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Harnessing Soil Ecology through Biochar and AMF Integration for Improved Growth and Enzymatic Dynamics in *Swiss Chard*

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

Biochar and arbuscular mycorrhizal fungi (AMF) are increasingly recognized for their potential to improve soil quality and plant productivity. This study evaluated the individual and combined effects of non-wood biochar and AMF on growth performance, root morphology, physiological attributes, and soil enzymatic activity in Swiss chard (*Beta vulgaris* L.) under pot conditions. A randomized block design was employed with four treatments and three replications: A_1 (control, no amendment), A_2 (biochar alone), A_3 (AMF alone), and A_4 (combined AMF and biochar). Results demonstrated that biochar application alone significantly enhanced plant growth parameters, including shoot length, leaf dimensions, leaf number, and biomass accumulation (fresh and dry weight), compared to the control. Improvements were also observed in root morphological traits, physiological performance, and soil enzymatic activities. AMF inoculation further contributed to plant and soil improvements; however, the combined application (A_4) produced the most pronounced effects across all measured variables. The synergistic interaction between AMF and biochar resulted in superior plant growth, enhanced root system architecture, improved physiological efficiency, and elevated soil enzymatic activity and microbial biomass. Overall, the findings highlight the synergistic potential of integrating AMF with biochar as a sustainable soil management strategy to enhance crop productivity and soil biological functioning.

Keywords: Non-wood biochar, AMF, Swiss chard, root morphological, soil enzymatic activities, microbial activity

1. Introduction

Biochar is obtained by pyrolysis of different types of carbonaceous feedstocks. The utilization of biochar is a means of mitigating climate change and decreasing atmospheric carbon dioxide levels, while also enhancing agricultural soil quality (Emenike et al., 2024; Iwuozor et al., 2024; Sieradzka et al., 2022). The use of biochar has been shown to enhance soil microbial activity and improve soil physiochemical traits (H Pangaribuan et al., 2022; Zhao et al., 2022). A study conducted by Khadem et al. (Khadem et al., 2021) found that the application of biochar enhanced soil productivity and health. According to Teodoro et al. (Teodoro et al., 2020), the application of biochar resulted in a substantial enhancement of the specific surface area, cation exchange capacity, and water holding capacity (WHC) of hostile soils. Biochar derived from rice husk substantially enhanced the organic matter content in soil by 50% as compared to the control group (Ayaz et al., 2022). According to several studies, biochar has been shown to enhance the functions of esterase, lipase-esterase, phosphohydrolase, trypsin, protease, alkaline phosphomonoesterase, phosphomonoesterase acid, phosphatase acid, alkaline phosphatase, dehydrogenase, and chymotrypsin enzymes when used alone (Antonia Sindesi et al., 2022). Biochar facilitates the enrichment of soil with essential nutrients like total carbon, sodium, magnesium, calcium, potassium, and nitrogen (Verma &

Reddy, 2020). Egamberdieva et al. (Egamberdieva et al., 2019) found that the incorporation of biochar into soil substantially enhanced the potassium, phosphorus, and nitrogen levels.

Biochar could be shown to improve productivity and nutritional composition of different plant species (Jatuwong, et al., 2024). Previous studies have demonstrated that the use of biochar resulted in enhanced germination of seeds and growth of plants and soybean production (Arshad et al., 2023). After biochar was added, the rate of germination was much higher than in the control group (Osei et al., 2023).

The levels of magnesium and calcium in maize (*Zea mays*) leaves were markedly greater when a high rate of biochar was applied compared to the control group (Gunes et al., 2023). The use of biochar enhanced the biomass of both the roots and shoots of buckhorn (Nirukshan et al., 2022). The application of biochar derived from rice straw showed a substantial enhancement in plant height, per plant bolls, average boll weight, and cotton seed output compared to the control group (Huang et al., 2024). According to Niu et al. (Niu et al., 2024), the application of biochar obtained from rice husk resulted in an increase in the final biomass, plant height, root biomass, and leaf numbers of cabbage and lettuce compared to plants grown without biochar. Biochar exerts a beneficial influence on the biochemical and physiological characteristics of plants. Multiple studies have demonstrated that the use of biochar enhanced transpiration rate, plant photosynthesis, and levels of chlorophyll (Lalay et al., 2024).

AMF are a prominent contributor to the rhizosphere microflora in ecological systems and have a crucial function in nutrient cycling within these ecosystems (Ishaq et al., 2023). Mycorrhiza is a symbiotic microorganisms that stimulate root development and significantly contribute to improving plant nutrition (Khaliq et al., 2022). AMF has a beneficial relationship with crops (Huang et al., 2024). The introduction of mycorrhiza into plant roots enhances the absorption of essential nutrients, including Mg, Ca, P, K, and N (Bhattacharyya & Furtak, 2022). Inoculated plants with mycorrhiza exhibited elevated levels of carotenoids and chlorophyll, as well as enhanced levels of antioxidant enzymes, including ascorbate peroxidase, peroxidase, catalase, dismutase, and superoxide (Nazari et al., 2023). The application of mycorrhiza enhanced the root system of plants and facilitated the growth and production of numerous field crops (Bhale et al., 2018). Previous studies have indicated that the use of both PGPR (Plant Growth-Promoting Rhizobacteria) and mycorrhiza through inoculation may have a positive impact on cultivation (Uwamungu et al., 2022). Mycorrhiza and biochar have demonstrated their efficacy in improving plant productivity while mitigating the severity of diseases. Singh et al. (Singh et al., 2022) found that inoculating maize with both biochar and AMF simultaneously greatly enhanced the growth of plants and phosphorus level.

Swiss chard is rich in essential components that have positive effects on human health, such as bioactive chemicals, minerals, and vitamins. The substance is abundant in bioactive chemicals that possess anticancer, hypolipidemic, hypoglycemic, and antiobesity traits (Kaparapu et al., 2020; Ivanović et al., 2019). The cultivation of chard is strongly influenced by both biotic and abiotic stress factors. Furthermore, the concurrent use of AMF and biochar is beneficial in mitigating the adverse effects of biotic stress, irrespective of abiotic stress (Tan et al., 2017). However, there is no data on the combined impact of AMF and non-wood biochar on chard. Non-wood biochar can be attractive when agricultural waste and side streams are used as raw materials. The objective of this work was to study the effect of simultaneously applying AMF and biochar to the soil of growing Swiss chard, compared with Jabborova et al. (Jabborova et al., 2020). The authors postulated that the concurrent use of AMF and non-wood biochar will cause positive impacts on soil characteristics and plant nutrients and thereby on the growth of plants and their physiological characteristics.

2. Materials and Methods

2.1. Soil and biochar description

The experiments were conducted using soil from the Agricultural Research field of Islamia University Bahawalpur, and the soil properties were noticed (EC: 0.33 µS/cm, pH: 7.66, SOC(soil organic carbon): 8.32 g/kg, CEC(cation exchange capacity): 19.11 cmol kg^{-1}, Available N: 54.19 mg/kg, Available P: 0.47 mg/kg, Available K: 80.1 mg/kg, Total N: 0.69 g/kg, Total P: 0.41 g/kg, Total K: 20.2 g/kg, Texture; silty loam). The biochar considered in this work was synthesized at 450°C using non-wood feedstock (corncobs). The biochar had a particle size smaller than 2 mm, and the following properties: pH: 8.7, VC: 22%, BET-surface area: 123 m^2g^{-1}; C: 44%, H: 2.80%, N: 2.69%, O: 12.46%, bulk density; 0.349 g/cm^3; CEC: 37.88 cmol kg^{-1}, EC: 5470 µS/cm, ash content: 1.3%, VM (volatile matter): 33.8%). Swiss chard seeds were obtained from Yunnan Zhuoyu Seeds Industry, China. AMF was obtained from the Microbiology research center at the same institute.

2.2. Experimental design

The experiments were planned as pot tests conducted in a shade house in a randomized block design (4 treatments, 3 replications). These treatments comprised a control A_1 (no biochar/AMF added into the soil), A_2 (only addition of biochar), A_3 (only addition of AMF), and A_4 (biochar combined with AMF). Permissions or licenses were obtained to collect Swiss chard seeds from the Regional Agricultural Research Institute (RARI) before starting the research. The seeds were planted in plastic containers with a depth of 15 cm and 15 cm in diameter, holding a soil mass of 4.5 kg. Every pot received irrigation every 3 days. At harvest, after 35-days, the length of the shoot, leaf width, number of leaves, fresh weight of shoot and root, dry weight of root and shoot were all measured, compared to Jatuwong et al (Jatuwong et al., 2024). Every pot received irrigation every 3 days. After that 35-day period, physiological data, including RWC (relative water content), transpiration rate, net photosynthetic rate, and photosynthetic pigment contents, were also measured.

2.3. Analysis of Swiss chard root morphological characteristics

After harvesting, the root system was meticulously rinsed with water. The complete root system was dissected and examined with an imaging system against a blue background. Analysis of digital photographs of the roots was conducted using the programme Win RHIZO (Regent Instruments Inc., Canada). Evaluated were the root length, total root surface area, root diameter, projected area, and root volume.

2.4. Quantification of physiological characteristics

Relative water content was determined using the technique described by Boussora et al. (Boussora et al., 2024). A quantity of 100 mg of fresh leaf biomass was promptly transferred into petri plates containing deionized water and incubated at ambient temperature for four hours as described by Jatuwong et al. (Jatuwong et al., 2024). Next, the samples were pulled from the soil, washed, and dried by blotting, and the weight was quantified. The samples were stored in a 75°C oven for >10h, and then the mass of the dry sample was measured, as described in Jabborova et al. (Jabborova, et al., 2021). Quantification of RWC was performed as:

$$RWC\,\% = [(FW - DW)/(TW - DW)] \times 100 \quad (1)$$

Here, FW (fresh leaf sample), DW (dry weight), and TW (turgid weight) are used.

The photosynthetic pigment contents were quantified using the modified approach by Hashemi et al. (Victoria et al., 2023). Fresh leaves were gathered in the early hours of the day. 50 mg of finely chopped fresh leaf samples were placed into test vials filled with 5 ml of dimethyl sulfate (DMS, CAS no. 77-78-1). Incubation was done at 37 °C for four hours in the absence of light and then prolonged until tissue rendered entirely devoid of colour was obtained. The extract's absorbance was measured at wavelengths of 470, 645, and 663 nm with a spectrophotometer, with a dimethyl sulfate blank as a calibrating reference; compare the procedure by Shahraki et al. (Shahraki et al., 2024). The concentrations of chlorophyll a, chlorophyll b, carotenoid, and total chlorophyll were calculated with the following formulas provided by Soman and Shetty (Soman & Shetty, 2018).

$$\text{Chlorophyll a (mg/g)} = [12.7(A663) - 2.69(A645)] \times V/W \quad (2)$$

$$\text{Chlorophyll b (mg/g)} = [22.9(A645) - 4.68(A663)] \times V/W \quad (3)$$

$$\text{Total chlorophyll (mg/g)} = [20.2(A645) + 8.02(A663)] \times V/W \quad (4)$$

$$\text{Carotenoid (mg/g)} = [(1000 \times A470) - (3.27 \times \text{Chlorophyll a} + 104 \times \text{Chlorophyll b})] \times V/W \quad (5)$$

Where A represents optical density, V represents the volume of dimethyl sulfate (in mL), and W represents the sample weight.

The net photosynthetic rate and the transpiration rate were quantified with a portable analytical instrument between 10:00 a.m. and 11:30 a.m. The measurement was conducted using the completely elongated youngest leaf. The measured value for temperature was 30°C, the concentration of CO_2 was 400 ppm, and photosynthetic active radiation (PAR) was 300 mmol m^{-2} s^{-1}.

2.4. Analysis of AMF spores

The spores of AMF were collected from soil samples weighing 10 grams employing a wet sieve and decanting technique. The sample of soil was passed through a sequence of soil sieves organized in a hierarchy of decreasing sieve diameters. The sterile spores were sifted through a mesh sieve and gently rinsed with deionized water multiple times before being put into a clean petri dish filled with water. The spores of AMF were enumerated using a stereomicroscope (Yusif et al., 2018).

2.5. Evaluation of soil microbial biomass

The biomass carbon measurement techniques were derived from those outlined by Tackenberg (Tackenberg, 2007). Three out of six 17.5-gram duplicates of each soil sample were subjected to 24-hour fumigation with finely purified chloroform. Following the elimination of chloroform, the carbon was obtained from both fumigated and unfumigated samples by subjecting them to a 0.5 M potassium sulphate solution for 1 hour under shaking. Sequential filtration of unfumigated and fumigated samples was performed using filter paper (Whatman no. 42). The supernatant was quantified at a wavelength of 280 nm via a spectrophotometer.

2.6. Soil Enzymes analysis

The activities of alkaline phosphatase were measured using the technique reported by Sugawara et al. (Sugawara et al., 2002). For each soil sample, 1 gram of the soil sample was tested in duplicate. A single set was employed as a control. Next, 0.2 mL of $C_6H_5CH_3$ (toluene) and 4 mL of buffer solution with a pH of 11 were applied. Additionally, 1 mL of $C_6H_6NO_6P$ (p-nitrophenyl phosphate) solution was introduced to the second set of samples, compared to Jabborova et al. (Jabborova et al., 2021). After agitating both flasks briefly to ensure thorough mixing of the contents, they were then positioned in an incubator set at 37 °C for around one hour. Then, 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.5 M NaOH were administered. Flasks were agitated briefly, and then 1 mL of a solution of $C_6H_6NO_6P$ was introduced to the remaining assemblage of samples. Rapid filtration of all suspensions via Whatman No. 1 filter paper was followed by measuring the absorbance at 440 nm.

The hydrolytic activity of fluorescein diacetate (FDA) was measured using the technique described by Adam and Duncan (Baloch et al., 2024). A quantity of 0.5 grams of soil was introduced into 25 ml of Na_3PO_4 (pH = 7.6; 0.06 mM). A 0.25 mL volume of a 4.9 mM fluorescein diacetate substrate solution was incorporated into each test vial. Each vial was vigorously agitated and then placed in a water bath set at 37 °C for 5 hours. The soil suspension was then centrifuged at 8000 rpm for 5 minutes. The spectrophotometer was used to probe the clear supernatant at 490 nm compared to a reagent blank solution as described in Jabborova et al. (Jabborova et al., 2021).

The activity of dehydrogenase was measured according to the procedure outlined by Tan et al. (Tan et al.,2017). 5 grams of freshly homogenized soil specimens were transferred into test tubes, followed by the addition of 5 milliliters of a 3% volume/weight substrate containing $C_{19}H_{15}C_lN_4$ (TTC, 2,3,5-

triphenyltetrazolium chloride). Incubation lasted 24 hours at 25 °C. For the blank, 1 mL of a phosphate buffer solution containing 3% 2, 3, 5-Triphenyltetrazolium chloride was used. Once incubated, the samples were subjected to centrifugation at 4500 revolutions per minute for 10 minutes. The synthetic triphenyl-formazan was isolated via methanol extraction. 5 ml of methanol was added to each tube, followed by vigorous shaking of the tubes for 10 minutes. The procedure was done twice, with 10 mL of CH_3OH dedicated to extraction. The tubes were once more subjected to centrifugation. The supernatant was transferred into a sterile tube, and the absorbance of the solution was quantified at a wavelength of 485 nm, based on the protocol by Jabborova et al. (Jabborova et al., 2021).

2.7. Statistical data analysis

Statistical analysis of experimental data was performed with ANOVA employing Stat-View Software (SAS Institute Inc.). The significance of treatment impact was assessed based on the level of the p-value ($p < 0.05$).

3. Results

Figure 1 shows that the application of AMF greatly enhanced both the leaf width and leaf numbers. The leaf length, length of shoot, leaf width, and leaf number were all considerably enhanced by 44%, 80%, 51%, and 49%, respectively, as compared to the control plant. The synergistic application of AMF and biochar resulted in a substantial 56% and 55% increase in leaf length and shoot length, respectively, compared to the control group. Furthermore, the application of AMF and biochar together resulted in a positive impact on both leaf width and leaf number, exhibiting a 40% and 29% enhancement, respectively, in comparison to the control group.

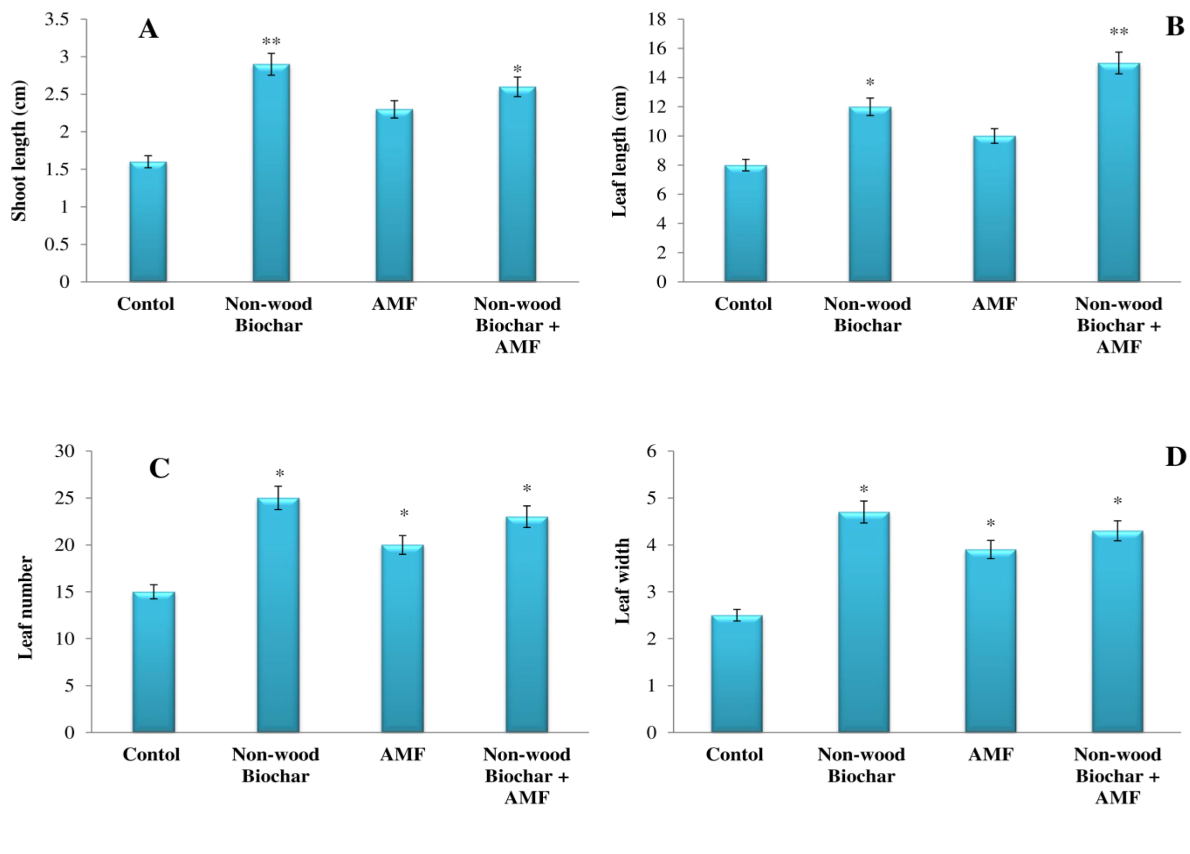

*Figure 1: AMF and biochar for the increment of (A) length of shoot, (B) length of leaf, (C) leaf numbers, and (D) leaf width of Swiss chard. Data are the means of 3 replicates (n = 3); * differed significantly at p < 0.05 *, p < 0.01 ***

In Figure 2, the biochar administration and the combination of AMF and biochar showed the greatest recorded values for shoot and root fresh weight as well as dry weight. The application of biochar demonstrated a notable enhancement in both the dry weight (49%) and fresh weight (61%) of roots over the control group (Figure 2). The biochar application resulted in a substantially higher fresh weight of the shoot by 40% and dry weight by 40%. The use of AMF gradually enhanced both the fresh and dry weight of the shoot. The application of AMF substantially enhanced the dry weight of both the roots and shoots in comparison to the control. Comparing the control to the simultaneous use of AMF and biochar, fresh and dry weight roots were considerably increased by 47% and 48%, respectively. In comparison to the control, the simultaneous use of AMF and biochar considerably increased the shoot's fresh weight (30%) and dry weight (31%).

