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Metabolism of the Bilirubin and its Biochemistry Role

Nurgun Mehbaliyeva[1], Narmina Abdullayeva[2*], Nigar Huseynova[2]

Abstract. *Bilirubin is a tetrapyrrolic bile pigment that plays a crucial role in several vital metabolic pathways of the human body. It is a yellow-colored compound that circulates in the bloodstream and participates in various physiological processes. Bilirubin is predominantly generated through the catabolism of hemoglobin following the breakdown of erythrocytes, and its biosynthesis is primarily mediated by the liver. The homeostasis of bilirubin is intricately linked to multiple physiological and biochemical functions, and its precise regulation is essential for maintaining systemic health. Elevated serum bilirubin levels may serve as a clinical biomarker for a range of pathological conditions, including hepatic dysfunctions, hematological disorders, and cholestatic syndromes.*

Keywords: *bilirubin, free radicals, liver, Kupffer cells, cholesterol*

Introduction

Bilirubin metabolism affects various physiological and biochemical processes of the body, and its proper regulation is essential for maintaining health. Bilirubin exists in two major forms: conjugated and unconjugated bilirubin. Direct bilirubin is generated by the conjugation process in the liver and excreted from the body by being excreted as waste in the moist intestines. Conjugated bilirubin is formed in the liver through the conjugation process and is excreted into the intestines as a waste product, eventually being eliminated from the body. Unconjugated bilirubin, on the other hand, is produced as a result of erythrocyte degradation and is processed in the liver where it is converted into direct (conjugated) bilirubin. Disruptions in this metabolic pathway can lead to hyperbilirubinemia, a condition clinically manifested as jaundice. Notably, bilirubin is not merely a metabolic waste product; it also functions as a physiological antioxidant, helping to neutralize harmful free radicals in the body (Chen et al., 2018).

Materials and Methods

Thus, the liver serves as the central organ in the synthesis, excretion, and metabolism of bilirubin. Bilirubin originates from the degradation of erythrocytes, which have a lifespan of approximately 120 days, and its proper handling is essential for maintaining liver health. Hepatic metabolic processes—particularly the production and excretion of bilirubin—constitute key aspects of this function. The presence and concentration of bilirubin serve as important biomarkers for the early detection of liver and hematological disorders, providing a valuable basis for future clinical and molecular research (Agius, 2018).

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Hepatic Glucose Metabolism. Hepatocytes are the primary cell type involved in glucose metabolism within the liver. Circulating glucose enters hepatocytes via the GLUT2 transporter, which is embedded in the plasma membrane. The specific deletion of GLUT2 in hepatocytes abolishes hepatic glucose uptake. In addition, GLUT2 facilitates the release of glucose from the liver into the bloodstream. However, the absence of GLUT2 does not impair hepatic glucose production during fasting, suggesting that glucose may also be released via alternative transporters (e.g., GLUT1) or other mechanisms (Evans et al., 2013). Once inside the hepatocyte, glucose is phosphorylated by the enzyme glucokinase into glucose-6-phosphate (G6P). This reaction reduces intracellular free glucose concentrations, thereby facilitating continued glucose uptake. Since G6P cannot be transported out of the cell, it remains within hepatocytes. In the fed state, G6P serves as a key precursor for glycogen synthesis. Additionally, G6P is metabolized to pyruvate via glycolysis. Pyruvate then enters the mitochondria and is fully oxidized through the tricarboxylic acid (TCA) cycle and oxidative phosphorylation, leading to ATP production (Fig. 1).

