict of Interest

The authors declare no conflicts of interest.

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Editorial Office Address: 17 A, Ahmad Rajabli Street,

III Parallel, Baku, Azerbaijan

Phone: +994 12 565 39 77

Email: rjaaa@wcu.edu.az

https://rjaaa.wcu.edu.az/

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