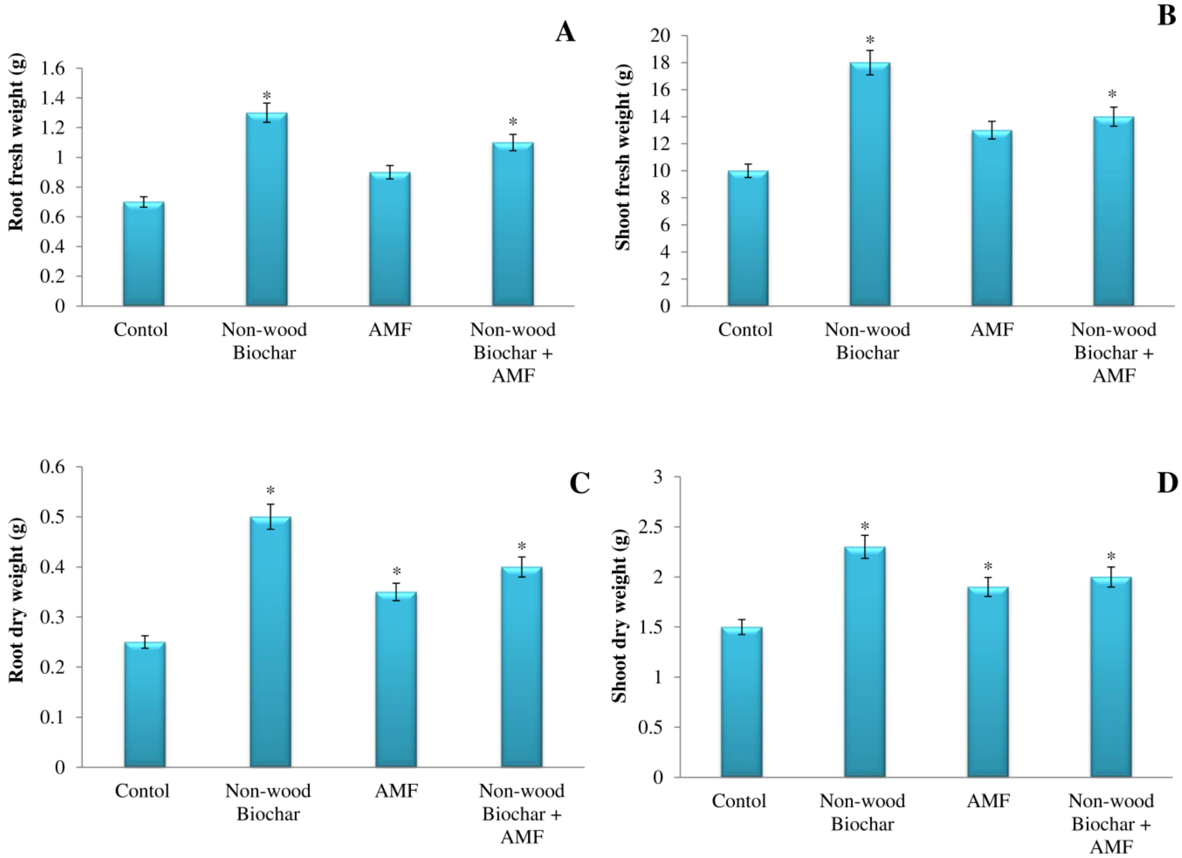

Figure 2: *AMF and biochar for the increment of (A) fresh weight of root, (B) fresh weight of shoot, (C) dry weight of root, (D) dry weight of shoot of Swiss chard. Data are the means of three replicates (n = 3); * differed significantly at $p < 0.05$**

Application of AMF increased the total length, diameter of root, projected area, and volume of the roots by 45%, 49%, 37%, and 38%, respectively, in comparison to the control group (Figure 3). Biochar application substantially enhanced the root volume and projected area by 60% and 65%, respectively, in comparison to the control. A 78% increase in total root length and 79% increase in the diameter of the root were observed after the biochar administration vs. the control. The simultaneous application of AMF and biochar resulted in a substantial 80% increase in total root length and an 89% increase in the diameter of roots compared to the control group. The mixed application of AMF and biochar resulted in a 49% increase in root volume and a 55% increase in the projected area.

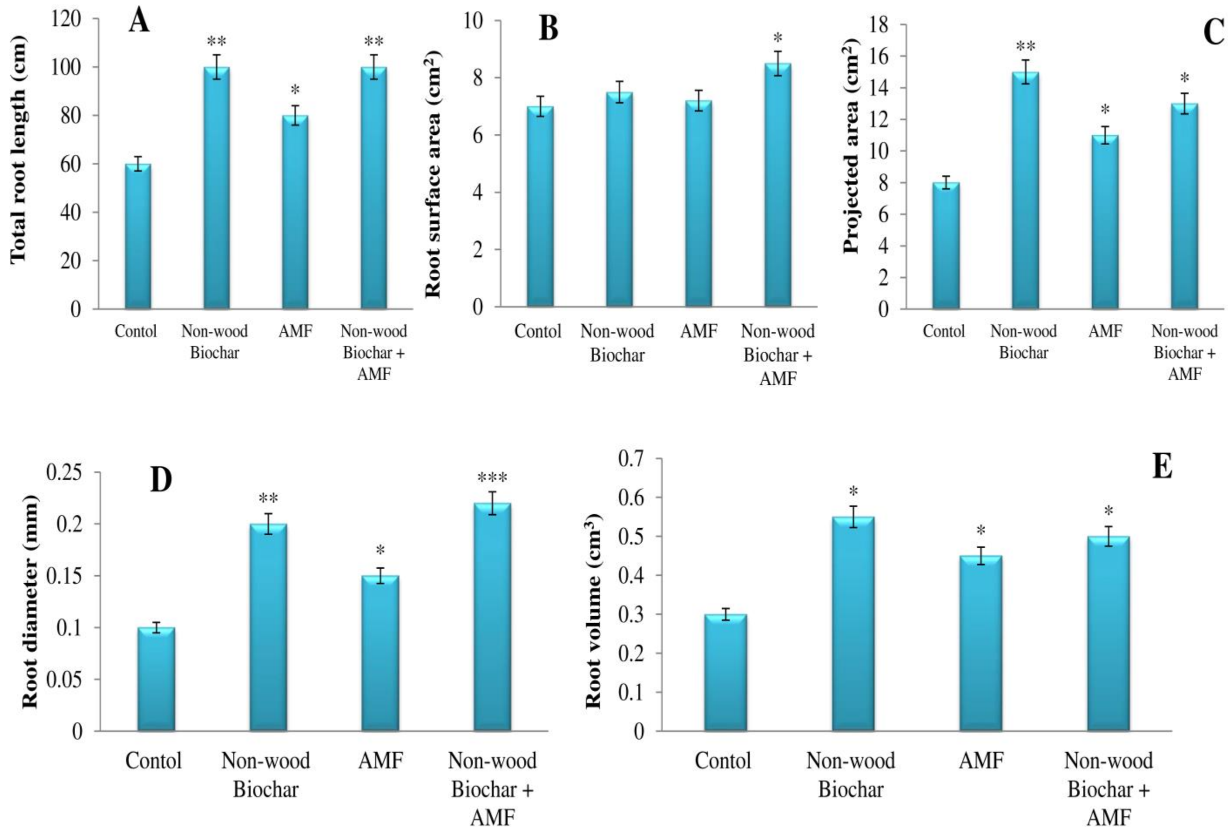

Figure 3: *AMF and biochar for the increment of (A) Total root length, (B) surface area of root, (C) projected area, (D) diameter of root, and (E) volume of root of Swiss chard. Data are the means of three replicates (n = 3); * differed significantly at p < 0.05*, p < 0.01**, p < 0.001****

The photosynthetic rate was significantly enhanced by 49% and 76%, respectively, when biochar was used alone and when combined with AMF, in comparison to the control group (Figure 4). The combination of AMF and biochar exhibited a substantial enhancement in stomatal conductance vs. the control. The rate of transpiration exhibited a substantial increase across all treatments in comparison to the control. The biochar administration yielded the highest value. A single application of biochar substantially increased the rate of transpiration by 47% in comparison to the control.

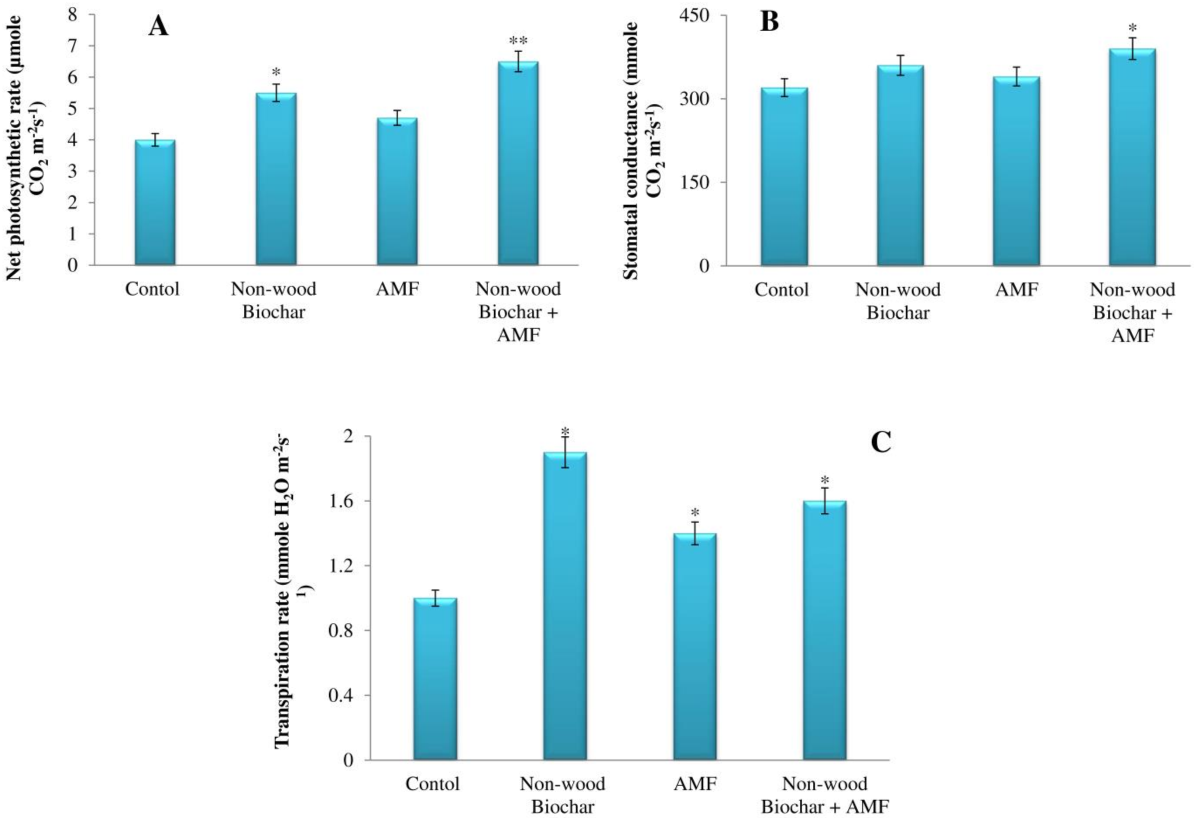

Figure 4: *AMF and biochar for the increment of (A) Net photosynthetic rate, (B) Stomatal conductance, and (C) Transpiration rate of Swiss chard. The averages of the three replicates (n = 3) are shown; * differed significantly at $p < 0.05$ *, $p < 0.01$ ***

Each of the treatments enhanced the levels of photosynthetic pigments in the leaf vs. the control (Figure 5). The biochar substantially enhanced the levels of chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid in the leaf by 14%, 30%, 19%, and 51%, respectively, compared to the control group (Figure 5). The sole application of AMF resulted in a substantial increase of 19% in the overall level of total chlorophyll, 27% in chlorophyll, and 11% in chlorophyll b, and 29% in the carotenoid level. The simultaneous application of AMF and biochar caused a substantial increase in the total chlorophyll level, chlorophyll a and chlorophyll b levels, and carotenoid level, with respective increases of 27%, 19%, 20%, and 40% compared to the control.

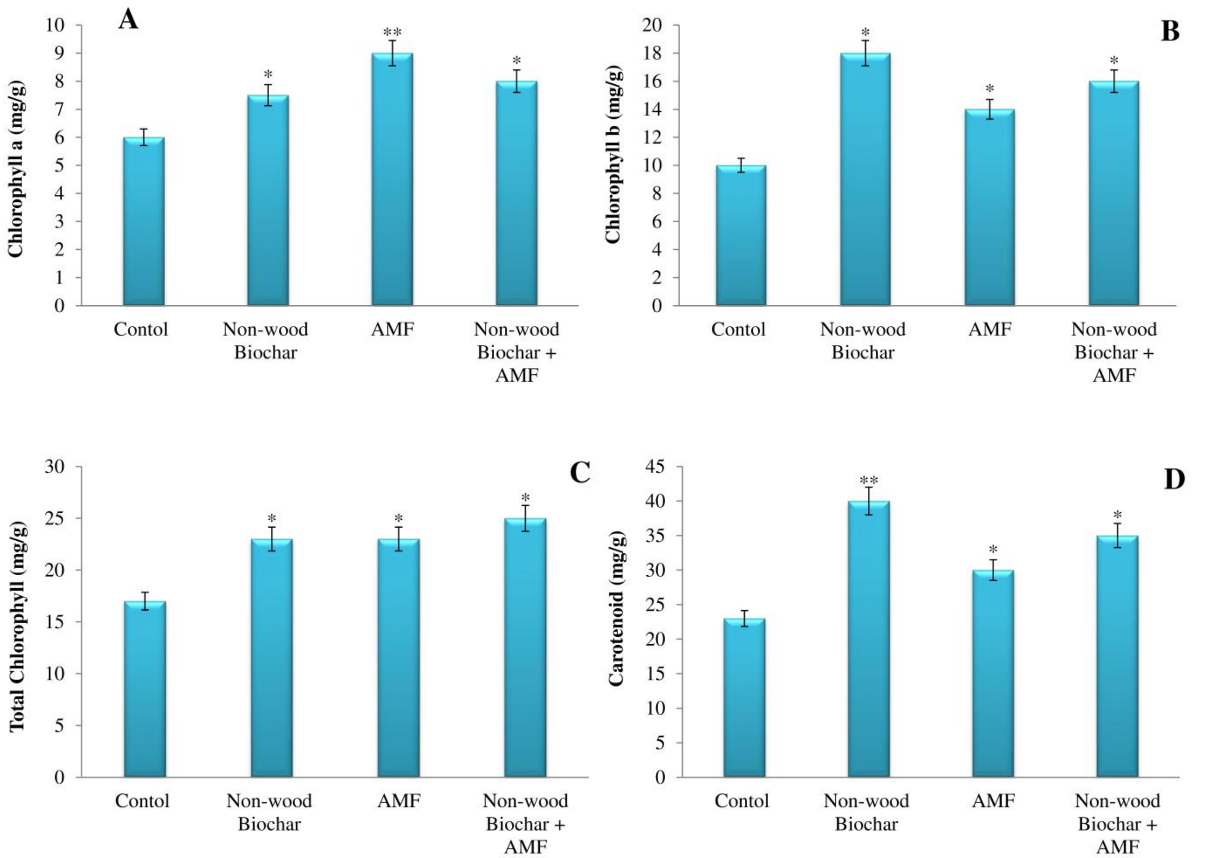

*Figure 5: AMF and biochar for the increment of (A) chlorophyll a, (B) chlorophyll b, (C) Total chlorophyll, and (D) carotenoid level of Swiss chard. The three replicates (n = 3) were averaged; *differed significantly at p < 0.05 *, p < 0.01 ***

Each treatment, namely only AMF, only biochar, and the use of AMF plus biochar, led to higher values of the RWC (relative water content) vs. the control group (Figure 6). In the mixture of AMF and biochar treatment, the leaf exhibited the highest RWC level, which was 19% greater than that of the control. In the application including AMF alone or biochar alone, the RWC increased by 22% and 17%, respectively, in comparison to control plants.

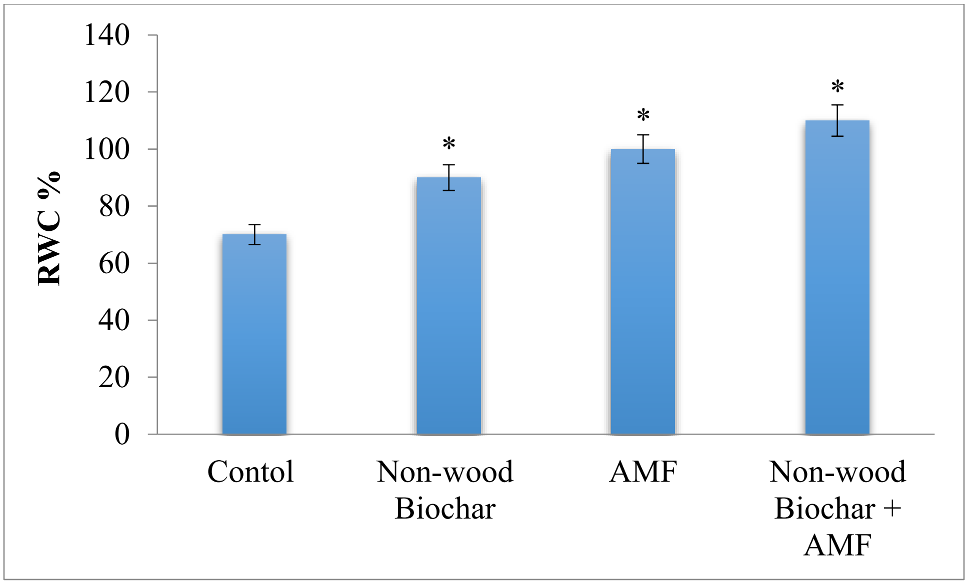

Figure 6: *AMF and Biochar for enhancement of the leaf RWC. Data of three replicates (n = 3) were averaged; *differed significantly at p < 0.05**

Both the application of AMF alone and the combination of biochar and AMF showed greater efficacy in enhancing the quantities of AMF spores in the soil compared to the control group (Figure 7). The population of AMF spores in soil exhibited a significant increase, ranging from 130% to 149% when exposed to AMF alone and when mixed with AMF and biochar, above the control group. The biochar application resulted in a 79% enrichment of AMF spores in soil compared to the control.