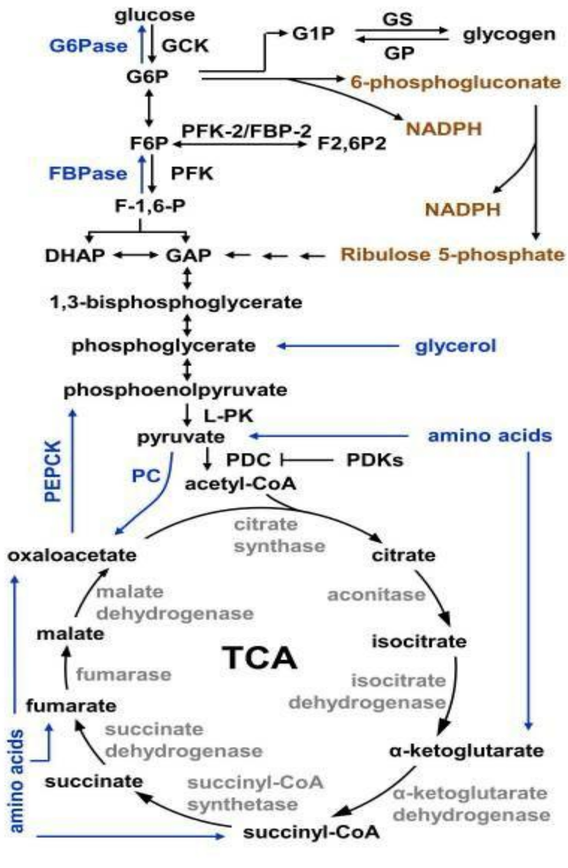

Figure 1. Glycogen metabolizm

In the fed state, glucose enters hepatocytes via GLUT2, is phosphorylated by glucokinase, and subsequently utilized by glycogen synthase for glycogen synthesis. During fasting, glycogen is hydrolyzed by glycogen phosphorylase to release glucose through glycogenolysis (Chew et al., 2023). The liver is considered the central regulatory organ responsible for maintaining whole-body cholesterol homeostasis (Fig. 2).

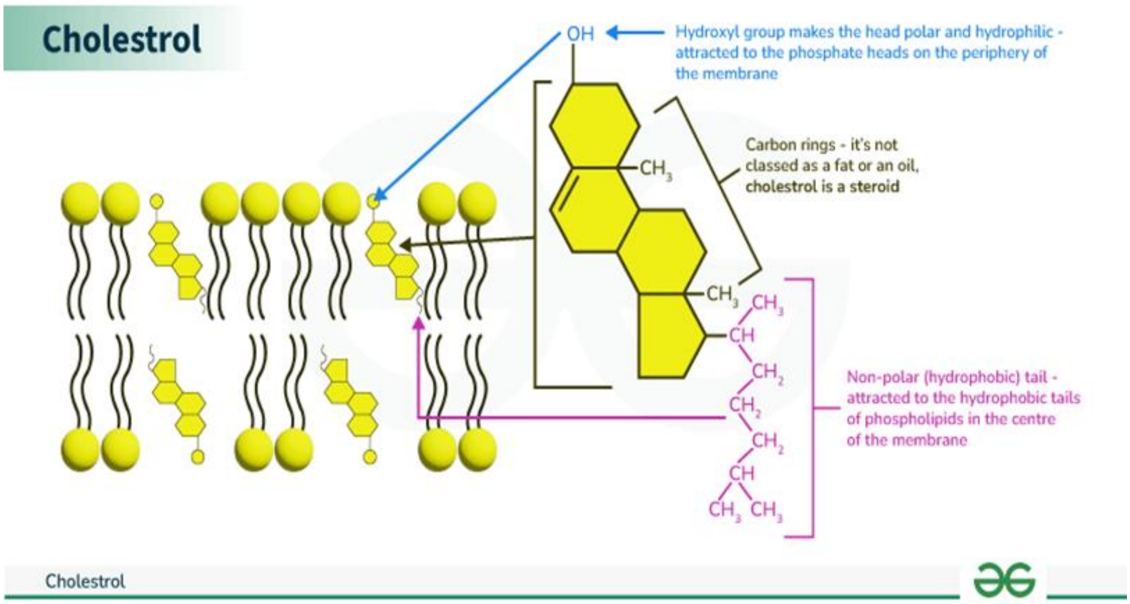

Figure 2. Structure of cholesterol

It serves as the primary site for de novo cholesterol biosynthesis, facilitates the clearance of cholesterol-containing chylomicron remnants and low-density lipoprotein (LDL) particles from the plasma, and makes a major contribution to the formation of high-density lipoproteins (HDL) (Zhang et al., 2023). Approximately 4 mg/kg of bilirubin is produced daily. Heme is a tetrapyrrolic macrocycle consisting of four pyrrole rings interconnected by carbon bridges, with a central iron atom. Bilirubin is primarily generated through a two-step sequential enzymatic degradation of heme within the reticuloendothelial system, particularly in the spleen. Other contributing cells include phagocytes and Kupffer cells of the liver. Once released into the plasma, bilirubin binds to albumin, the main transport protein in the bloodstream (Pirone et al., 2009).