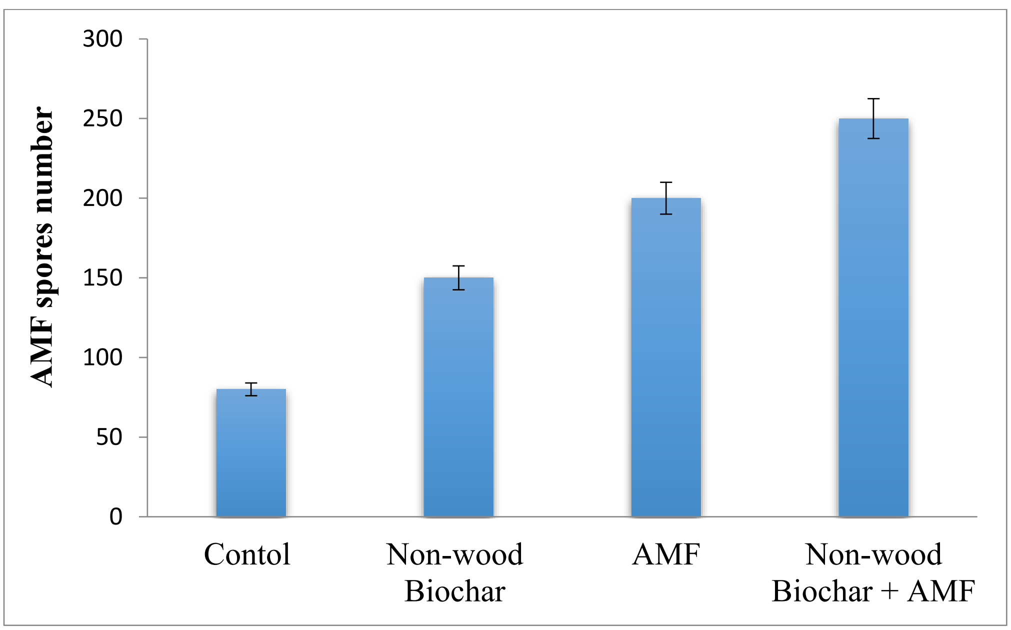

Figure 7: *AMF and Biochar for the enhancement of AMF spores in the soil. Data are the averages of the three replicates (n = 3); *differed significantly at p < 0.05 *, p < 0.01***

Both the application of only biochar and the combination of AMF and biochar treatment resulted in an increase in carbon content within the microbial biomass in the soil vs. the control (Figure 8). The mix of AMF and biochar treatment yielded the greatest carbon content among all the treatments, surpassing the control by 29%.

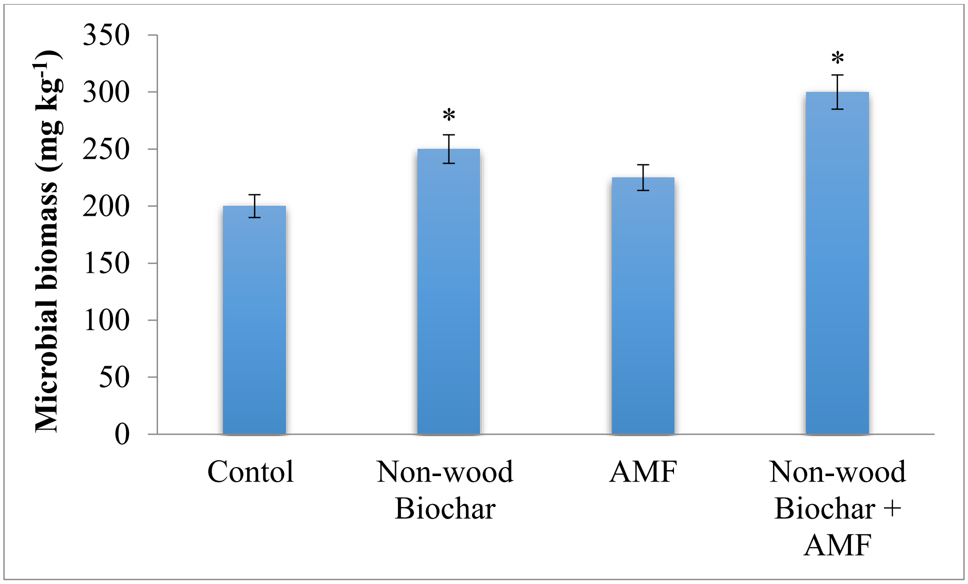

Figure 8: *AMF and Biochar for the enhancement of microbial biomass in the soil. Data are the means of three replicates (n = 3), * asterisk differed significantly at p < 0.05 **

All treatments exhibited a positive impact on alkaline phosphomonoesterase activity, resulting in an increase in enzymatic activity within a range of 59% to 91% (Figure 9). The combination treatment of AMF and biochar resulted in the highest observed alkaline phosphomonoesterase activity in soil. The administration of AMF alone (61%), as well as the combination of AMF and biochar (49%), had a more positive impact on the activity of dehydrogenase in the soil than the control. Moreover, the application of biochar and the combination of AMF and biochar treatment showed a positive impact on the activity of fluorescein diacetate in the soil in comparison to the control treatments. The combined use of AMF and biochar resulted in the greatest enhancement in the activity of fluorescein diacetate, surpassing the control by 59%.

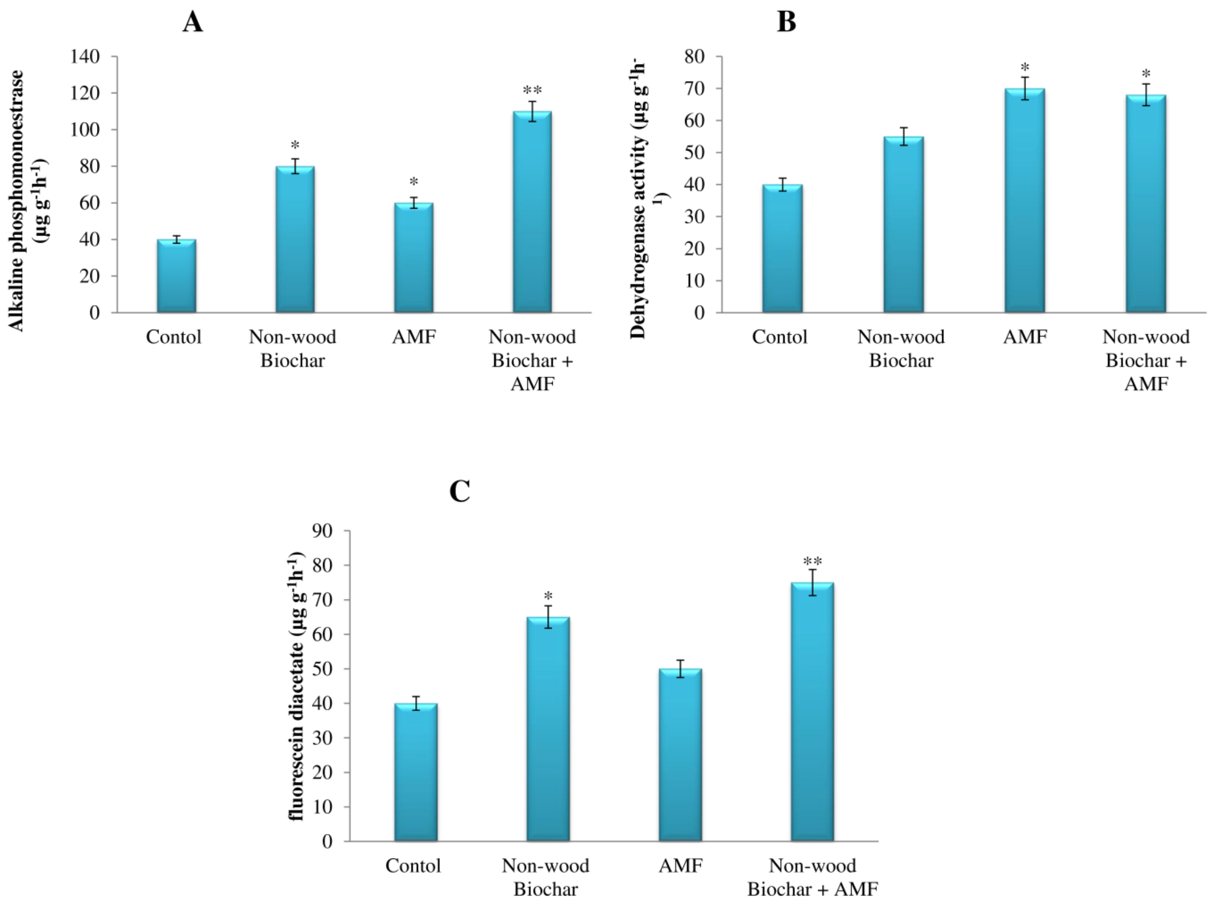

*Figure 9: AMF and Biochar for enhancement of soil enzymes (A) alkaline phosphomonoestrase (B) dehydrogenase (C) fluorescein diacetate. The three replicates (n = 3) are shown as means; *differed significantly at $p < 0.05$ *, $p < 0.01$ ***

4. Discussion

4.1. Impact of AMF and biochar on the Swiss chard growth

Overall, the application of biochar resulted in notable improvements in several aspects of plant growth-related parameters, including length of leaf, shoot length, leaf width, and leaf number, in comparison to the control group. In a similar vein, the application of biochar caused a substantial increase in both the fresh and dry weights of the roots and shoots compared to the control group. This result aligns with the study conducted by Zhang et al. (Zhang et al., 2021), which reported a notable improvement in the development of black locusts when exposed to biochar. Furthermore, Dobariya et al. (Dobariya et al., 2022) revealed that the application of biochar derived from castor waste increased the castor crop biomass. Multiple studies have documented that biochar is effective in enhancing growth and productivity in various crops (Murtaza et al., 2024). Results have been reported by Shoudho et al. (Shoudho et al., 2024) regarding the positive impact of biochar addition on the beans' shoot length, root length, shoot biomass, root biomass, and total yield. Ye et al. (Ye et al., 2020) found that the use of biochar derived from rice husk resulted in higher levels of final biomass, plant height, root biomass, and leaf numbers in cabbage and lettuce plants than the controls. Farrar et al. (Farrar et al., 2021) also documented an increase in dry weight, root biomass, and leaf biomass when biochar was applied. According to Jin et al. (Jin et al., 2024), biochar from rice straw showed a substantial enhancement in the height of the plant, per plant bolls, weight of boll, and seed output when compared to the control plants. The leaf width and number, fresh shoot weight, and dry root and shoot weight all exhibited a notable increase following AMF administration. Several studies have documented that the use of AMF enhanced plant growth characteristics (Begum et al., 2019). In their study, Khajeeyan et al. (Khajeeyan et al., 2024) observed a significant enhancement in plant growth indices of tea plants when AMF were applied. These parameters included the leaf area, leaf numbers, root length, shoot length, plant height, and weight of shoot and root. The simultaneous addition of AMF and biochar yielded positive results in terms of leaf length and numbers, and dry and fresh weights of root and shoot compared to the control. The research conducted by Malik (Malik, et al., 2019) revealed that both AMF and biochar enhanced the growth performance of maize. Ndiate et al. (Ndiate et al., 2021) also had similar findings; their research demonstrated that AMF and biochar substantially enhanced the height of the plants, the diameter of the plants, the dry weight of the roots, and the shoots of the plants in comparison to the control.

4.2. Root morphology changes through AMF and biochar

Significant enhancements in root morphological indices, including total root length, root volume, root diameter, and projected area, were seen after biochar addition in comparison to the control. Several studies have documented that the application of biochar enhanced the growth of plant roots (Kumar et al., 2024), thereby validating our findings. A notable augmentation in root length, root volume, and surface area of the root was documented by Yin et al. (Yin et al., 2024) after the utilization of biochar derived from woodchips and rice residue. Similar findings of substantial enhancement in root development resulting from the incorporation of biochar were also documented by (Ghorbani & Amirahmadi, 2024). Mahmoud et al. (Mahmoud et al., 2022) reported that the use of biochar enhanced root volume, taproot length, and total root area for absorption in tobacco plants. Mona et al. (Mona et al., 2024) reported that the inclusion of biochar had a substantial impact on the structure of the roots at both 40% and 60% field water capacity. AMF administration resulted in a substantial increase in the projected area, total root length, root volume, and root diameter compared to the control. The application of AMF to tomato seedlings resulted in a greater total root length and an increased number of root tips (Liu et al., 2024). The study conducted by Anli et al. (Anli et al., 2020) revealed that AMF have the ability to mitigate root stress by altering the root integrity. Seedlings of Melia azedarach treated with *Gigaspora margarita* exhibited markedly increased plant diameter, height, and dry weight of roots and shoots (Meng et al., 2023). Results on the combined application of AMF and biochar treatment revealed a notable enhancement in both the diameter and total length of the roots compared to the control. This result validates a previous study conducted by Chen et al .(Chen et al., 2020), which demonstrated that the application of both AMF and biochar administration resulted in a substantial enhancement of the chickpea root length. The consumption of underground nutrients and water by plants is significantly influenced by the combined addition of AMF and biochar, and this dependence is also contingent upon the root morphology (Thanni et al., 2024).

4.3. Impact of AMF and biochar on plant physiological attributes

Research demonstrated that the incorporation of biochar had a beneficial impact on the physiological characteristics of chard. Treatment with biochar alone resulted in a substantial increase in both the net transpiration rate and photosynthesis rate. The treatment with biochar also substantially enhanced the levels of chlorophyll a and b, carotenoid, total chlorophyll, and leaf RWC compared to the control group. Several studies have shown that the application of biochar enhances photosynthesis, transpiration rate, and chlorophyll content in several plant species (Duan et al., 2024). In their study, Isik and Ortas (Işik & Ortaş, 2024) found that the use of biochar was associated with a substantial enhancement in both photosynthetic rate and the concentration of chlorophyll in C3 plants. The study conducted by Zulfiqar et al. (Zulfiqar et al., 2021) revealed a significant and beneficial impact of biochar addition on the rate of photosynthesis in okra. Gharred et al. (Gharred et al., 2022) showed that the use of biochar increased the levels of chlorophyll a and chlorophyll b, and total photosynthetic pigments. Treatment with AMF alone increased the net photosynthetic rate, transpiration rate, and stomatal conductance. The inclusion of alone AMF greatly enhanced the levels of chlorophyll a and b, carotenoid, total chlorophyll, and leaf RWC.

Similar findings have been recorded by Cong et al. (Cong et al., 2023), indicating that the introduction of AMF greatly enhanced the activity of antioxidant enzymes and net photosynthetic rate in maize. Inoculation of AMF enhanced the chlorophyll concentration and rate of photosynthesis in chickpeas and maize (Gale & Thomas, 2019). The simultaneous use of AMF and biochar provided beneficial outcomes on the net photosynthesis rate, transpiration rate, stomatal conductance, photosynthetic pigments, and RWC in comparison to the control group (Figures 4, 5, 6). Loo et al. (Loo et al., 2022) have also revealed similar findings, demonstrating that simultaneous use of biochar and AMF substantially enhanced the chickpea RWC, photosynthetic rate, chlorophyll a and b, and total chlorophyll level under control conditions. Rehman et al. (Rehman et al., 2024) found similar results that confirm the substantial increase in photosynthetic rate and chlorophyll levels in corn. As depicted in Figure 10, it is indicated that biochar and AMF can boost siderophore synthesis and nitrogen fixation, simultaneously improving the absorption and availability of nutrients. Furthermore, they stimulate the synthesis of endogenous phytohormones and the creation of antioxidants.

4.4. Impact of AMF and biochar on AMF spore count, microbial biomass, and enzymatic activity of soil

The use of biochar markedly enhanced the activity of fluorescein diacetate and alkaline phosphomonoesterase in comparison to the control. Similar results showing increased enzymatic activity in soil resulting from the incorporation of biochar derived from soybeans were documented by Benaffari et al. (Benaffari et al., 2022). Soussani et al. (Soussani et al., 2023) similarly reported upregulated soil enzymatic activity as a result of biochar treatment. Previous research has documented an elevation in the levels of esterase, protease, lipase-esterase, phosphohydrolase, trypsin, and chymotrypsin enzymes when biochar is applied (Kakabouki et al., 2023). By biochar application, Lopes et al. (Lopes et al., 2021) observed a substantial rise in the activity of urease, phosphatase, and invertase. The highest dose (12 t ha^{-1}) could be observed at depths of the soil ranging from 0 m to 0.1 m. AMF spores and microbial biomass in the soil also exhibited an increase in comparison to the control. Similarly, Aziz et al. (Aziz et al., 2024) reported a comparable rise in AMF spores as a result of biochar addition. Multiple experiments have demonstrated that the administration of biochar enhanced the rates of AMF colonization (Jaffar et al., 2024). In comparison to the control, alone AMF administration increased the activity of dehydrogenase and alkaline phosphomonoesterase activity, AMF spores, and microbial biomass. Yang and Lu (Yang & Lu, (2022) revealed similar results that biochar upregulated phosphatase and urease activities as well as the microbial biomass in soil. The simultaneous addition of AMF and biochar greatly enhanced the enzymatic activity of fluorescein diacetate, dehydrogenase, and alkaline phosphomonoesterase, and also increased AMF spore yield and microbial biomass. The microbial activity in the corn rhizosphere was shown to be greatly enhanced by the simultaneous use of biochar and AMF, as described by Dobo (Dobo, 2022). Figure 10 provides a summary of the mechanism via which biochar and AMF exhibit their combined impact.

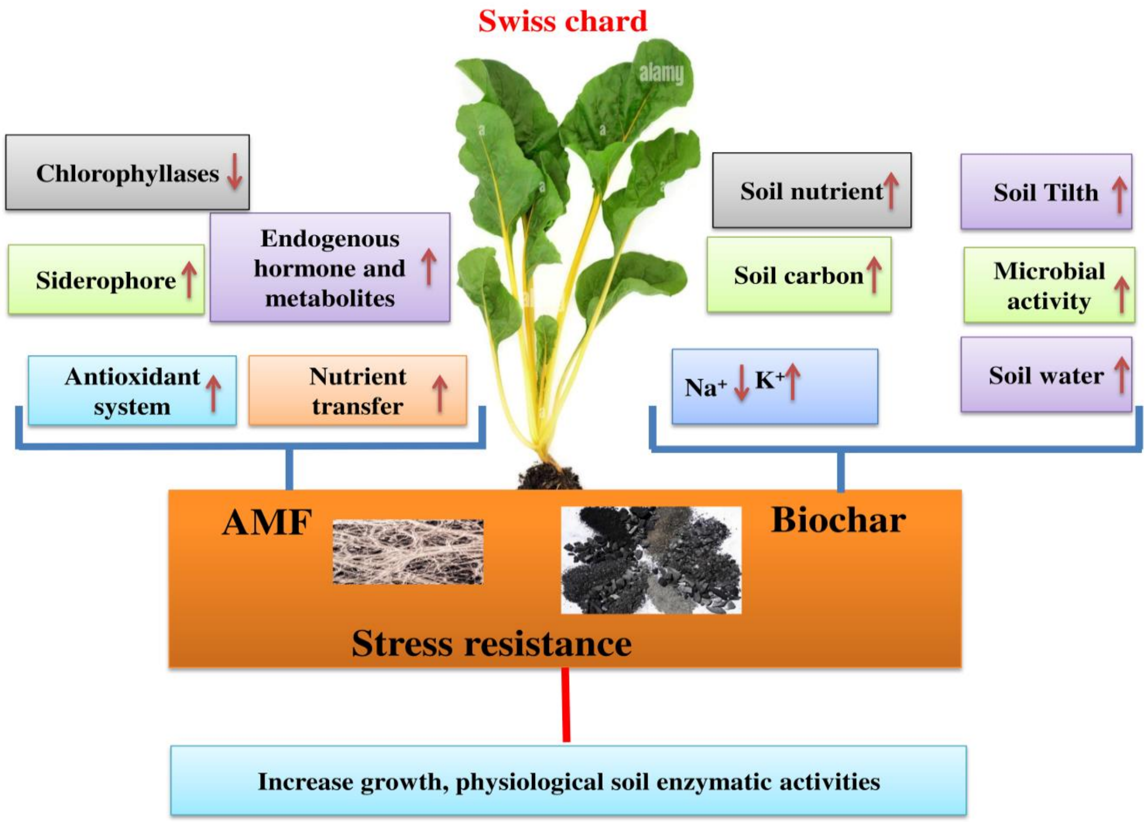

Figure 10: *Mechanism summaries for the synergistic impact of AMF and biochar on enhancing the growth of plants and enzymatic activity in soil*

5. Conclusion

Applying biochar has enhanced the development of root morphological characteristics and promoted plant growth. Furthermore, it has a beneficial impact on enzymatic activity in soil. The synergistic use of AMF and biochar had a notably beneficial effect on the Swiss chard growth, the morphological characteristics of their roots, the physiological attributes, and the enzymatic activity observed in the soil. Therefore, we figured out that conducting more research on the precise interactions among biochars can reduce the need for mineral-based fertilizers. The synergistic usage of AMF and biochar can serve as a highly effective biofertilizer to enhance the growth and productivity of Swiss chard plants in a field trial.

Authors Contributions

G.M. and M.U. designed the sampling strategy. G.M. designed the experiments. G.M performed the experiment. M.U. provided materials and supervision. G.M wrote the manuscript. R.I reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

All the raw data in this research can be obtained from the corresponding authors upon reasonable request.

Ethics declarations

Ethics approval

Permissions or licenses were obtained to collect Swiss chard (*Beta vulgaris*) seeds from the Regional Agricultural Research Institute (RARI) before starting the research. All experimental studies and experimental materials involved in this research are in full compliance with relevant institutional, national, and international guidelines and legislation.

Consent to participate

Not applicable.

Clinical trial number

Not applicable.

Consent for publication

Not applicable.

Competing interests

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

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Research on the Impact of Transportation on Greenery in the Urban Envıronment

Naila Guliyeva [1] **and Oruceli Mirzazade** [1]

[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

The main purpose of this study is to scientifically analyze the impact of the development of transport systems on urban and peri-urban greenery against the background of the urbanization process, to determine the negative effects of transport activity on ecosystems, biodiversity, and the ecological sustainability of the urban environment, and to investigate the possibilities of forming an optimal transport-greenery balance in the context of sustainable urban development. Research method: The study used a systematic approach, comparative analysis, and content analysis methods. Official statistical data, scientific articles, and reports of the European Union and international organizations were analyzed to assess the relationship between transport and greenhouse gas emissions, air and noise pollution, land use, and the reduction of greenery. Research results: The study found that the expansion of the transport sector leads to the reduction of urban greenery, the fragmentation of ecosystems, and an increase in the ecological load. Despite technological advances, the increase in the overall intensity of transport limits the reduction of ecological impacts.

Keywords: transportation, greenery, civilization, technological progress

1. Introduction

The formation of human settlements and the historical stages of civilization development have been closely linked to the development of transport systems. Historically, settlements that arose around trade routes, ports, caravan routes, and later railways have become economic and social centers. Rapid advances in transport technologies, especially after the industrial revolution, have enabled the spatial expansion of cities and the intensification of urbanization. From the introduction of steam engines to modern urban transit systems, the development of transport has acted as one of the main driving forces for the growth of urban areas.

In modern cities, the development of buses, metros, light rail, regional railways, and other types of public transport has not only facilitated the daily mobility of the population but also created conditions for the economic and social integration of remote areas with centers. This process has led to the expansion of cities beyond their administrative borders, the formation of new residential areas, and industrial zones. As a result, the growing transport infrastructure has required the rapid expansion of street networks, bridges, and tunnels, which has led to the intensification of land use and the reduction of urban greenery.

Globally, industrialization and urbanization processes have significantly increased the demands on people's lifestyles, work schedules, and socio-travel behaviors. These changes have had a direct impact on land use structures, transport planning, and infrastructure provision. The increase in land and real estate prices, especially in urban centers, has forced a part of the population to move to the outskirts of cities. Settlement in peri-urban areas has led to increased distances between residences and workplaces, increased daily transport demand, and increased dependence on private cars.

The expansion towards the outskirts of cities has created additional pressure on transport systems, leading to increased traffic jams and a decrease in the efficiency of public transport. This process has also been accompanied by the encroachment of urban and suburban green spaces by transport infrastructure, the fragmentation of ecosystems, and the disruption of green spaces. The reduction of green spaces as a result of the expansion of roads and parking areas has strengthened the "heat island" effect in cities, creating conditions for worsening air quality and reducing biodiversity (Fig. 1).

Thus, while the important role of transport in urbanization and economic development is undeniable, its uncontrolled development has posed serious challenges for urban ecosystems and greenery. In this regard, ensuring a balance between the development of transport systems and the protection of greenery in modern urban planning is one of the main conditions for sustainable development.

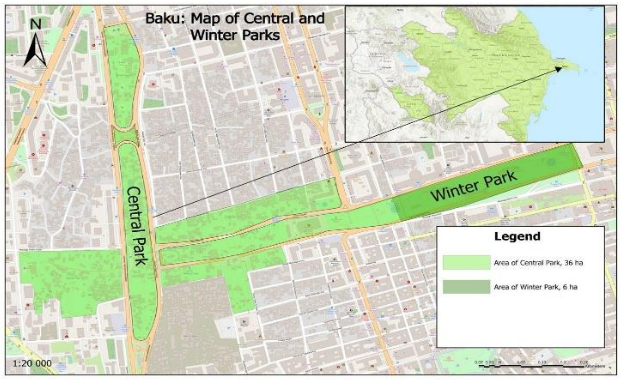

Figure 1. *Baku City Central Park*

The relevance of the research is precisely related to the scientific analysis of the impact of transport activities on urban greenery and the identification of effective approaches to reducing these impacts.

2. Materials and methods

The methodological structure of the study is formed by a systematic approach and multidisciplinary analysis methods that allow us to assess the impact of urbanization processes on urban ecosystems in terms of quantity and quality. To form the material base of the study, international fiscal and environmental organizations, including the European Environment Agency (EEA), transport and emission reports, the European Commission's "Green Deal" strategic documents, Eurostat, and the European Automobile Manufacturers' Association (ACEA), dynamic statistical data covering the years 1990–2024 were used as empirical sources. Also, modern scientific literature studying the impact of transport infrastructure on the urban landscape and biodiversity, including the official methodologies of the World Health Organization (WHO) on acoustic pollution, was involved in the study.

The systematic approach applied in the research process made it possible to consider transport infrastructure, urban green zones, and urbanization dynamics as interdependent components of a single system. A comparative analysis method was used to compare the emission indicators of the transport sector with other economic sectors (industry and energy), and a qualitative content analysis method was used to measure the effectiveness of existing regulatory and legal acts and decarbonization strategies. The impact of transport on greenery was assessed by grouping four main indicators - emission load (CO2 and nitrogen oxides), physical space loss (hardening of the soil cover), acoustic pressure, and thermal effect ("heat island" effect). This methodological approach serves to reveal the contradictions between technological progress and increasing transport intensity and to identify optimal solution models for the ecological sustainability of the urban environment.

3. Research results and discussion

The transport system plays a crucial role in shaping the socio-economic structure of modern society. Transport infrastructure, which ensures the integration of people, cultures, cities, and regions with each other, creates conditions for the continuity of production and trade chains, the expansion of labor markets, and increased access to services. The expansion of road and rail networks, especially in remote and peripheral areas, contributes to increased economic activity, the introduction of agricultural products to markets, and the reduction of interregional inequality (Banister, 2011; Rodrigue, Comtois & Slack, 2020). At the same time, the expansion of transport infrastructure is accompanied by a decrease in urban and peri-urban greenery, soil sealing, and the fragmentation of ecosystems, which pose serious risks to the ecological balance.

Current transport models, especially car-oriented development strategies, have a significant negative impact on the environment and human health. According to the European Environment Agency (EEA), the transport sector is responsible for around a quarter of total greenhouse gas emissions in the European Union and is also one of the main sources of air pollution in urban environments (EEA, 2023a). Nitrogen oxides (NOx), particulate matter (PM2.5 and PM10), and volatile organic compounds (VOCs) from road transport have a negative impact not only on human health but also on the photosynthetic capacity of urban green spaces, plant growth rates, and biodiversity (Nowak et al., 2014).

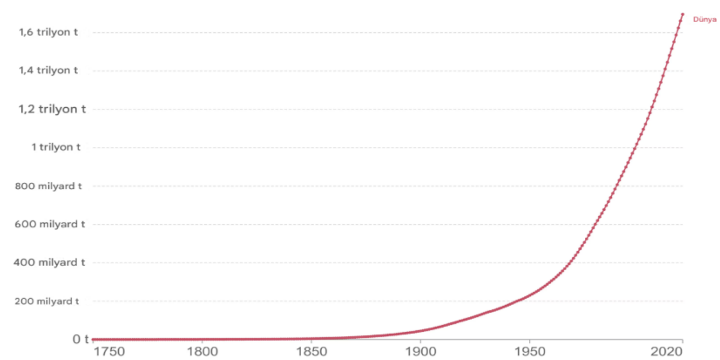

Figure 2: *Growth dynamics of European greenhouse gas emissions*

It is particularly noteworthy that the transport sector is the only major economic sector in Europe where greenhouse gas emissions have increased since 1990. While other sectors – energy production and industry – have made some progress in decarbonisation, the increasing motorisation of transport and the intensification of freight transport make it difficult to reduce emissions (European Commission, 2022). This process weakens the ecological functions of urban green spaces, as high concentrations of pollutants accumulate on the leaf surfaces of plants, reducing their filtration and climate-regulating potential (Fig. 2).

Although technological improvements and increased energy efficiency of transport vehicles are considered important advances, these changes cannot compensate for the increase in overall transport activity. The increasing intensity of passenger cars, trucks, aviation, and maritime transport across Europe leads to persistently high greenhouse gas emissions (IEA, 2023). Increasing traffic density results in the replacement of greenery in the urban landscape with road networks and parking lots, which intensifies the "urban heat island" effect (see p. 1).

Table 1. *The rate of decarbonization of the transport sector and its impact on urban ecosystems*

Indicator / Sector	Trend (Compared to 1990)	Environmental Impact Mechanism	Impact on Urban Green Areas
Total Transport Emissions	+26% increase	Growth in greenhouse gas (CO_2) emissions	Exceeding carbon sequestration capacity
Energy and Industrial Sector	Decreasing trend	Transition to renewable energy sources	Relative reduction of ecological pressure
Road Transport (NOx, PM)	Local decrease	Implementation of the “Euro” emission standards	Increased filtration load on leaf surfaces
Infrastructure Expansion	Rapid increase	Soil sealing and surface hardening	Fragmentation of green corridors
Noise Pollution	High (60+ dB)	Acoustic disturbance	Disruption of biodiversity (bird migration patterns)

Statistics show that in 2022, greenhouse gas emissions from the transport sector in the European Union increased by about 26% compared to 1990 and accounted for 29% of total greenhouse gas emissions (EEA, 2023b). These figures reveal that the transport sector, unlike other major economic sectors, has shown weaker progress in the decarbonization process. While there has been an increase in the share of renewable energy sources and a decrease in emissions due to technological modernization in the energy production and industrial sectors, this positive trend is offset by the increasing level of motorization in transport, the intensification of freight transport and increased intercity mobility. Against the background of the increasing rate of decarbonization of other sectors, the relative share of transport in the total emissions structure is projected to increase further, which creates additional risks for urban ecosystems. In particular, urban and peri-urban green spaces will have to bear a greater burden in terms of compensating for increased carbon emissions. However, the limited area of existing green spaces and the fragmentation of ecosystems significantly limit their carbon absorption potential. As a result, a mismatch is formed between the increase in emissions from transport and the ecological functions of greenery, which weakens the climate regulation capacity of cities and leads to a decrease in the level of ecological sustainability. Despite existing and planned policy measures, greenhouse gas emissions from transport in the European Union are projected to decrease by only 14% by 2030 and by about 37% by 2050. These indicators reveal that current policy mechanisms applied in the transport sector are not sufficiently effective in achieving climate goals. However, the “European Greening Policy” Agreement has set an ambitious strategic target of reducing greenhouse gas emissions in the transport sector by 90% by 2050 (European Commission, 2019). The significant gap between current projections and this target indicates the need for structural and systemic changes in the transport sector. To achieve this goal, technological improvements in transport vehicles and the introduction of alternative fuels alone are not enough. At the same time, environmental priorities at the level of urban and regional spatial planning are required to be strengthened. The protection and expansion of greenery, the formation of green corridors within and between cities, as well as the integrated planning of green spaces with transport infrastructure, can play an important role in reducing emissions. This approach allows for partial compensation of the environmental burden caused by transport by strengthening the carbon absorption and microclimate regulation functions of urban greenery and forms a more realistic basis for the goals of sustainable urban development.

According to preliminary data from the European Automobile Manufacturers’ Association, average CO_2 emissions from newly registered cars continued to decline in 2023. The increasing share of electric vehicles is considered to be the main reason for this positive trend (ACEA, 2024). However, as the expansion of electric vehicle infrastructure also creates additional land use and landscape changes, a long-term balanced approach to urban greening is required.

The movement restrictions, border closures, and economic slowdown imposed during the COVID-19 pandemic have led to a sharp decline in transport activity, leading to a temporary drop in greenhouse gas emissions. According to the European Environment Agency, greenhouse gas emissions from the transport sector in the European Union fell by around 12–15% in 2020 compared to the previous year, the steepest decline recorded in recent decades (EEA, 2023c). The decline in air transport and international passenger transport in particular was one of the main reasons for this decline. However, with the gradual resumption of economic activity and mobility since 2021, emissions from the transport sector have increased again. According to preliminary estimates, transport emissions increased by about 8.6% in 2021 compared to the previous year, and by a further 2.7% in 2022 (EEA, 2023c). This increase is mainly associated with increased private car use, reduced reliance on public transport, and increased freight transport. Thus, the emission reduction observed during the pandemic was not structural, but mainly the result of restrictions imposed by emergency conditions. This trend shows that short-term emission reductions achieved without big structural changes in the transport sector do not produce sustainable results. To achieve sustainable emission reductions, it is necessary not only to limit mobility but also to radically transform transport systems, switch to cleaner and more active modes of transport, and integrate transport planning with urban green spaces and ecological infrastructure. Otherwise, the environmental benefits achieved during temporary crises are rapidly lost during the recovery phase, and the negative impact of transport on urban ecosystems continues.

In recent decades, strict environmental standards applied to road transport, including "Euro" emission standards, the widespread use of catalytic converters and improved fuel quality, have led to some reductions in emissions of a number of key air pollutants – nitrogen oxides (NOx), sulphur dioxide (SO_2) and particulate matter (PM). According to the European Environment Agency, the levels of some air pollutants originating from road transport have decreased significantly compared to the 2000s. However, the opposite trend has emerged in the aviation and maritime transport sectors over the same period, with the increase in international flights and freight transport in particular leading to an increase in emissions in these sectors (UNEP, 2021).

The increase in emissions in the aviation and shipping sectors mainly negatively affects coastal and marine ecosystems, as well as green zones located in port cities. Sulfur compounds and nitrogen oxides emitted from ship engines worsen the quality of sea air and intensify acidification processes in soil and aquatic ecosystems. At the same time, greenery in port areas and coastal cities is directly affected by these pollutants and cannot fully fulfill its ecological functions. This leads to a decrease in biodiversity in these areas and a weakening of the ecological sustainability of the urban environment.

Although the increase in the share of renewable energy sources in the transport sector is considered an important positive trend, the current indicators are still not considered sufficient to achieve the climate neutrality goals. According to Eurostat, the share of renewable energy sources in transport in the European Union in 2022 was only 8.7% (Eurostat, 2023). Although the rapid spread of electric vehicles contributes to the reduction of noise levels in urban environments and the limitation of local air pollution, as long as the overall intensity and spatial expansion of transport continue, the environmental pressure on urban and peri-urban green spaces does not decrease. This shows that long-term environmental sustainability cannot be achieved without integrated planning measures that prioritize the protection of green spaces and the reduction of transport demand, along with technological transformation.

Traffic noise is also a serious problem for urban ecosystems. Long-term noise has a negative impact not only on human health, but also on bird behaviour, biodiversity, and the ecological functions of urban green spaces (WHO, 2018).

Thus, achieving climate neutrality for Europe by 2050 is possible not only through technological innovation, but also through sustainable spatial and ecological planning that takes into account the transport-green interaction. More active modes of transport, green infrastructure, and reduced transport demand should act as the main pillars of this process.

Based on the results of the study and the challenges of modern urbanization, the following list of strategic proposals has been developed to ensure the balanced development of transport systems with urban green spaces. These proposals aim at both environmental sustainability and the efficiency of urban infrastructure:

1. Establishment of a network of "Green Corridors" - It is envisaged to create continuous green strips along the edges of transport highways within the city. This not only has an aesthetic purpose, but also plays the role of a "biological bridge" between ecosystems fragmented by transport infrastructure. Multi-level greening (trees, shrubs, grass) can reduce noise levels by 10-15 decibels and perform the function of a natural filter that prevents the spread of harmful solid particles (PM10, PM2.5) into residential areas.

2. Application of water-permeable infrastructure against "Soil Sealing" - Instead of traditional asphalt pavement on roads and parking areas, environmentally sustainable, porous materials and "grass stones" should be used. This approach does not interrupt the contact of areas allocated for transport with the soil, allows rainwater to integrate into groundwater, and extends the life of urban plants by maintaining the oxygen supply of the root system of trees.

3. Integrated planning of micro-mobility and green zones - Bicycle paths and pedestrian routes should be isolated from highways and run directly inside or outside existing parks and gardens. This encourages the population to move away from private cars and use active modes of transport. As a result, the need for new road expansion projects decreases, and the process of "absorption" of urban greenery by infrastructure stops.

4. Application of Vertical and Roof Greening Systems - In city centers with high traffic density and limited space for additional tree planting, building facades and roofs should be greened. This method neutralizes the "heat island" effect by absorbing heat emissions from traffic and, in addition to increasing the energy efficiency of buildings, improves air quality at the local level.

5. Transition of public transport hubs to the "Eco-Hub" model - Bus stops and metro exits should be designed as "mini-ecosystems" rather than just transport points. Greening the roofs of parking lots and creating small "pocket parks" around them ensures citizens' contact with the ecological environment while waiting for transportation and increases the city's overall "green index".

4. Conclusion

Transport systems have historically been one of the main driving forces of human settlement, urbanization, and economic development. However, in modern times, the development model of transport, especially the automobile-oriented one, has created serious environmental problems such as the reduction of greenery in urban and peri-urban areas, hardening of soil cover, fragmentation of ecosystems, and weakening of biodiversity. As a result of the spatial expansion of cities and the intensive development of transport infrastructure, the ecological functions of greenery – air purification, carbon absorption, microclimate regulation – have weakened, putting the ecological sustainability of the urban environment at risk.

The research results also prove that although technological innovations and increasing energy efficiency in the transport sector are of great importance, these measures cannot fully compensate for environmental pressures against the background of the increase in the total volume of transport activity. Although some progress has been made in reducing greenhouse gas emissions in the European Union, the transport sector still remains one of the main sources of emissions. This situation leads to the fact that urban greenery has to bear the increasing ecological burden alone and its protective potential is limited.