The active transport of unconjugated bilirubin is mediated by carrier proteins, although the exact identity and mechanism of these transporters remain poorly understood (Fig. 3) (Blumgart et al., 2017). Albumin has a very high binding affinity for bilirubin, and under physiological conditions, unbound (free) unconjugated bilirubin is virtually undetectable in the plasma (Chew et al., 2023). Bilirubin is taken up by hepatocytes from the hepatic sinusoids via two distinct mechanisms: passive diffusion and receptor-mediated endocytosis. Passive diffusion does not require energy and occurs along the concentration gradient, resulting in a bidirectional flow.

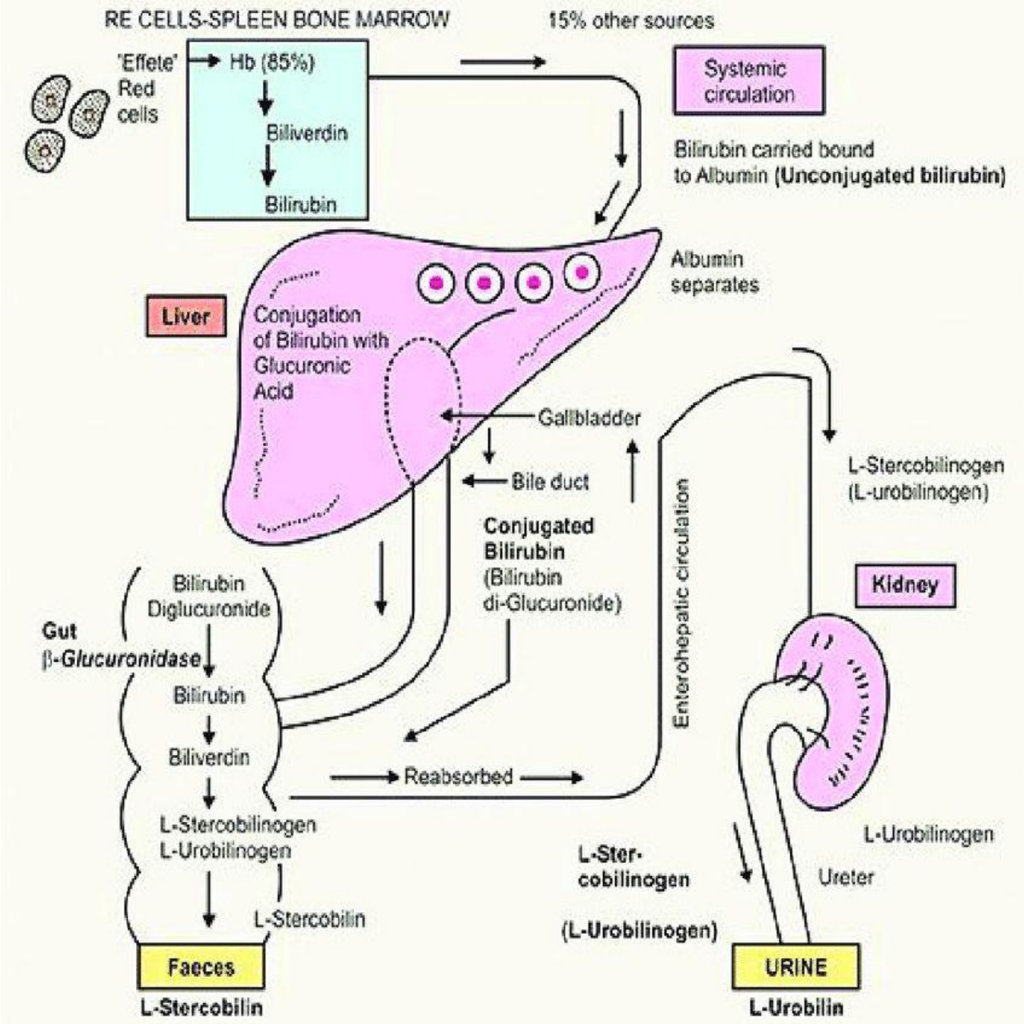

Figure 3. Bilirubin synthesis in the liver

Results and Discussion

The study demonstrated, that bilirubin is an important metabolite of heme (ferroprotoporphyrin IX), a coordination complex that links iron in various proteins. It is a potentially toxic substance. However, the body has developed mechanisms for its safe detoxification and excretion. Bilirubin and its metabolites also provide a distinctive yellow color of bile and feces and, to a lesser extent, urine. This topic summarizes the mechanism of heme metabolism and bilirubin synthesis (Bauer & Kämper, 2016). Bilirubin is formed by a 2-stage sequential catalytic degradation reaction that occurs primarily in the cells of the reticuloendothelial system, specifically in the spleen. Other cells include phagocytes and Kupfer cells of the liver. Receiving Heme these cells receive heme and the enzyme heme oxygenase acts on them. The enzyme releases chelated iron by catalyzing the oxidation of the alpha-carbon bridge. This reaction produces equimolar amounts of carbon monoxide, which is excreted by the lungs and leads to the formation of the green pigment biliverdin (Chisari & Ferrari, 2018). Bilirubin, insoluble in aqueous solution, binds in circulation to albumin, which is a reversible and covalent type of binding.

Metabolism of bilirubin. Albumin binding: after bilirubin is released into plasma, it is taken up by albumin, a carrier throughout the body. The binding affinity of albumin to bilirubin is quite high, and under ideal conditions, free (non-albumin-bound) unconjugated bilirubin does not appear in plasma. To a lesser extent, especially in cases of hypoalbuminemia, binding with high- density lipoproteins also occurs. Albumin binding limits the outflow of bilirubin from the vascular cavity, minimizes glomerular filtration and prevents its deposition and deposition