Thus, to achieve a sustainable urban environment, it is necessary to apply a systematic and integrated approach between the planning of transport systems and the protection of green spaces. Promoting cleaner and more active modes of transport, expanding green infrastructure, reducing transport demand, and strengthening environmental priorities in spatial planning should be key directions in terms of protecting urban ecosystems. These approaches can not only reduce the negative impact of transport on the environment but also contribute to ensuring the sustainability of urban green spaces and improving the quality of human life.

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A Study of the Impact of Flood Events on Settlement Areas in the Kish River Basin

Aruz Mikayilov[1], and Elmira Seyidova [1]

[1] Department of Ecology and Environment, School of Advanced Technologies and Innovative Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan

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Abstract

The research will seek to understand the factors that cause flooding in the Kish River basin, the development of the flooding, and the effect of the flooding on the surrounding communities. The region is located on the southern slopes of the Greater Caucasus Mountains. It is under pressure from environmental factors as well as anthropogenic activities. At higher elevations, undulations typically begin with mud-like movements that carry large volumes of sediment down the slope. As you move further into the valley, the narrowing walls and steeper slopes cause the water to gain speed, further exacerbating soil erosion. The danger increases in areas close to the base because towns are situated on fan-shaped deposits of unstable material. The floods devastated life and the economy in Kish, Sheki, and the surrounding villages. Since sudden downpours often overwhelm drainage systems, weather conditions largely determine when floods will occur. As temperatures rise, melting snow puts additional pressure on rivers that are already rising due to stormwater runoff. Human activities such as cutting down trees, farming too close to slopes or allowing animals to destroy vegetation further worsen surface runoff. When vegetation on the slopes decreases, water flows more quickly into the streams below. Instead of relying on a single solution, a combination of green restoration and smart management is required to mitigate the risk. Deep-rooted varieties are planted to slow down the runoff. Changes are made in the methods of ploughing the land to retain moisture. Engineering is required to ensure safety during the management of excess water. Success is not achieved by individual measures, but rather by the extent to which the measures are combined with the principles. Safety is not achieved by using force, but rather by adapting to the environment, which means making a choice that takes the practical changes into account.

Keywords: mountain rivers, river basin, flood, geomorphology, hydrological processes, settlement, erosion.

1. Introduction

The floods in the mountainous regions of Azerbaijan, especially in the southern region of the Greater Caucasus, impact not only the land but also the settlements. The steepness of the mountains, geological changes, types of rocks, weather conditions, and anthropogenic activities altering the soil often result in floods. Out of all the flood-affected areas, the Kish River basin is considered one of the most flood-prone areas in Azerbaijan. This region, in the heart of Sheki-Zagatala, has a special characteristic of constant changes beneath its surface.

Steep slopes, deep river and canyon-type valleys, flood-prone areas covered with large rock fragments, and intensive erosion and denudation processes make the formation of flood flows in the Kish River basin inevitable. Studies show that the parts of the basin above 3.000 m are covered with bare cliffs, nival-glacial debris, and moraines, which activate the initial formation stage of flood masses. At the same time, agricultural lands, urban and rural settlements in the middle and lower reaches, especially the village of Kish, Oxud, and the city of Sheki, have suffered significant damage from flood events. According to historical sources, the Kish River almost completely destroyed the city of Sheki in 1772 and has repeatedly posed a serious threat to settlements in the 20th century and beyond. For this reason, the scientific study of the causes of flood events in the Kish River basin, their impact on populated areas, and flood mitigation measures is of current and strategic importance. Existing research proves that the prevention of flood events cannot be limited to hydrotechnical measures alone; it requires the comprehensive implementation of phyto-meliorative, agronomic, ecological management, and soil conservation measures. Geographic location and general characteristics. The Kish River basin is situated on the southern slope of the Greater Caucasus mountain system and represents one of the most complex and dynamically evolving natural-geographic regions of Azerbaijan in terms of relief, climate, and geological structure. In the center of the Sheki-Zagatala region lies a basin where high mountains meet low slopes and plains. The gaps between these different areas cause nature to constantly reshape the landscape. Observations show that erosion is progressing rapidly here, and floods occur with equal frequency. (Budagov, 1961). Starting near the Kish River - stretching roughly 34km – the basin spreads across over 265 km^2. High peaks of the Greater Caucasus rise along its north edge, yet toward the south, the terrain dips slowly into rolling hills and flat stretches. This setup forces quick shifts in height, making scenery shift fast within small spans (Budagov 1962). Because hills rise sharply here, rainwater rushes fast instead of soaking in. Pools of water rapidly collect and concentrate as they seep into narrow channels in the upper and middle parts of the basin. Rivers become turbulent within minutes because there is little room for them to spread. As the terrain strengthens the flow, its speed increases; floods become more severe because the ground does not allow it to slow down. (Budagov, 1963). People have lived around the Kish River for a long time. Near the village of Kish and the city of Sheki, houses are located in areas where flood waters often reach, that is, in large, flat areas formed by flood waters. Since rivers flow through that area, the danger is very great when storms begin. While this may have something to do with the landform, there is no reason for humans to survive. Scientists are carefully studying these areas to better understand flooding. This study examines the landforms, rock types, water flow, weather conditions, human impacts prior to floods, and current floods in the Kish River region. The main goal of this study is to examine the effects of floods on settlements. In addition, there is a need to come up with strategies that are effective in reducing the risks associated with floods. To achieve this objective, there is a focus on a series of steps. These steps are connected. There is a direction for every step. The direction is clear when all details are aligned. The steps follow one after another, but no progress is made.

Now we need to focus on what is important:

1. Floods in the Kish River basin usually start after heavy spring rains and rapid snowmelt. Steep slopes and saturated soils increase runoff, causing rivers to rise quickly. Water overflows into low-lying areas, especially in narrow valleys and forest loss further worsens flooding;
2. Examining the role of human activities in the development of flood processes;
3. Proposing comprehensive measures to reduce flood risk in the basin.

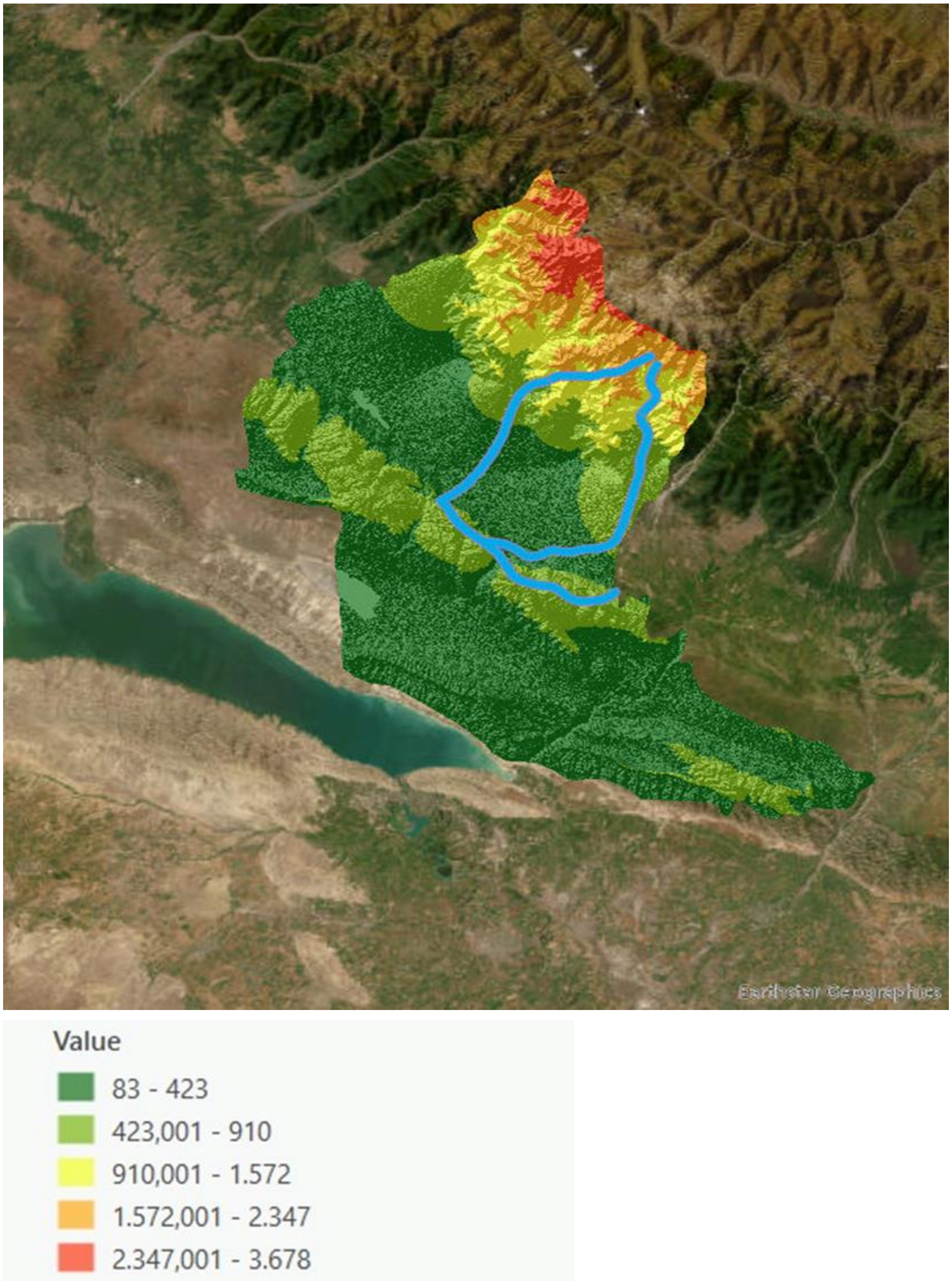
2. Materials and Methods

Flooding patterns in the Kish River basin were examined through landform features, water flow records, and map analysis, along with spatial tools instead of relying on just one method (GIS). Settlement zones felt these impacts directly when overflow occurred during heavy runoff periods. The material basis of the study is scientific publications dedicated to flood and erosion processes on the southern slope of the Greater Caucasus (Budaqov,1963; Rustamov,1978), regional physical-geographical descriptions, hydrological and geomorphological data, as well as cartographic materials reflecting the natural conditions of the Kish River basin, formed the material basis of the study.A digital elevation model (DEM) was used as the primary data source for the analysis of terrain features. Based on the DEM data, the basin's elevation differences, slope angles, and the degree of terrain ruggedness were determined. Height zones were identified and visualized using color imagery by applying the hipsometric analysis method. Geomorphological analysis methods were applied to assess the role of landforms in the formation of flood flows. The prevalence of circular and moraine landforms, steep and canyon-like valleys, the location of alluvial cones, and the steepness of the slope have been considered to be key factors in the occurrence of flood events (Budaqov, 1963; Mustafabayli, 2016). Hydrogeological analysis was conducted using digital elevation model (DEM)-based flow direction and flow collection methods. This methodology allowed us to identify the main river bed, its tributaries, and areas where surface runoff is concentrated, which allowed the identification of areas with high flood risk. Particular attention was paid to flow behavior within the hydrological framework of the study, the rapid increase in surface runoff following heavy rainfall, and the transport of solid materials during flood events.

Cartographic and cartographic-schematic methods were widely applied throughout the study. To assess the spatial distribution of flood events and their interaction with settlements, topographic features, and river networks, elevation zones were integrated and analyzed in a GIS environment. One way to assess the impacts of weather was to analyze heavy rainfall, snowmelt, and climate variability using local climate records and previous studies (Rustamov, 1968; Budagov, 1963). Another approach involved identifying indicators such as historical flood traces, eroded surfaces, changes in river channels, and areas of sediment accumulation through direct field observations and in situ imaging.

3. Analysis and Discussion.

Heavy rains here often lead to swollen rivers because the land tilts sharply down from high mountains. Found along the southe edge of the Greater Caucasus, this region carries water fast throught broken, uneved ground. When storms occur, rising rivers flow down the slopes instead of collecting in one place. The natural structure - steep hills and rugged geography - causes rapid flooding over large areas. The water is constantly moving, transforming isolated waves into widespread downstream movements. In the highest parts of the basin, the mountains are the starting point of events. Glaciers left sacred places there in ancient times. These cavities are covered with piles of rock fragments, and the sediments lie loosely on top of older layers. Rock types break easily when wet. When it rains heavily, the water moves everything around it. Sometimes, melting snow adds more volume, and the soil can't absorb it quickly enough. Water flows along the surface. Steep slopes cause the flow to increase rapidly. The river's speed increases imperceptibly downstream. Flood waters flow through narrow valleys where the riverbed descends step by step. Therefore, with each wave of the river, pieces of rock and gravel are carried downstream. With each wave, they sink deeper into the riverbed and erode the banks. As coastlines erode under pressure, new imprints are created in the soil. More damage increases the likelihood of flooding occurring again. Flooding in the lower reaches of the basin is mainly due to mud accumulation. The risk of flooding is higher in areas where people live in fan-shaped sedimentary beds or in flat river regions. Even when the flow of water slows, piles of debris accumulate there, destroying homes, roads, and farmland. The floods in Kish and Sheki are causing serious damage to lives and livelihoods. People are unknowingly making the floods worse. Cutting down trees, overgrazing animals, and allowing bears to live there weakens the soil and causes it to retain less rainwater. On the contrary, water runs over it quickly. Doing construction work close to the river, performing unwanted excavations, and obstructing the natural water course interfere with the flow of water during a storm. Nature dictates the occurrence of floods. However, human activities provide an added force that further adds to the threat. When both factors occur together, the threat is enhanced. The buildup of water in the Kish River area happens in a complex manner that cannot be addressed in a single manner. Since landforms, water flow, and human activities are interrelated with each other, the solution to the hazard must consider these three factors as interrelated components. By analyzing these three areas together, it is possible to get a better understanding of where the floods might spread and what might be affected. Looking back at the floods in the Kish River area, there is a significant threat. Nature and human life go hand in hand here. These factors act as guides that help construct better strategies in dealing with future threats of floods.



Map 1. The topographic description and elevation band distribution of the Kish River basin were prepared based on a digital elevation model (DEM).

The data collected from the DEM on the GIS device showed the path the water took along the Kish River. Using the hypsometric methods, the different elevations on the terrain were identified and categorized according to their elevations. Then. In the slope-based computation, the streamlines were generated to indicate the source of the main stream. Then, the streams were superimposed on the elevation bands to give a simple illustration of the relationship between landform and drainage. The Kish River runs through different areas, from mountain tops to plains. Its path is determined by the changes in the terrain. Its path is guided by steep slopes rather than gentle slopes. The speed of the water changes where the terrain changes sharply from one level to the next. The river runs from elevations between 83 meters and 3678 meters above sea level. Dark green indicates the areas that are lowland and plain, located at elevations between 83 meters and 423 meters. The rivers run slowly, their beds are wide, and the land slopes gently. The light green indicates the foothills of the mountains. The altitude ranges from 423 to 910 meters. This section is like a bridge, with the mountains allowing the water to flow gently. At this point, when the water is at intermediate levels, it is stable in behavior. From an altitude of 910 meters, the terrain is rough with steep slopes, with the middle section marked in yellow and ending at 1572 meters. At this point, the slopes thicken, which makes the water flow faster downstream. The orange color is shown above, indicating the section rising from 1,572 meters to 2,347 meters. At this point, erosion increases rapidly, with rivers eroding deeper layers in the earth. The red color shown above, rising from 2347 meters, indicates the peaks rising up to 3678 meters, which is the source of the Kish River. The melting of snow and ice from the rivers at this point determines the amount of water flowing downstream. The terrain increases rapidly from a low altitude of 220 meters to a height above 3,500 meters. In this period of growth, changes on this scale occur in a very short period. Because of the different altitudes, transparent layers appear along the path. Climate changes rapidly with altitude. The unique characteristics of the different regions depend on the altitude. The behavior of the terrain, like the weather, is always changing (Rustamov, 1975). The plain area is below 500 meters. It extends for more than 200 meters upwards. The land is very fertile. Crops are grown because of the efforts of the people in the area. In the fields formed naturally, villages develop densely compared to the rest of the land (Rustamov, 1980). Broadleaf forests are present at altitudes between 500 and 1500 meters. However, the cutting down of trees increases the risk of flooding, despite the protective effect of the forests (Mustafabayli, 2016). Subalpine meadows are widespread at elevations of 1500-2500 m, while alpine landscapes are common at 2500-3000 m. These zones are considered the main formation areas for flood flows, as the accumulated snow reserves and precipitation here undergo an intensive melting process during the spring-summer season (Budaqov, 1963). At elevations above 3000 m, cirques, glacial remnants, and bare rock outcrops predominate. In these areas, the weakness of the soil cover and the susceptibility of the rocks to weathering create the initial foci for flash flood events. As a result of vertical zonality, water and rock fragments accumulated in the upper slopes are transported to the lower zones as powerful flood flows, which increases the inevitability of flood events (Budaqov, 1961).

The table below shows the distribution of the basin by elevation intervals.

Table 1. Distribution of Elevation Zones in the Kish River Basin

Elevation Interval (m)	Area (km²)	Share of Total Area (%)
230-520	99	37,5
520-1200	38	14
1200-1700	37	14
1700-2200	41	16
2200-2700	20	8
2700-3200	14	5
3200+	15	6
Mean elevation:1190m		

As this table shows, more than 53% of the basin is above 1,500 m, meaning that the mountainous areas where flash floods form are very extensive. As shown in the table, the largest portion of the area in the Kish River basin belongs to the 230-520 m elevation zone, accounting for 37.5% of the total area. The middle and high mountain belts (1200-2200 m) also have a significant share, which indicates that the terrain is predominantly mountainous. The average elevation of 1190 m proves the diversification of elevations and the existence of geomorphological diversity in the basin. Down in the Kish River basin, land cuts sharply into itself - this shaping plays a big role when floods start up.

Where the mountains rise, the slopes curve sharply; water flows rapidly through narrow ditches shaped by the winding terrain (Budagov, 1961). Above, you'll see bowl-like depressions carved by the ice, and sharp rocks cutting through the landscape, narrow valley extensions; however, they stretch across the landscape in broken lines. On these slopes, the inclinations generally range from 60° to 70° and sometimes exceed the point where cracks sharply divide the soil. Large areas of bare stone are visible on the surface; this prevents the formation of thick layers of soil and causes the material to be quickly washed away when water moves through it. This situation creates moments when flash floods are more likely to occur compared to calmer areas (Alizadeh, 2010). Sellers rush through narrower valleys where steep slopes along the waterway accelerate the flow. Riverbed steps sharpen that rush downstream. Erosion carves out deeper paths here, widening channels across mid-basin stretches. Faster surges follow when terrain funnels rising waters into confined spaces. The active erosion of the slopes causes a large volume of coarse material to be incorporated into the flood flows (Mustafabayli, 2016). *In the lower reaches,* broad alluvial cones have formed as a result of the deposition of soil and rock particles. It is on these cones that the village of Kish and the surrounding settlement areas are located. This factor maximizes the damage potential of flood events, as flood flows here both reduce their velocity and deposit large volumes of material. As a result, settlements are more exposed to the risk of flooding (Mustafabayli, 2017). This structure causes the main source points of the flood flows to be concentrated at elevations of mainly 2000-3000 m (sch 1).

Scheme 1. Orographic Structure of the Kish River Basin

North (3300-3600 m) :	• Main Caucasus Range:rocky outcrops,nival zone
Upper reaches (2500-3000 m) :	• cirque formations, moraines, landslide masses
Middle reaches(1200-2000m) :	• deep valleys, canyons, and steep slopes
Lower reaches(220-800m) :	• wide valleys, alluvial fans, and settlements

This structure causes the primary sources of flood flows to be concentrated mainly at elevations of 2,000-3,000 m.

A river cuts through layers shaped by ancient shifts deep below. Fault lines twist beneath its path, common where mountains fall toward lowlands. Layers from long-ago seas appear alongside newer rubble washed down over time. Hard stone from ages past mixes with loose mud carried by rain and gravity. Much of what lies underfoot comes from times when dinosaurs walked near rising cliffs (Budagov, 1961). Floods often carry chunks of rock because some layers break apart so easily. Water moves through weak spots in

Jurrasic limestone, softening everything nearby. Slippery mud forms when clay-rich shale gets wet, making slopes give way without warning. Rock debris pours into streams after heavy rain eats at sandstone walls. Downstream, big chunks of rock get carried along when sudden floods happen. Cracked and heavily worn Cretaceous limestones mixed with muddy layers add variety to the types of stone found here. These broken-up formations make it easier for slopes to fail, helping trigger slides and similar ground shifts. The power of rushing water grows stronger because debris adds weight and impact (Budagov, 1963). Spread across much of the basin - especially toward its central and lower zones-are layers of loose material like deluvial, proluvial, and alluvial sediment. Reaching dozens of meters thick in certain spots, such buildup shapes how fan-like landforms develop over time. Because floodwaters move them so readily, these poorly bound particiles shift often when rivers swell. As a result, waterways here alter their paths quite regularly. Down in the Kish River basin, waterways twist tightly through the land, feeding frequent floods. Ranging between 0.62 and 1.25 km/km^2, the web of rivers packs more channels than most highland areas hold. Up higher among steep slopes, these streams cluster thickest, speeding up how fast rainwater rushes across the ground (Budagov, 1961). High up where the land climbs sharply, Damarchin begins its flow, shaped by melting snow. Rain pours down on rocky ground, pushing water fast through Chuxadurmaz’s narrow paths. From cold springs and sudden storms, Sariguney gathers strength without warning. When clouds burst above, Qaynar surges forward, pulled downhill by gravity’s pull. Deep in cracked stone layers, hidden waters feed Goytapa, at odd times. Steep walls of earth channel every drop into quick, sharp rises downstream. Small valleys here react violently when rain hammers the soil for too long (Budagov, 1962). Water rushes fast where streams drop sharply, carrying chunks of stone far downstream. When floods hit, boulders roll alongside gravel while sand shifts under muddy swirls. Instead of smooth runs, drops pop up now and then, mostly higher up or midway along the path. These jumps crank up the force, scraping away rock more aggressively (Budagov, 1963). Flow slow down across flat areas, so sand and silt settle out. Near towns, shifting paths become common because of loose bed material. Where the land flattens, streams spread wider, building fan-shaped deposits over time. Unstable beds emerge when sediment drops at bends and blockages form midstream. Close by villages face greater danger from rising water levels during heavy rains. Steep side valleys feed fast-moving flows into main branches downstream. Branch patterns multiply through wet seasons, shaping how floods grow in size (Table 2).

***Table 2**. Key Hydrological Characteristics of the Main Tributaries of the Kish River*

River Name	Length (km)	Catchment Area (km²)	Average Slope
Damarchin	12	46	0.207
Chuxadurmaz	14	48	0.189
Sariguney	9	12	0.262
Qaynar	11	19	0.300 (upper)
Donuzcha	2,7	5-7	high

Down below, several rivers cut through tight gorges-narrow passages where rising water surges forward without slowing. The data reveals how each arm feeding into the Kish varies widely in size and reach, shaping its movement pattern uniquely. Take Qaynar or Sariguney- they drop sharply, rushing with force due to sharp inclines along their path. Even Donuzcha, though brief in stretch, plunges just as abruptly downhill. From above, it looks like nature carved these paths amid peaks, proving elevation drives much of what happens here.

Floods in the Kish River are do not happen by chance or stand alone. Because of land shape, rock type, weather patterns, together with people’s actions they emerge. The way often floods come, also how strong they are, ties tightly to how easily soil washes away there (Budagov, 1962). Hills shape how floods happen. Slopes here often tilt between 35° and 70°, sometimes nearly vertical. Because of such angles, rain slips fast instead of soaking in. Water races downhill without delay. Gullies carved by Damarchin, Chuxadurmaz and Sariguney streams push that rush even harder. Steep-walled channels turn sudden flows into forceful surges. High up in the basin, land climbs fast, starting near 220m and rising to the summit between 3500 and 3685m. Because of this steep change in height, rainwater rushes down slopes while carrying rocks and soil along with it. Weather patterns shape how floods form in the Kish River area. Sitting on the south face of the Great Caucasus, the region shifts in climate as elevation changes - this alters rain, heat, and watr flow (Budagov, 1963). Flooding here often starts with brief yet heavy downpours. When rain falls too quickly, the soil is unable to absorb the water. In this case, the water quickly runs off the surface instead of penetrating the soil. Steep slopes speed up the work, especially in areas where vegetation provides little protection. Changing weather patterns and rotating weather systems are altering the distribution of precipitation across the sky. Floods usually occur within a few hours of heavy rain. Spring and summer storms have a greater impact - rapidly increasing water risks (Rustamov, 1978). The strong volume reductions that occur during sudden and rapid rainfall events alter the soil's ability to withstand these conditions. The sky suddenly turning gray can cause problems downstream when night falls. Snow melting during the winter months plays a significant role in the formation of floods. Rising temperatures in summer accelerate the melting process, especially in areas where snow accumulates at high altitudes in the mountains. If heavy rain falls while the snow melts, the floods will become even more severe. When both forces combine, water levels in rivers rise rapidly and carry tons of trash (Budagov, 1963). The risk of flooding increases, especially in areas where landforms and rock types are similar, when heavy rain combines with melting snow. Weather forecasts are extremely important because they help identify problems before rivers flood. Important things manifest themselves in patterns that are almost impossible to ignore. When floods occur, the movement of water becomes important. Due to the steep slopes and numerous streams, rainwater runs off rapidly; flash floods occur violently and quickly (Budagov,1961). The Kish River, flowing from the mountains, receives its water mostly from melting snow, and some from storms; groundwater contributes less. At higher altitudes, snowmelt directs runoff. Further downstream, heavy rains take the place of runoff. These changes cause river levels to fluctuate sharply throughout the seasons. As spring gives way to summer, rivers often swell rapidly; melting snow mixes with torrential rains, raising the water level so high that it overflows the banks (Budagov, 1985). Floods cause the water level of streams to rise in minutes, shattering riverbeds and dragging rocks and debris downstream. Steep slopes accelerate the flow, causing floods to strike with greater force (Budagov, 1962). In the lower reaches of the basin, floods often carry significant amounts of mud that float in the water. Instead of remaining where they are, rocks that break off from high mountain slopes are carried along rivers. These debris form fan-shaped deposits in areas where streams slow down. These changing flows often reshape river courses, leading to further expansion of alluvial deposits. As the water moves toward lower areas, it carries less material but leaves more material behind. The accumulated debris increases the danger when nearby homes are flooded. Near the village of Kish and the town of Sheki, the behavior of the Kish River significantly influences the outcome of floods. The seasonal patterns are closely linked to the harm felt by the people living there. Floods are becoming more severe across the basin due to human activities. When forests disappear, the soil holds less water, water runoff increases, erosion worsens, and bare areas expand with each heavy rain, especially in the middle parts of the mountains (Alizadeh, 2010). Whereas the soil is kept together by roots, the stakes leave it bare, and this is worsened by overgrazing, which makes it prone to leaching. Unsustainable use of land on steep slopes makes water find new paths to flow rapidly. Construction works that do not follow natural order cause rivers to flow in different beds from their natural courses. Even changing or digging channels alters the rate and distance water can flood. Land that used to remain stable is sliding towards chaos faster when floods come (Alizadeh, 2005). In places like those near Kish and Sheki, agriculture is done in the plains, and during floods, pressure is applied, making restoration works more challenging with each flood (Mustafabayli, 2016). The floods that occur in the Kish River region are a result of a combination of natural and human factors. Land use regulations for the reduction of flood risk must be carried out in conjunction with the protection of trees and forests. Similarly, agriculture must be carried out in accordance with proper scientific principles. As you peruse Table 3 above, you will notice that the slope of the land is a major contributor to flooding. The slopes of the land in this region vary between 37° and 70°. As a result, the rainwater does not seep into the soil but rather runs off the surface. As a result of the speed with which the rain runs up the surface when the slopes are steep due to storms, the angle of the slope is regarded as very important in the formation of floods.

Table 3. *Strength of Main Factors Influencing Flood Formation*

Factor	Impact Strength	Brief Explanation
Slope gradient	high	Slopes of 37-70°
Geological fragmentation	high	Layers of schist and sandstone
Rainfall intensity	high	Short, torrential rains
Snowmelt	high	Intensifies in spring
Deforestation	high	Increases erosion
Overgrazing	medium	Soil compaction and erosion
Channel modification	high	Occurs on alluvial fans

Cracks in the soil play an important role in increasing flooding in the Kish River region. Layered rocks such as shale and sandstone are widespread in the region, are weak against pressure, and disintegrate quickly when wet. Slope debris flows into the flood waters, increasing their force, but not slowing down once they start. When rocks are so easily displaced, rising waters intensify faster than expected. This structure means that what lies beneath directly determines how serious the flood will be. The amount of precipitation is more important than other weather conditions. Even if it is short-lived, heavy rains overwhelm the soil's ability to absorb moisture and cause water to run off the surface rapidly. Since such floods often cause flash floods, their impacts are serious. Warm weather in the spring causes snow to accumulate quickly in the higher parts of the mountains. As temperatures rise rapidly, water flows down from the melting hills. Flooding is worse than usual because it can rain while it's snowing. This mixture quickly turns slow currents into raging waves. Thus, the role of melting snow in measuring hazard levels is clearly evident. Floods become more severe when people cut down forests. Without trees, the soil holds less water. Rain runs off faster instead of soaking into the bare soil. This flowing water erodes the slopes more quickly. When storms occur, larger areas become vulnerable. Flood patterns feel a touch of grazing, but this is less important than many forces. When animals graze too much, vegetation becomes sparse and soil becomes compacted; flooding changes through chain reactions rather than direct causes. Considering how events are connected behind the scenes, the process of bringing the cattle ashore takes it a step further. When the flow of rivers changes due to human-induced changes, flood patterns change dramatically. Instead of flowing freely, water is pushed into new paths, especially into flat areas where soil is formed. These altered routes tend to bring floodwaters closer to homes and roads. Because of this, changing a river's path ranks among the most serious actions that raise flood danger. Floods in the Kish River area happen because nature and people's actions mix in tangled ways. To handle flood risks well, each cause needs to be looked at on its own - yet also how they link together. Not just isolated pieces, but parts of a shifting whole.

4. Conclusion

The conducted research and a comprehensive analysis of the geomorphological, geological, hydrological, and anthropogenic conditions of the Kish River basin indicate that the basin is one of the mountain systems in Azerbaijan with the highest flood risk. The intensity and frequency of flood events are primarily associated with the steep topographic dissection, the widespread presence of steep slopes, the tectonic instability of the geological structure, the easy weathering of schist and sandstone, high rainfall intensity, and strong anthropogenic impacts. In the upper reaches of the basin, especially in Damarçin, in the headwaters of the Chukhadoruz and Sariguney rivers, the flash flood sources are enriched with debris from high mountain rocks, and the downstream transport of these materials in large masses causes successive flash flood events. The middle-order zone is characterized by erosion and deepening of river valleys, which increases the velocity of the flood mass.

Downstream, especially in the areas of Kish village, Baltali, Oxud, and the city of Sheki, the settling of materials in the alluvial cones, frequent channel shifts, and intensified flooding are observed. Human activities such as deforestation, overgrazing, farming on steep slopes, river channel changes, and unplanned construction increase the natural processes that lead to floods. Therefore, flood risk reduction in the basin cannot depend solely on engineering structures. Ecological and landscape management approaches that protect natural systems are also important. As a result, flood safety in the Kish River Basin requires long-term and comprehensive management strategies. These strategies should focus on regulating land use, restoring natural ecosystems, and promoting sustainable environmental practices. Such measures should help protect soil and vegetation, regulate riverbeds, and increase the safety of local communities.

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Research on the Physical and Chemical Properties of Water in Boyukshor and Khojasen Lakes

Ulviyya Karimova-Japharova[1] and Sabir Azimov[1]

[1] Department of Ecology and Environment, School of Advanced Technologies and Innovative Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan

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Abstract

The article is a comparative evaluation of the physicochemical and microbiological parameters of the water in Lake Boyukshor and Khojasan, which are ecologically sensitive water bodies on the Absheron Peninsula. As emphasized in the article's introduction, the lakes have been impacted by the production of oil, industrial wastes, domestic wastewater, and urbanization for a number of years due to the closed hydrological regime and low self-purification ability; as a result, the accumulation of substances has increased. The analysis results show that the pH in both lakes is weakly alkaline (Boyukshor 8.44; Khojasan 8.22), and the temperature is typical for the summer season. Color, turbidity, and salinity indicators are higher in Lake Boyukshor; TDS (35,200 mg/L), electrical conductivity (58,900 µS/cm), and chloride (24,959 mg/L) confirm its hypersaline nature. A dissolved oxygen level of 1.92 mg O_2/L indicates that the oxygen deficit has reached a critical level. In Lake Khojasan, the OCT of 177 mg O_2/L indicates a higher content of oxidizable organic matter, and the high level of enterococci in microbiological indicators indicates that sanitary risks remain strong. The proposed measures include pollution source control, aeration, biogen limitation, it is based on selective sediment treatment and strengthening of systematic monitoring. Overall, the results show that ecological risks are still high in both lakes. However, it shows that the main problems in the lakes are dominated by different directions (hypersalinity and oxygen deficiency in Boyukshor, organic load and microbiological risk in Khojasen).

Keywords: Lake Boyukshor, Lake Khojasan, physical properties, water composition, chemical composition.

1. Introduction

Lakes Boyukshor and Khojasan are considered the largest and most ecologically sensitive water basins of the Absheron Peninsula, and have been subjected to intensive anthropogenic impacts for many years. Since the areas where both lakes are located were formed under the influence of industrial enterprises, transport infrastructures, and densely populated areas, their hydroecological status is of particular importance in terms of the overall ecological security of the region (State Statistical Committee, 2023). In particular, oil production, industrial waste, domestic wastewater, and urbanization processes have seriously affected the water quality of Lake Boyukshor and Lake Khojasan; as a result, significant changes were observed in the physical and chemical properties of water. For this reason, a scientific study of water quality indicators in both lakes is an urgent and necessary issue. The physical and chemical properties of water are among the main indicators in assessing the ecological status of water bodies. Physical parameters such as temperature, color, transparency, turbidity, electrical conductivity, and density characterize the intensity of hydrological and physicochemical processes occurring in the aquatic environment. Chemical indicators reflect the quantity and quality of dissolved substances in water, and these include hydrogen ion concentration (pH), salinity, total hardness, oxygen regime, biogenic elements, heavy metals, and petroleum products. A comprehensive study of these indicators makes it possible to determine the source and scale of pollution processes occurring in Lakes Boyukshor and Khojasan. One of the specific features of both lakes is that they were formed as closed water bodies for a long time, and the natural self-cleaning potential is weak. This factor accelerated the accumulation of pollutants in lakes and caused a disruption in the physical and chemical balance of water. As a result, negative conditions such as increased salinity, oxygen deficiency, and accumulation of heavy metals and petroleum products have occurred in both Boyukshor and it was also observed in the Khojasan lakes. These changes affect not only water quality but also the biological diversity of the lakes and have had a negative impact on the overall health of the environment. According to modern ecological approaches, monitoring of closed water bodies should be carried out continuously and systematically. The study of the physical and chemical properties of water in Lakes Boyukshor and Khojasan will allow for an objective assessment of the current ecological situation, and it will allow for the determination of pollution levels and the scientific planning of future remediation measures. These studies are also important from the point of view of evaluating the efficiency of rehabilitation and reclamation work. The study of the physical and chemical properties of water in Lakes Boyukshor and Khojasan is not only a study of local ecological problems, but it is a means of creating scientific foundations for the protection of water resources in connection with urbanization. The research carried out on this topic is a significant contribution to the issue of ecological security on the Absheron Peninsula, as well as maintaining a healthy aquatic environment for future generations. The scientific literature on the study of the physical and chemical properties of water in Lakes Boyukshor and Khojasan is mostly based on the fact that there has been an intense urbanization process on the Absheron Peninsula **(**Bayramoğlu, 2011). Both lakes are among the most sensitive hydroecological objects on the peninsula and are characterized by long-term accumulation of anthropogenic load. In the literature, there are many studies on the physical and chemical parameters of lake water, especially pH, salinity, electrical conductivity, dissolved oxygen, biogenic elements, biological oxygen demand (BOD), and chemical oxygen demand (COD) monitoring are noted as the main research directions . Studies show that Lakes Boyukshor and Khojasan are particularly vulnerable to external pollutant flows due to their closed hydrological regime and have limited self-purification potential. For this reason, changes in physicochemical parameters turn into cumulative ecological risks in a short time (Hajiyeva et al., 2020). In the hydroecological approach, physical parameters — temperature, turbidity, transparency, electrical conductivity, and salinity — describe the processes of metabolism in water, which explains the mechanism of accumulation of salts and suspended particles, particularly in these lakes. Chemical indicators include the oxygen regime, the intensity of organic pollution, which allows determining the dynamics of nitrogen-phosphorus compounds, and the level of toxic components.In the literature, projects implemented to restore Lake Boyukshor and Khojasan have formed a separate line of research. Official data indicate that industrial and domestic wastewater have been discharged into both lakes for many years. Within the framework of rehabilitation projects, these flows are sharply restricted, and oil products. It is noted that a decrease in the concentrations of heavy metals has been observed. Evaluation of the results of these projects, monitoring the changes in physical and chemical parameters over time, and a comparative analysis of Lake Boyukshor and Lake Khojasen are also important in terms of assessing the real effectiveness of the ecological restoration of water bodies

2. Research object and methodology

2.1.Research object

The main object of this study is the central and western part of the Absheron Peninsula, the aquatic ecosystems of Lake Boyukshor and Khojasan are highly exposed to anthropogenic impact. The object of the study includes the physicochemical composition of the mentioned lakes, which are situated in an area facing significant geoenvironmental problems related to urban groundwater management and industrial impact **(**Alekperov et al., 2006). The object of the study includes the physicochemical composition of the mentioned lakes, water quality indicators, salinity level, and microbiological contamination level. The fact that both lakes have a closed hydrological regime and are located in an urban environment is a reason for assessing the ecological status in the context of modern hydrogeological conditions (Namazov et al., 2024).

Lake Boyukshor is a lake of strategic importance because of its large surface area and past oil pollution. Lake Khojasan was analyzed as an ecosystem directly affected by the residential areas.

As part of the study, the transparency, color, degree of mineralization, and oxygen balance of the lake water were comprehensively studied. The research object includes the following:

- Water mass of Boyukshor and Khojasan lakes;
- Water samples taken from the coastal zones of lakes;
- Physical parameters of water (temperature, turbidity, color);
- Chemical composition of water (pH, chlorides, sulfates, salinity);
- Microbiological indicators (coliform bacteria, enterococci).