in tissues (de Sauvage et al., 2011). Bilirubin is taken from hepatic sinusoids into hepatocytes by two different mechanisms: passive diffusion and Receptor-Mediated Endocytosis. The passive diffusion process does not consume energy and, as a result, proceeds with a concentration gradient, making the flow bidirectional. Active transporter intake of unconjugated bilirubin from hepatic sinusoids is carried out through carrier proteins that are not well understood. Part of the conjugated and unconjugated bilirubin within the hepatocyte is transported back into the sinusoidal space, and this fraction is again transported downstream of the sinusoidal flow. Conjugation is mandatory to dissolve bilirubin in water and facilitate its secretion through the canalicular membrane and excretion with bile. Bilirubin binds to glucuronic acid in the hepatocyte by a family of enzymes called uridine-diphosphoglucuronic glucuronosyltransferase (UDPGT) (Sedlak et al., 2017). The process of glucuronidation is one of the many important detoxification mechanisms of the human body. Under normal conditions, bilirubin is the main molecule from which diglucuronide is synthesized. However, if the conjugation system fails under conditions of excessive bilirubin synthesis, most of the bilirubin may be conjugated as bilirubin monoglucuronide. The combination of bilirubin into a water-soluble form involves breaking hydrogen bonds, an important process for its excretion by the liver and kidneys. This is achieved by glucuronic acid, which binds the side chains of propionic acid of bilirubin (Liu et al., 2008).

Conclusion

In summary, the liver is the central organ involved in the synthesis, excretion, and metabolism of bilirubin. Bilirubin is generated from the degradation of erythrocytes, which have a lifespan of approximately 120 days, and its proper processing is essential for maintaining hepatic function. The metabolic activities of the liver - particularly those related to bilirubin production and elimination - constitute critical aspects of its physiological role. The plasma concentration of bilirubin serves as a valuable biomarker for the early detection of both hepatic and hematologic disorders. Bilirubin metabolism affects various biochemical processes, and its regulation is essential for maintaining health, and it provides a foundation for diagnostic research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Study of Diagnostic Methods and Control Measures For Listerosis Disease Among Big-Horned Animals in the Ganja-Gazakh Zone