2.2. Research methods

The research methodology is based on the principles of water quality monitoring, ecological chemistry, and sanitary-microbiological analysis. To ensure the scientific integrity of the study, laboratory analyses were carried out using methodologies in accordance with international standards (ISO and SM). In the research process, general scientific methods were used - comparative analysis, systematic approach, and statistical evaluation methods. Laboratory tests conducted on samples taken on 10.07.2025 allowed us to compare the current state of both lakes in terms of dynamics.

The main methods used in the study:

- Photometric and titrimetric methods: For the determination of chemical elements (chloride, sulfate, calcium, magnesium);
- Electrometric method: for measuring pH and electrical conductivity;
- Winkler method (or membrane electrode): For the determination of dissolved oxygen;
- Membrane filtration method: For the analysis of microbiological indicators (CFU/100 ml);
- Comparative analysis method: To compare the results with the current sanitary and hygienic standards (SHS) of Azerbaijan.

3. Results obtained and their analysis

The hydrochemical regime of lakes depends mainly on arid climatic conditions and man-made waters **(**Mamedov, 2007). The water of Lake Boyukshor has a high degree of mineralization and is mainly composed of chloride, sulfate, and sodium. In this lake, the evaporation process exceeds precipitation, increasing the concentration of salts, creating a hypersaline environment. The values confirm the hypersaline nature of the lakes, characterized by high concentrations of specific anions and mineral salts, which aligns with recent findings on the physicochemical parameters of water samples from the Absheron region (Hajiyeva et al., 2024). Lake Khojasan, on the other hand, exhibits a more distinct ecological profile due to its morphological structure. Here, high levels of organic pollution (OCT and OBT) strain the oxygen regime of the water and accelerate eutrophication processes (Hajiyeva et al., 2020). Although both lakes play an important role in the landscape structure of the Absheron Peninsula, anthropogenic pressure limits their natural functions. The concept of assessing the ecological status of water bodies was first introduced into scientific circulation in the context of the protection of natural resources and included within the framework of its restoration. In Western scientific approaches, watershed monitoring is considered an important component of the concept of "Sustainable Development". Scientific literature emphasizes the management of aquatic ecosystems, minimizing impact on nature and preserving biological diversity, it is explained as a form of activity that has environmental education as its main goal. This concept emerged in the late 20th century and has been closely linked to the principles of sustainable development. The main idea is to ensure the regeneration and long-term conservation of natural resources while using them (Ceballos-Lascuráin, 1996). One of the most important features of aquatic ecosystem monitoring is that it is based on the principle of environmental responsibility. According to this principle, anthropogenic activities (industrial and domestic effluents) should not exceed the carrying capacity of the ecosystem, nor should they hinder the natural development of flora and fauna species. All interventions, especially in sensitive water bodies such as Boyukshor and Khojasan, must be carried out within established norms and regulations. This fundamentally differentiates a scientific restoration process from disorderly man-made impacts. The theoretical basis of scientific research in water comes from environmental ethics. Ecological ethics entails establishing harmony in the relationship between man and nature. Ecological ethics assert that man not only uses nature but also protects it. This principle of ecology should be applied in aquatic ecosystems under stressful conditions, such as Lake Boyukshor and Lake Khojasan, which are located on the Absheron Peninsula. Scientific research indicates that a well-designed system of monitoring can play an important role in protecting an ecosystem. The information obtained from physical and chemical analysis of water can be used to improve park infrastructure. It can be used to enhance scientific research. In addition, there is also an ecological educational function in the process of restoring water bodies, as well as a function of creating environmental awareness (UNEP, 2020). The implementation of theoretical foundations in the management strategy for Lakes Boyukshor and Khojasan is related to environmental policy in the country. In this case, monitoring activities are not just about collecting numbers; it also has to do with a scientific, educational, and conservation-oriented process. This approach is considered to be more effective in terms of biodiversity conservation (Weaver, 2001). The key principles for protecting aquatic ecosystems include integrity, environmental education, and the involvement of local communities in this process (Honey, 2013). According to Buckley (2011), watershed restoration can make a real contribution to biodiversity conservation with rigorous planning and constant monitoring.

The results obtained as a result of the analysis were as follows:

Table 1. *Physico-chemical indicators of Lake Boyukshor*

№	Parameter	Unit	Result	Measurement uncertainty	Analysis date	Method	Quality requirements
Physico-chemical parameters							
1.	**pH**	**pH unit**	**8,44**		10.07.2025	**ISO 10523:2008**	
2.	**Temperature**	**^{o}C**	**22,2**		10.07.2025	**SM 2550 B:2017**	
3.	**Smell**	**honey**	**0**		10.07.2025	**QOST-3351-74**	
4.	**Color**	**mg Pt /L**	**109,6**		10.07.2025	**ISO 7887 C:2011**	
5.	**Turbidity**	**NTU**	**59,1**		10.07.2025	**SM 2130 B:2017**	
6.	**COD**	**mg O_2/l**	**57**		10.07.2025	**SM 5220 B:2017**	
7.	**Ammonium as Nitrogen**	**mg/L**	**0,78**		10.07.2025	**SM 4500-NH_3^- C:2017**	
8.	**Total hardness**	**mg $CaCO_3$ /L**	**13100**		10.07.2025	**SM 2340 C:2017**	
		mg-ekv/L	**262**				
9.	**Bicarbonate**	**mg /L**	**1232**		10.07.2025	**ISO 9963:1994**	
10.	**Total Dissolved Solids**	**mg/L**	**35200**		10.07.2025	**SM 2510 B:2017**	
11.	**Dissolved oxygen**	**mg O_2/l**	**1,92**		10.07.2025	**SM 4500 0_2 C:2017**	
12.	**(Cl^-) Chloride**	**mg/L**	**24959**		10.07.2025	**İSO 9297:1989**	

№	Parameter	Unit	Result	Measurement uncertainty	Analysis date	Method	Quality requirements
Physico-chemical parameters							
13.	Nitrate as Nitrogen	mg/L	7,6		10.07.2025	SM 45 00NO_3^- D:2017	
14.	(NO_2^-) Nitrite as Nitrogen	mg/L	<0,006		10.07.2025	SM 4500 NO_2^- :2017	
15.	(SO_4^{2-}) Sulfate	mg/L	3593		10.07.2025	SM 4500 SO_4^{2-}-E:2017	
16.	Phosphate as phosphorus	mg/L	13		10.07.2025	SM 4500 P C:2017	
17.	Transmittance	%	53,0		10.07.2025	SM 2120 D:2017	
18.	Conductivity	µS/cm	58900		10.07.2025	SM 2510 B:2017	
19.	BOD	mg O_2/l	15,5		15.07.2025	SM 5210 B:2017	
20.	İron	µg/L	<1		11.07.2025	EPA 200.7:2001	
21.	Manganese	µg/L	5,6		11.07.2025	EPA 200.7:2001	
22.	Zinc	µg/L	1,1		11.07.2025	EPA 200.7:2001	
23.	Nickel	µg/L	<1		11.07.2025	EPA 200.7:2001	
24.	Cobalt	µg/L	<1		11.07.2025	EPA 200.7:2001	
25.	Chromium	µg/L	1,3		11.07.2025	EPA 200.7:2001	
26.	Molybdenum	µg/L	<1		11.07.2025	EPA 200.7:2001	
27.	Cadmium	µg/L	<1		11.07.2025	EPA 200.7:2001	
28.	Lead	µg/L	<5		11.07.2025	EPA 200.7:2001	
29.	Copper	µg/L	<5		11.07.2025	EPA 200.7:2001	

The results of physicochemical and microbiological analyses conducted on Lake Boyukshor allow for a comprehensive assessment of the current ecological state of the lake (Hajiyeva et al., 2017). The quality of the aquatic environment is not only determined by comparing individual indicators with standards, but it is also determined based on an analysis of the interactions between these parameters. The presented indicators clearly reflect the intensity of both natural and anthropogenic processes in the lake. A pH of 8.44 indicates that the aquatic environment is alkaline. This situation is due to the climatic characteristics of the Absheron Peninsula, which is explained by the high evaporation rate and the abundance of salts dissolved in the water. An alkaline environment is characterized by the presence of some biogenic elements, and it can affect the behavior of heavy metals in water, changing their sedimentation or bioavailability. The temperature of 22.2 °C is considered typical for the summer season and creates conditions for the acceleration of biochemical reactions. Color (109.6 mg Pt/L), turbidity (59.1 NTU), and light transmittance (53%) indicate that the water in the lake is loaded with large amounts of suspended particles and colloidal matter. Physical parameters are often associated with organic pollution, surface runoff, and re-mixing of bottom sediment. High turbidity may influence the oxygen balance in the ecosystem in a negative way by limiting photosynthesis. Chemical parameters clearly indicate the level of pollution in the lake. The values of OKT

(57 mg O_2/L) and OBT_5 (15.5 mg O_2/L) indicate a large amount of organic matter in the water. This led to intensive oxygen consumption and a critically low dissolved oxygen level of 1.92 mg O_2/L. Such conditions create stress for aquatic organisms and can lead to the dominance of anaerobic processes. The very high total dissolved salts (35200 mg/L), electrical conductivity (58900 µS/cm), and chlorides (24959 mg/L) indicate that the lake water is hypersaline in nature. This situation is closely related to Lake Boyukshor being a closed water body, strong evaporation, and long-term pollution. High hardness (13100 mg $CaCO_3$/L) and sulfate (3593 mg/L) levels confirm that the water is exposed to man-made influences. Regarding biogenic substances, ammonium nitrogen (0.78 mg/L), nitrate nitrogen (7.6 mg/L) and phosphate phosphorus (13 mg/L) indicate a high risk of eutrophication. Especially high concentrations of phosphate can accelerate the processes of algal bloom and oxygen deficiency. Most trace elements and heavy metals present at low or below the detection limit can be considered a positive case. Microbiological indicators showed very high levels of total coliform bacteria; however, E. coli was not detected, indicating a predominantly non-fecal microbiological contamination.

Table 2. *Physico-chemical indicators of Lake Khojasen*

№	Parameter	Unit	Result	Measurement uncertainty	Analysis date	Method	*Quality requirements*
			Physico-chemical parameters				
30.	**pH**	**pH unit**	**8,22**		10.07.2025	**ISO 10523:2008**	
31.	**Temperature**	**^{O}C**	**22,3**		10.07.2025	**SM 2550 B:2017**	
32.	**Smell**	**honey**	**0**		10.07.2025	**QOST-3351-74**	
33.	**Color**	**mg Pt /L**	**85**		10.07.2025	**ISO 7887 C:2011**	
34.	**Turbidity**	**NTU**	**53,9**		10.07.2025	**SM 2130 B:2017**	
35.	**COD**	**mg O_2/l**	**177**		10.07.2025	**SM 5220 B:2017**	
36.	**Ammonium as Nitrogen**	**mg/L**	**1,5**		10.07.2025	**SM 4500-NH_3^- C:2017**	
37.	**Total hardness**	**mg $CaCO_3$ /L**	**1300**		10.07.2025	**SM 2340 C:2017**	
		mg-ekv/L	**26**				
38.	**Bicarbonate**	**mg /L**	**756**		10.07.2025	**ISO 9963:1994**	
39.	**Total Dissolved Solids**	**mg/L**	**27300**		10.07.2025	**SM 2510 B:2017**	
40.	**Dissolved oxygen**	**mg O_2/l**	**4,21**		10.07.2025	**SM 4500 0_2 C:2017**	
41.	**(Cl^-) Chloride**	**mg/L**	**20917**		10.07.2025	**İSO 9297:1989**	
42.	**Nitrate as Nitrogen**	**mg/L**	**8,3**		10.07.2025	**SM 45 00NO_3^- D:2017**	

№	Parameter	Unit	Result	Measurement uncertainty	Analysis date	Method	*Quality requirements*
Physico-chemical parameters							
43.	**(NO_2^-) Nitrite as Nitrogen**	**mg/L**	**<0,006**		10.07.2025	**SM 4500 NO_2^- :2017**	
44.	**(SO_4^{2-}) Sulfate**	**mg/L**	**3304**		10.07.2025	**SM 4500 SO_4^{2-}-E:2017**	
45.	**Phosphate as phosphorus**	**mg/L**	**2,3**		10.07.2025	**SM 4500 P C:2017**	
46.	**Transmittance**	**%**	**61,8**		10.07.2025	**SM 2120 D:2017**	
47.	**Conductivity**	**µS/cm**	**45500**		10.07.2025	**SM 2510 B:2017**	
48.	**BOD**	**mg O_2/l**	**13,5**		15.07.2025	**SM 5210 B:2017**	
49.	**İron**	**µg/L**	**13,5**		11.07.2025	**EPA 200.7:2001**	
50.	**Manganese**	**µg/L**	**21**		11.07.2025	**EPA 200.7:2001**	
51.	**Zinc**	**µg/L**	**6,7**		11.07.2025	**EPA 200.7:2001**	
52.	**Nickel**	**µg/L**	**3,8**		11.07.2025	**EPA 200.7:2001**	
53.	**Cobalt**	**µg/L**	**1,5**		11.07.2025	**EPA 200.7:2001**	
54.	**Chromium**	**µg/L**	**<1**		11.07.2025	**EPA 200.7:2001**	
55.	**Molybdenum**	**µg/L**	**6,5**		11.07.2025	**EPA 200.7:2001**	
56.	**Cadmium**	**µg/L**	**<1**		11.07.2025	**EPA 200.7:2001**	
57.	**Lead**	**µg/L**	**<5**		11.07.2025	**EPA 200.7:2001**	
58.	**Copper**	**µg/L**	**<5**		11.07.2025	**EPA 200.7:2001**	
Microbiological parameters							
59.	**Total Coliform Bacteria**	**CFU/ 100 ml**	**$5,4x10^4$**		12.07.2025	**SM 9222 B:2017**	
60.	**E.Coli**	**CFU/ 100 ml**	**0**		12.07.2025	**SM 9222 B:2017**	
61.	**Enterococci**	**CFU/ 100 ml**	**$6,0x10^3$**		15.07.2025	**EN ISO 7899-2:2000**	

Source: Prepared by the author's own research.

The table presented reflects a comprehensive analysis of the water sample of Lake Khojasan on physicochemical and microbiological indicators, and the results allow for an assessment of the water quality status. According to the analysis, the pH value is 8.22, indicating a weakly alkaline environment, which is in line with the generally accepted range for natural waters. The temperature of 22.3 °C indicates that the sample was taken under seasonal conditions. However, the turbidity (53.9 NTU) and color index (85 mg Pt/L) are high, which indicates a high concentration of suspended particles and organic matter in the water. This indicates poor aesthetic quality and the need for additional cleaning steps. High chemical oxygen demand (COD = 177 mg O_2/L) indicates the presence of oxidizable organic and inorganic substances in the water, indicating an abundance of inorganic substances. However, the BOD_5 indicator of 13.5 mg O_2/L confirms the presence of biodegradable organic pollution. Dissolved oxygen at a level of 4.21 mg O_2/L indicates a weakened oxygen balance in the aquatic environment. Mineralization indicators are particularly noteworthy. Total dissolved salts (TDS = 27,300 mg/L) and the very high electrical conductivity (45,500 µS/cm) indicate that the water is highly saline. The high concentrations of chloride (20,917 mg/L) and sulfate (3,304 mg/L) ions reinforce this result. A total hardness of 1300 mg $CaCO_3$/L indicates that the water is very hard, which can cause problems in technical use. Concentrations of heavy metals (iron, manganese, zinc, nickel, etc.) are relatively low, and most are below the detection limit, indicating that toxic metal contamination is not serious. However, microbiological indicators are risky: high levels of total coliform bacteria (5.4×10^4 CFU/100 ml) and enterococci (6.0×10^3 CFU/100 ml) pose a sanitary-epidemiological threat, highlighting the ongoing impact of natural and anthropogenic factors on the microbiological quality of water resources in the region (Jafarova, 2026).

Lakes Boyukshor and Khojasan are closed water bodies located on the Absheron Peninsula; despite being formed under similar climatic and anthropogenic conditions, they exhibit certain differences in terms of water quality indicators. The pH values in both lakes are 8.44 and 8.22, respectively, reflecting a weakly alkaline environment, which is also associated with high evaporation and mineral accumulation. The fact that temperature readings are almost at the same level (22.2–22.3 °C) indicates that seasonal effects are similar for both lakes. In terms of physical indicators, turbidity (59.1 NTU) and color (109.6 mg Pt/L) in Lake Boyukshor are higher than in Lake Khojasan. This indicates that the re-mixing of suspended particles, colloidal substances, and bottom sediments in Boyukshor is more intense. In terms of chemical indicators, the total dissolved salts in Lake Boyukshor (35,200 mg/L), the fact that its electrical conductivity (58,900 µS/cm) and chlorides (24,959 mg/L) are significantly higher than those of Lake Khojasan proves that it is more hypersaline in nature. At the same time, the critically low level of dissolved oxygen in Boyukshor (1.92 mg O_2/L) indicates that the oxygen deficit is more acute. The fact that the OCT index (177 mg O_2/L) in Lake Khojasan is significantly higher than in Boyukshor indicates that there are more oxidizable organic substances in the water. Although microbiological indicators are risky in both lakes, the level of total coliform bacteria (1.36×10^5 CFU/100 ml) in Boyukshor is higher than in Lake Khojasan. Thus, the comparison shows that Lake Boyukshor, with its higher salinity and oxygen deficiency, is characterized by stronger organic pollution.

The results of the conducted physicochemical and microbiological analyses show that the ecological status of Lake Boyukshor is still in a high-risk zone and necessitates the implementation of complex, phased, and scientifically based measures to improve this situation. The proposed measures should be aimed at both eliminating pollution sources and restoring the lake's own ecological functions.

- First of all, the full identification and control of pollution sources entering the lake should be identified as a top priority. The channels through which surface flows, rainwater, industrial, and domestic waste enter the lake should be mapped, and primary mechanical and biological treatment systems should be established for these flows. Especially considering the high organic matter load, the direct discharge of wastewater into the lake should be completely stopped.
- Critically low dissolved oxygen levels pose a serious threat to biological life. To reduce the high organic load in the lakes, advanced treatment technologies such as the photocatalytic removal of organic pollutants could be considered as part of a long-term remediation strategy (Khalilova et al., 2018).
- Due to the high concentration of nitrogen and phosphorus compounds, the entry of biogenic substances into the lake is to be minimized. In this regard, the system of fertilizers and domestic waste management is to be improved in the surrounding areas, along with the creation of a green zone. At the same time,

the introduction of phosphorus-absorbing substrates or phytoremediation methods will increase the lake's self-regulating ability.

- Taking into account the high salinity and mineralization of the water, measures should be taken to regulate the hydrochemical balance. If possible, a controlled supply of relatively low-mineralized water to the lake, optimizing the water balance and reducing the impact of evaporation, can help stabilize the lake's physical and chemical parameters. Although this process requires long-term planning, it is important for ecosystem restoration.
- Sediments, where organic matter and pollutants have accumulated over a long period of time, act as a secondary source of pollution for the lake. Therefore, it is advisable to apply technologies such as selective removal, stabilization, or capping of sediments. These measures prevent toxic substances from re-entering the water column.
- High levels of total coliform bacteria are considered to be a sign of sanitary risks. In this case, it is necessary to carry out microbiological monitoring, disinfection of possible sources of contamination, and a risk analysis for public health. At the same time, it is necessary to introduce temporary restrictions on recreational activities, and economic activities around the lake should also be considered.