Ayten Agayeva[1*], Rahila Farmanli[1]

Abstract. *The purpose of the research is to study the diagnostic methods and control measures for listeriosis among cattle in farms of the Ganja-Gazakh zone. The research was conducted in various farms located in Shamkir, Samukh and Goygol districts, in the laboratory of the Department of "Episootology, Microbiology and Parasitology" of the Faculty of "Veterinary Medicine" of the Azerbaijan State Agrarian University of Veterinary Medicine. Depending on the immune status of the organism and the virulence of the pathogen, the disease manifests itself in acute, and subacute forms among animals. Based on the high efficiency of their application in combination with sulfagin, gentomycin and oxytetracycline for the specific treatment of the disease, we recommend their use for the prevention of listeriosis before vaccination. In case of listeriosis, along with specific treatment, we carried out symptomatic treatment. We carried out disinfection, disinsection and deratization works in livestock farms in an organized manner.*

Keywords: *cattle, disease, listeriosis, bacteriological examination, morphological, cultural, biochemical, antigenic, pathogenic properties*

Introduction

Listeriosis is an infectious disease of animals and humans caused by the bacteria Listeria monocytogenes and is characterized by nervous system disorders, septic conditions, puerperal disease and mastitis. An asymptomatic (latent) form of the disease is also observed. Many species of domestic and wild mammals, birds and humans are affected. It can occur as a secondary or mixed infection in a number of infectious diseases in pigs and birds. The disease has been recorded in Azerbaijan (Shirinov, 2002; Eyubov, 2005).

Many scientists have determined that the occurrence of listeriosis in various types of animals and birds depends on the amount of precipitation, the nature of the feed, pH, the degree of contamination of the soil with the causative agent of the disease, the presence of antagonistic microflora in the soil and the degree of virulence of the causative agent of listeriosis. P. R. Lazarev, V. I. Gershun and I.I.Guslavskaya show that incompleteness of the feed ration due to cold and soluble protein, as well as changes in the pH of silage, reduce the overall resistance of animals and increase their susceptibility to listeriosis (Kalinin, 1987).

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Listeriosis causes a decrease in animal productivity, causes metritis during calving, and causes great economic damage. At the same time, it causes a certain amount of financial resources to be spent on various health measures (Mammadli, 2015).

Listeriosis is a zoonotic disease of animals and humans, characterized by polymorphism of clinical signs or asymptomatic carriage and high mortality. M.M. Halimbayov, A.A. Annaghiyev, M.G. Ganiyev, A.M. Khalilov, A. Khankishiyev, H.A. Rahimova, Y. Ahmadov, C.N. Mammadova, A.G. Abbasov, F.M. Gulubayov played a special role in studying the epizootology, pathogenesis and specific prophylaxis of listeriosis in various types of agricultural animals in the Republic of Azerbaijan. In our country, the first vaccine against listeriosis of agricultural animals in world veterinary practice was developed and this preparation was used in the specific prophylaxis of listeriosis of sheep in 1965–1978. In 1980, a colored antigen was prepared for the diagnosis of listeriosis of agricultural animals with AR (A.A. Annaghiyyev, E.A. Aliyev, F.M. Gulubeyov), an author's certificate was obtained for the diagnostic, and it is currently used in both veterinary and medical practice (Aliyev, 2013; Mammadli, 2020).

Listeriosis is an infectious disease characterized by meningoencephalitis, balanitis, metritis, mastitis, septicemia. The incubation period lasts from one week to 1 month. Listeriosis occurs in septic, nervous, genital and atypical forms. Factor (0.3-0.5 and 0.5-2.0 μm) is a bacterium located singly, in pairs or in clusters. In some cases, bacteria occur in polymorphic rod, cocci, vibrio forms. Bacteria stain positively with all aniline dyes and the Gram method. Microbes do not form capsula and spores. In fresh (4-6 hours) broth culture, bacteria are motile. On meat-peptone agar-agar, bacteria form thin, fleshy colonies similar to Pasteurella, with a diameter of 1-1.5 mm (Lysak, 2007).

When studying culture strains obtained from various sources by I.A. Bakulov, O.V. Krivonosov, I.V. Gershun, it was determined that there are both virulent and weakly virulent variants of listeria. In addition, various literature data show that external environmental factors play an important role in the occurrence and course of listeriosis (Bessarabov, 2007).

The disease has a mortality rate of up to 40%, and causes considerable damage to agriculture as a result of reduced productivity and calving in animals. In addition, a system of various health measures is used, which leads to the expenditure of a certain amount of financial resources (Gadimov, 1990).

Materials and Methods

To achieve the set goal, we selected 26 sick animals related to the red desert and local breeds, divided them into 6 groups of 4 animals in each group, and conducted scientific research on them. The research work was carried out in various cattle farms of the Ganja-Gazakh zone (Shamkir, Samukh and Goygol), at the Department of Epizootology, Microbiology and Parasitology of the Azerbaijan State Agricultural University. In recent years, the climate in the Republic of Azerbaijan has changed dramatically, the amount of precipitation has decreased and drought has increased. As a result, the composition of feed in many regions has changed, its quality has deteriorated, and the number of insects and rodents has increased. As we know, the main source of infection is various wild and domestic animals, especially rodents, birds and insects, which carry the causative agent of the disease. The microbe enters the body through the mucous membranes (nose, conjunctiva, mouth) through water, feed, air, dust, etc. It is assumed that infection also occurs through blood-sucking insects, especially ticks.

As a result of all these factors, listeriosis was recorded among cattle in various farms of Shamkir, Samukh and Goygol regions. Based on the appeal of the heads of these farms, employees of the Department of Epizootology, Microbiology and Parasitology of the ASAU were engaged in studying the occurrence, course, treatment and many other issues of the disease.

It turned out that the farms mentioned were healthy due to listeriosis and had no contact with unhealthy farms. Listeriosis infection was recorded in August-October 2022. The disease was mainly observed in 18-28-month-old heifers, and infection was not detected in the causative bulls. The incubation period of the disease is 7-30 days. In addition to fever, general weakness, and loss of appetite, some animals showed signs of central nervous system dysfunction, including loss of balance, convulsions, severe nervous excitability, paralysis of some muscle groups, neck flexion, and conjunctivitis. In a group of sick animals, blindness, stomatitis, anemia of visible mucous membranes, and comatose state were noted.

Listeriosis mainly has an acute, subacute, and chronic course. Listeriosis occurs in several clinical forms: nervous, septic, mixed, latent-asymptomatic, with damage to the reproductive system (parturition, delayed ejaculation, endometritis, and metritis) and udder (mastitis). In large horned animals, the CNS is more affected. The disease begins with weakness and loss of appetite. Serous-mucous discharge occurs from the nasal cavity, and abundant mucus is secreted from the mouth. After 3-7 days, uncontrolled movements, convulsions, fits of excitement, paresis of individual muscle groups, loss of vision, conjunctivitis, stomatitis are observed. Body temperature rises at the beginning of the disease or remains within the normal range. Listeriosis in calves proceeds in the form of septicemia, sometimes accompanied by damage to the CNS.

Results and Discussion

From the research work we conducted, it became clear that the pathological-anatomical changes in large horned animals were mainly sharp changes in the brain, especially the engorgement of cerebral blood vessels, blood leakages were observed on the brain and cerebellum. In the cranial cavities and ventricles of the brain, a cloudy fluid mixed with pus was seen. To diagnose listeriosis, we took into account its epizootological characteristics, clinical signs and pathological-anatomical changes, used blood culture, bacteriological examination and serological reactions. While the animal was alive, we used the blood of the sick animal (5-10 ml), the discharged pupa, pupal discharge, pupal membrane, nasal passages, conjunctival fluid, and milk taken from the inflamed scrotum. We also sent the brain and spinal cord to the laboratory for examination.

We examined the pathological samples received in the laboratory based on the bacteriological scheme. Bacteriological examinations play an important role in the diagnosis of listeriosis. During microscopy, we prepared a smear from the pathological material and stained it using the Gram method. During microscopy, listeria were found singly or in pairs. In some cases, we determined that listeria were observed in coccus-like, diplobacteria, rod-shaped, and chain-like forms.