4. Result

The measurements conducted confirm that the water quality of Lake Boyukshor and Lake Khojasan is characterized by a high level of risk indicators from an ecological standpoint. The most critical result of the conducted analysis is the low level of dissolved oxygen. This, in combination with a high level of organic matter (indicated by OCT and OBT_5), can lead to anaerobic processes in the aquatic ecosystem. The hypersaline character of the water (high TDS, chloride, and electrical conductivity) indicates a high level of evaporation processes in the lake's water balance. At the same time, it acts as a limiting factor in terms of biological diversity. The high level of phosphate phosphorus indicates a high level of eutrophication and algal bloom in the lake. This suggests that these processes can further contribute to a deficiency in oxygen.

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The Role of Ecotourism in Biodiversity Conservation on the Caspian Sea Coast of the Shirvan Nature Reserve

Govhar Aydamirova and Arzu Gondolova
[1] Department of Ecology and Environment, School of Advanced Technologies and Innovative Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan

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Abstract

This article presents a scientific and theoretical analysis of the impact of ecotourism activities on the conservation of biological diversity in the coastal region of the Shirvan Nature Reserve. The main objective of the study is to determine the role of ecotourism in biodiversity conservation based on the natural ecological characteristics of the reserve, as well as to assess the principles of sustainable development of the activity. The study of the protected area's natural geographical features and the ecological benefits of its position on the Caspian Sea coast is a component of the research endeavor. Another part is to systematically study the interactions between semi-desert ecosystems and wetlands based on scientific sources. The study analyzed the diversity of the reserve's flora and fauna. The role of ecotourism in the conservation of rare and endangered species was assessed. It has been found that well-planned, scientifically based ecotourism activities can make a positive contribution to the protection of biodiversity and the strengthening of environmental awareness. In addition, ecotourism has been found to have a positive impact on the socio-economic development of the local population. It has also been found to increase employment and foster a responsible attitude towards environmental protection. However, it has been observed that the unplanned and uncontrolled implementation of ecotourism has a negative impact on ecosystems. The text emphasizes the importance of planning ecotourism activities based on the principle of sustainability. Establishing monitoring mechanisms and implementing science-based management measures are also essential for the sustainable protection of biodiversity.

Keywords: biodiversity, ecotourism, Shirvan National Nature Reserve, Caspian Sea coastal ecosystems, sustainable development

1. Introduction

In recent decades, the rapid loss of biodiversity has become one of the most serious environmental challenges around the world. Factors such as industrial development, intensive agriculture, urban expansion, the excessive use of natural resources, and climate change have significantly affected ecosystems and reduced their stability (Məmmədov & Xəlilov, 2006; Millennium Ecosystem Assessment, 2005). Many studies show that biodiversity loss creates not only environmental problems but also economic and social risks (Dasgupta, 2001).

Specially protected natural areas play an important role in addressing this problem. These zones play an important role in maintaining ecological balance, providing ecosystem services, and protecting endemic species (Ismayilov, 2005). The Republic of Azerbaijan's advantageous geographical location plays an essential role in ensuring biodiversity, and the protection of this natural resource has been identified as the country's number one priority (Xəlilov, 2006).

One of the most important protected regions in Azerbaijan's Caspian Sea coastal region is the Shirvan State Nature Reserve. The reserve includes different ecosystems such as semi-desert landscapes, coastal territories, and wetlands, which support a variety of plant and animal species. In particular, protecting the population of gazelles and preserving the habitats of migratory birds are among the main conservation goals of the reserve (ETSN, 2022).

The concept of ecotourism was first introduced into scientific circulation by Ceballos-Lascuráin and explained as "a form of nature-based, ecologically responsible tourism." In Western scientific approaches, ecotourism is considered an important component of the concept of sustainable development. The concept of ecotourism is explained in the scientific literature as a form of tourism that has minimal impact on nature and that considers biodiversity conservation and environmental education as its main goals. This concept was first formulated in the late 20th century and is closely associated with the concept of sustainable development. The main idea of ecotourism is to ensure the restoration and long-term conservation of natural resources while using them (Ceballos-Lascuráin, 1996).

The main principles of ecotourism are ecosystem protection, environmental education, and participation of local communities (Honey, 2008). Buckley (2011) notes that ecotourism can only make a real contribution to biodiversity conservation if serious planning and control mechanisms are in place.

Ecotourism helps to create a responsible attitude towards nature in society through environmental education (Ballantyne & Packer, 2011). In addition, revenues from ecotourism play an important role in the protection of reserves and funding of scientific research (Eagles et al., 2002).

Involving local communities in ecotourism stimulates socio-economic development and makes biodiversity conservation a social responsibility. The impact of ecotourism on biodiversity conservation is multifaceted and encompasses ecological, social, and economic aspects. These impacts are especially evident in specially protected areas.

First of all, ecotourism plays an important role in environmental education. Visitors to the reserve are informed about the natural environment and rare and endangered species. As a result of this process, people develop a responsible attitude towards nature and strengthen ecological behavior. Ecological education is one of the main factors that has a positive impact on the protection of biodiversity in the long term.

The second important impact is related to the formation of financial resources. Eco-tourism revenues can be used to maintain reserves, do research, or repair destroyed habitats. In Shirvan Nature Reserve, such revenues would be helpful in conducting tracking of animals as well as the initiatives for increasing populations of the antelopes native to the reserve. At times, a steady source of revenue makes it possible to plan in the long term for the preservation of nature.

Nature tourism gives people an opportunity to improve the local economy and the social conditions of their settlements. When participating in ecotourism ventures, locals may increase their salaries as well as find new directions in which to work, thus improving economic conditions. With the change in approach, the protection of nature takes a new dimension since wildlife conservation becomes locals' business, not just some government project

In addition, ecotourism offers great opportunities for science to progress further. During guided hikes along paths, scientists observe the natural behavior of organisms that are not disturbed by human activity. The result of such research is a better understanding of the species' well-being based on the patterns observed. Changes that can be monitored help determine the correct action required for conservation. Information on the dynamics of changes becomes clearer due to the gentle observation of nature

Non-destructive influence is one of the most essential principles of ecotourism. The idea behind it is that no trip must lead to an ecosystem collapse or interfere with wildlife. Limitations on human activities, such as using designated routes and following rules, are important to minimize the negative impact on the environment. Such constraints distinguish small-scale travel from overcrowded destinations

Another thought which is behind ecotourism can be linked with the moral concept of nature. Moral conception suggests that people have to improve their relations with nature. Utilization of natural resources should go together with the protection of nature. It is especially important when it comes to vulnerable ecosystems like Shirvan State Nature Reserve.

Ecotourism that is carefully developed can play an essential role in protecting natural sites on scientific principles. Money made from it often flows into better reserve facilities instead of vanishing elsewhere. Some pay for studies that track animal behavior over time. Monitoring setups also get funding where they might otherwise lack support. In addition, ecotourism also performs an ecological education function and serves to form the ecological awareness of society.

In recent years, the development of ecotourism has created new opportunities in such areas, both in terms of conservation and education. In international scientific publications, ecotourism is considered an area of activity that acts as a bridge between biodiversity conservation and sustainable development (Weaver, 2008; Honey, 2008). However, the impact of ecotourism is not unambiguous and can only yield positive results if planned on scientific grounds (Buckley, 2011).

The main objective of the study- The aim of this study is to systematically investigate the impact of ecotourism on biodiversity conservation in the Caspian coastal zone of Shirvan State Nature Reserve from scientific, theoretical, and practical aspects. Within the framework of this goal, determining the role of ecotourism in preserving the ecological balance existing in the reserve area and assessing the advantages and limitations of ecotourism activities in terms of sustainable biodiversity conservation have been identified as key priorities. At the same time, the study also included an analysis of the level of compliance of the current situation in the Shirvan State Nature Reserve in comparison with successful models of ecotourism applied in international practice for biodiversity protection.

To achieve the goal of the study, the following tasks were identified:

- To determine the general natural and geographical features of the Shirvan State Nature Reserve and the impact of the Caspian coastal areas on ecosystems;
- To assess the current state of biodiversity in the reserve;
- To analyze the mechanisms of impact of ecotourism on biodiversity, to determine the ecological impacts of this type of activity.
- To evaluate the possibilities of implementing a sustainable ecotourism model by analyzing the methods of planning and managing ecotourism in the Shirvan Reserve;
- To determine the impact of a sustainable ecotourism model on the protection of biodiversity in the area, maintenance of ecological balance, and socio-economic development of local communities.

2. Research object and methods

2.1. Research object

- The object of the study is the natural ecosystems of the Shirvan State Nature Reserve located in the Caspian coastal zone and the ecotourism activity formed in interaction with the protection of biodiversity within those ecosystems. The study focused on semi-desert and wetland landscapes, the diversity of flora and fauna in the area, especially the gazelle population and migratory bird species.
- In addition, ecotourism routes, observation infrastructure, visitor flows, and the mechanisms of impact of these activities on biodiversity were comprehensively assessed in the reserve. In the context of the interaction between tourism and conservation activities, a systematic approach was used; the study subject was not restricted to natural elements.

2.2. Research methods

Modern approaches to ecotourism, the principles of ecological management, and the idea of sustainable development formed the basis of this study's methodology. In order to thoroughly analyze the subject, the whole study used a methodical approach. To guarantee the validity of the research findings, theoretical and practical techniques were used.

Based on international scientific research, a methodology was established, which included an assessment based on government statistics and the experience gained from observations of other countries. Further, the results had to be collated and reconstructed into more detailed conclusions about the effect of natural tourism on biodiversity. Trends started to appear during extrapolation and interpolation, gradually providing broader results. Every stage was linked to reality, forming opinions based not on subjective suppositions but on objective logic.

The degree of correspondence between international models of eco-tourism and existing practices in the Shirvan Reserve was estimated using the comparative method of analysis. The application of statistical and dynamic methods made it possible to identify the condition of biodiversity and, specifically, the dynamics of the gazelle population.

The study focused on ecological risk assessment. Using this method, it was possible to identify possible ecological risks associated with an excessive increase in ecotourism activities and to suggest the best management strategies. Additionally, the idea of carrying capacity has been used to theoretically support the ideal visitor numbers in order to safeguard the sustainability of ecosystems.

The selected approach has made it possible to objectively and methodically evaluate the effects of ecotourism on biodiversity conservation, as well as to produce both theoretical and empirical outcomes.

3. Conclusions and analyses

3.1. The effects of ecotourism on biodiversity

How ecotourism is regulated in the Shirvan National Nature Reserve has a significant impact on its success. Here, ecotourism shouldn't be considered just a leisure pursuit. Additionally, it should support environmental education, nature conservation initiatives, and scientific research. Weaver (2008) believes that this method is superior for maintaining biodiversity over the long term.

According to a study, ecotourism has both direct and indirect impacts on biodiversity. Conservation receives funding, and surveillance receives increased attention. In other instances, learning becomes innovative at schools, and the economic benefits spill over to the local community (Honey, 2013).

Near the Caspian Sea, where the terrestrial ecosystem meets the marine ecosystem, changes occur rapidly when species are added or removed. The birds that migrate require such places for rest due to the easy availability of food and shelter. Considering that such changes impact ecosystems in marginal places, tourism requires sensitivity regarding natural phenomena. The relationship between living things dictates human behavior.

When people limit how many visitors enter an area, choose viewing spots carefully, yet spread out travel paths thoughtfully, nature tends to stay balanced. Ecosystems often struggle when too many show up, especially if no clear plan guides where they go.

Figure 1. *Schematic map of the Shirvan National Nature Reserve*

Considering the present-day problems associated with the environment, it becomes even more significant to preserve the diversity of life forms that exist in the coastal areas of the Shirvan National Nature Reserve, which lies near the Caspian Sea. Management measures, besides conservation efforts, are needed to maintain ecological balance.The Report on the ecological status of Shirvan State Nature Reserve (ETSN, 2024**)** confirms that these management strategies have been effectively implemented, ensuring that the reserve's ecosystems remain resilient against both natural and anthropogenic pressures. This official data provides a baseline for evaluating how regulated ecotourism activities interact with the current state of vegetation and wildlife

From this point of view, the concept of ecotourism plays a vital role in connecting the goals of preserving nature with socioeconomic development. By means of ecotourism projects implemented in the protected area, it is possible not only to increase the awareness related to ecology but also to manage the impact of anthropogenic influence (Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, 2019). Moreover, ecotourism contributes to maintaining biodiversity by ensuring the preservation of different types of flora and fauna.

In order to evaluate the effectiveness of ecotourism, it is necessary to compare areas with ecotourism to other areas lacking it.

Table 1*. Ecotourism events in the Shirvan Reserve*

Indicators	**Without ecotourism**	**When ecotourism is applied**
State of vegetation	High risk of trampling and degradation	Security measures are strengthened, and vegetation is protected
Number of animal species	Likelihood of decline due to poaching	Due to increased monitoring, the number of species remains stable or increases.
Bird colonization	Displacement and decline due to disturbance	Monitoring zones are being established, and birds are being protected
Human impact	Uncontrolled access, litter	Activity is regulated by routes and rules
Attitude of the local population	Remaining outside the reserve	Be interested in conservation by earning income from ecotourism.
Sustainability of biodiversity	Long-term risk	Continuous and controlled protection

3.2. Potential risks

In attempts to preserve fauna, ecotourism may adversely impact nature itself – according to researchers, lack of proper planning results in damage (Buckley, 2004; Buckley, 2011; Weaver, 2008). One such peril involves human disruption of the natural behaviors of the wild creatures. Disturbances from noise, tourists' activity, transport, and humans themselves might disrupt their schedule. This can lead to considerable stress in sensitive and endangered animals (Steven et al., 2011). In particular, gazelles are believed to be at risk in the Shirvan reserve.

Plant damage occurs frequently enough. Uncontrolled walking and trampling on plants results in erosion of the soil and, consequently, harm to plants. On the Caspian seacoast, vegetation and soil barely survive under pressure.

Lack of waste management may become rather problematic. With more tourists coming to the area, the amount of garbage increases, thus posing risks to contamination of the earth and rivers. Though often overlooked, the link between travel growth and environmental strain shows clearly here.

Socioeconomic risks should also be taken into account. Local communities may become discontent if the advantages of ecotourism are not distributed equitably, which might undermine support for conservation initiatives (Honey, 2013). Moreover, the effectiveness of ecotourism initiatives may be hampered by inadequate laws, inefficient control mechanisms, and a shortage of qualified employees, which are all examples of poor governance (Eagles et al., 2002).

There are a number of recommendations in the scientific literature on how to lower risk:

- Limit the number of visitors
- Clearly mark ecological trails
- Create initiatives to raise awareness of environmental issues
- Use ongoing monitoring systems (Buckley, 2011)

Therefore, if ecotourism is carried out scientifically and with institutional support, it may have a beneficial effect on biodiversity. The utilization of sustainable ecotourism principles in the reserve is essential for the conservation of biodiversity.

3.3. Gazelle population dynamics (1961–2025)

Shirvan Reserve is one of the main protected areas established in Azerbaijan for the protection of gazelles (Gazella subgutturosa). Long-term monitoring shows that the gazelle population has had positive dynamics since the second half of the 20th century.

- According to initial observations conducted in 1961, the number of gazelles in the reserve was 77. Uncontrolled hunting and anthropogenic impacts have led to a decline in the population.
- After the official establishment of the reserve in 1969, conservation measures were strengthened, and the number of gazelles reached 400.
- In the mid-1980s, the population increased to 4,800 as a result of systematic protection and feeding conditions.
- During the establishment of the Shirvan National Park in 2003, a relative stabilization was observed in the population, with the number reaching approximately 4,500 individuals.
- According to 2025 estimates, the average number of gazelles in the reserve and adjacent areas is 6,500 (Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, 2015–2024).
- This indicator confirms the strategic importance of the reserve in protecting rare and endangered species.

Table 2. *Dynamics of the gazelle population in the Shirvan Reserve, 1961–2025*

Year	Gazelle population (estimated)	Note
1961	~77 heads	A small population before the reserve's protection began.
1969	~400 heads	Protective measures began with the establishment of the reserve.
1983	~4 800 heads	The effects of conservation measures are increasing.
2003	~4 500 heads	Transition to the National Park stage.
2025	~6 000-7 000 heads	Sustained growth based on recent monitoring.

3.4. Sustainable ecotourism model in the Shirvan Reserve

The sustainable ecotourism model ensures the balancing of ecological, social, and economic objectives in specially protected areas. In Western scientific literature, sustainable ecotourism is considered a management approach that ensures the long-term conservation of ecosystems and contributes to the well-being of local communities (Weaver, 2008). The application of this model in the Shirvan State Nature Reserve is important in terms of biodiversity protection.

One of the main principles is to plan ecotourism activities according to their carrying capacity. Carrying capacity refers to the number of visitors an area can accommodate without disrupting its ecological balance (Buckley, 2011). The coastal regions and wetlands of the Shirvan Reserve are extremely vulnerable to human interaction; visitor numbers must be controlled according to the time of year and particular routes.

Paths that follow natural landscapes form a key part of responsible travel focused on nature. Thoughtful layout helps protect plants and animals, at the same time offering people better chances to observe wildlife up close. In places like the Shirvan Reserve, these paths could pass through shoreline zones, areas where gazelles live, or spots ideal for watching birds. Careful planning, along with signs that guide clearly, lowers the chance of accidental damage to surroundings - according to research done by Eagles and others back in 2002.

Nowhere is tracking more vital than in caring for nature long-term. Without steady observation, judging ecotourism's true impact stays out of reach - this comes straight from UNEP. In the Shirvan Reserve, watching how plants and animals change over time matters deeply. Especially fragile creatures need close attention again and again. All this was highlighted clearly in 2020 by the same source.

Community involvement is equally important. Involving local people in ecotourism activities ensures the protection of nature while improving their living conditions. Local people in Shirvan participate in the management of the program, provide services, and educate tourists. Employment opportunities emerge through such roles, while nature conservation becomes more pronounced (Honey, 2013; Ballantyne & Packer, 2011).

Environmental education transforms tourists' behaviors while traveling. Some locations provide tourists with environmental education in the form of exhibits, classes, or information boards to make better decisions in conserving the environment (Ballantyne & Packer, 2011). International experience shows that the successful implementation of a sustainable ecotourism model requires institutional cooperation. Coordination between government agencies, non-governmental organizations, and research institutions increases the environmental effectiveness of ecotourism. Strengthening these cooperation mechanisms in the Shirvan Reserve can ensure the long-term sustainability of ecotourism (Kulakova, 2019).

Consequently, the sustainable ecotourism model in the Shirvan Reserve is of strategic importance in protecting biodiversity. The joint application of scientifically based planning, monitoring, local community participation, and environmental awareness mechanisms ensures the real and sustainable contribution of ecotourism to maintaining the ecological balance of the reserve.

4. Conclusion

The study shows that ecotourism plays an important role in biodiversity conservation in the Caspian coastal zone of the Shirvan State Nature Reserve. The reserve's location between semi-desert and coastal ecosystems provides unique biodiversity and requires scientifically based management.

Properly planned ecotourism:

- Directs financial resources to scientific monitoring and restoration activities in protected areas;
- Ensures the protection of rare and endangered species of flora and fauna;
- It indirectly impacts biodiversity by increasing the ecological knowledge of visitors.
- It serves long-term sustainability through social and institutional cooperation.

At the same time, uncontrolled development of ecotourism can pose a risk to biodiversity: excessive visitor flow, disregard for carrying capacity, and unplanned expansion of infrastructure have negative consequences for flora and fauna. Therefore, the development of ecotourism should be accompanied by strict environmental regulation and monitoring mechanisms.

Overall, the implementation of scientifically based and sustainable ecotourism in the Shirvan Reserve can make a real contribution to both the preservation of ecological balance and the implementation of sustainable development strategies at the national level.

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