We obtained a pure culture of the factor by inoculating the blood of sick animals from the parenchymatous organs of dead animals into various nutrient media, prepared smears on glass slides, examined them under a microscope, and used biological tests. After obtaining a pure culture of the listeriosis pathogen, it was examined for its morphological, cultural, tinctorial, and biochemical properties, and its pathogenicity was determined. It turned out that the pathogen forms a precipitate in liquid nutrient media and, when shaken, rises up like a hair, resembling small, transparent dewdrops in solid nutrient media.

Table 1.
Treatment of cattle with listeriosis

Treatments	Injection method	Dose (once)	Number of patients	Conclusion	
				Survived quantity	%
Sulfagin and gentomis	Perosal and intramuscular	25 g+2.5 ml	4	4	100
Sulfagin and oxytetracycline	Peros	25 g+2.5 ml	4	4	100
Gentomycin	Intramuscular	2.5 ml	4	3	75
Oxytetracycline	Intramuscular	2.5 ml	4	3	75
Sulfagin	Peros	25 g	4	2	50
Control	–	–	4	4	–

As can be seen from Table 1, while sulfagin in combination with gentomycin and oxytetracycline achieves 100% recovery, only 50-75% of animals recover from the use of these drugs alone. Based on the high efficiency of sulfagin in combination with gentomycin and oxytetracycline, we recommend their use for the prevention of listeriosis before vaccination. In the case of listeriosis, along with specific treatment, we carried out symptomatic treatment. The main goal of symptomatic treatment is to stimulate the functional activity of the cardiovascular system and the digestive system. In order to ensure the healthy and vigorous development of large-horned animals, and to prevent them from contracting listeriosis, we set ourselves the goal of timely implementation of preventive measures. One of such measures and the main one is timely and high-quality vaccination of animals with the appropriate vaccine.

According to researchers, individuals who have contracted listeriosis and recovered from it in natural conditions develop relative immunity. Precipitins, agglutinins, and complement-binding antibodies are detected in the blood serum of animals that have recovered from the disease naturally. However, the serum of convalescents does not have therapeutic properties. The first vaccine against the disease was prepared by A.A. Annagiyev from the "A" strain. A dry live vaccine prepared from the "AUF" strain was proposed in 1974 and is used based on the current instructions (Alasgarov, 2016).

We vaccinated all clinically healthy animals 10 days after treatment with a dry vaccine prepared from the AUF strain against listeriosis. We vaccinated 687 cattle on farms according to the instructions. We injected the vaccine intramuscularly twice with an interval of 10 days. We periodically sent samples to the laboratory to determine the quality indicators of feed and water. We applied the feed ration, which is important for feeding large horned animals. We implemented the solution of the following issues in disease prevention. In order to ensure the protection of healthy livestock farms from the disease due to listeriosis:

- We ensured that animals brought to farms were kept in quarantine for 30 days.
- We ensured the systematic elimination of rodents.
- We eliminated blood-sucking insects and ticks.
- Ensuring constant quality control of feeds (especially silage and mixed feed)
- We ensured the conduct of bacteriological examinations in accordance with the relevant requirements.
- In cases of abortion or stillbirth, we implemented a strict approach and sent pathological samples for examination.

We boiled milk from large horned animals (with a positive result in serological reactions) for 15 minutes. We banned the transportation of feed that had been in contact with sick animals. We carried out disinfection, disinfestation and deratization work in livestock farms in an organized manner. We biothermally neutralized manure on the farm. We disinfected stables and farmyards. For this purpose, we used 3% sodium hydroxide, 2% chlorinated lime solution, and 6% creolin emulsion. We periodically carried out deratization measures on the farm. We lifted the restriction 2 months after the last patient recovered from the farm and after receiving a negative result during serological tests.

Conclusion

The results of the study showed that 100% recovery was achieved when sulfagin was used in combination with gentamicin or oxytetracycline for the treatment of sick animals in unhealthy farms due to listeriosis. During the research work we conducted, we vaccinated all animals susceptible to listeriosis in unhealthy farms with a dry vaccine prepared from the AUF strain according to the relevant instructions. For the prevention of listeriosis, animals should always be brought to the farm from healthy farms. We always monitored the quality of feed and fought against rodents. We used preventive measures when the disease was observed on the farm.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The Possibilities of Using the Nature of Semiconductors in Practical Life

Gunay Dadashzade

Abstract. *The transformation of the global automotive market with the increase in the production of electric vehicles in recent years has created an incredible demand for the development of electronic components based on SiC and GaN semiconductors with a wide band gap in the world, without which it is impossible to imagine the electronics of modern and future hybrid and electric vehicles, communication systems, mobile devices and space technology. This demand has led to a sharp increase in investment in the development and development of new technologies for SiC and GaN wafers of larger diameters in order to reduce the cost of manufacturing electronic products and continue to displace classic silicon components. Every year, semiconductor devices based on SiC and GaN are penetrating deeper into our lives. The past 2021 allowed them to make an impressive breakthrough and lay the foundation for growth in their consumption in the next five years and beyond. The main driver of this growth is the automotive market, or more precisely, hybrid and electric cars.*

Keywords: *electric vehicle, components, battery, power, semiconductors*

Introduction

Semiconductors are materials that can conduct electricity, but to a limited extent. Their unique feature is that their electrical conductivity can be controlled and modified by introducing appropriate dopants or by changing external conditions, such as temperature, pressure, or an electric field. Under normal conditions, semiconductors act as insulators, but under certain circumstances, they can conduct electricity, making them indispensable in the production of electronic components.

Natural semiconductors, such as pure silicon, do not have sufficient electrical properties for use in modern electronic devices. To increase their ability to conduct electricity, doping is used, which involves introducing small amounts of other chemical elements into the semiconductor structure. Depending on the type of dopant, two main types of doped semiconductors can be distinguished:
An n-type semiconductor is formed by doping a semiconductor with elements with a large number of electrons, such as phosphorus or arsenic. The introduction of these impurities creates an excess of electrons that can move freely within the material, increasing its conductivity. A p-type semiconductor is formed by doping a semiconductor with elements with a smaller number of electrons, such as boron or aluminum. These impurities form so-called electron holes, which act as positive charge carriers and also help improve the material's conductivity.

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The most common semiconductor materials are silicon (Si) and germanium (Ge), although many other compounds with semiconducting properties exist, such as gallium arsenide (GaAs) and indium phosphide (InP). These materials are used to manufacture semiconductor components such as diodes, transistors, and integrated circuits, which form the basis of modern technology. The share of hybrid and electric vehicle sales in the country reached 94.9%. Norway is actively building charging and service infrastructure, and numerous tax breaks for citizens buying electric vehicles are stimulating the transition away from internal combustion engine vehicles. Next-generation electric vehicles require power devices that can improve the efficiency of the vehicle (with a subsequent increase in the driving range) and the speed of battery charging. Figure 1 shows the key nodes of the vehicle where SiC and GaN electronic components can be used. SiC inverters have proven to be a key solution to meet these requirements. In addition to converting the input DC to AC, the inverter regulates the level of power supplied to the motor in accordance with driving needs (Challenges and Future Perspectives).

Methods

The progress of silicon carbide technology, in terms of increasing diameter, production volume, improving quality and decreasing cost of SiC, has reached the point where mass production of 150 mm wafers is based on the use of silicon carbide blanks, as shown in Fig. 1. The progress of silicon carbide technology, in terms of increasing diameter, production volume, improving quality and decreasing cost of SiC, has reached the point where mass production of 150mm wafers is based on the use of silicon carbide blanks, as shown in Fig. 1.

Figure 1. Production of 150 mm thick silicon carbide plate

Findings and Discussion

The role of the inverter is increasing as the electric vehicle industry gradually transitions from 400 to 800 V. The efficiency of transferring battery power to the motor in a traditional inverter is 97–98%, while the efficiency of a SiC inverter reaches 99%. Note that an increase in efficiency of one or two decimal places provides very significant benefits to the entire vehicle (Compound Semiconductor Quarterly Market Monitor, 2021).

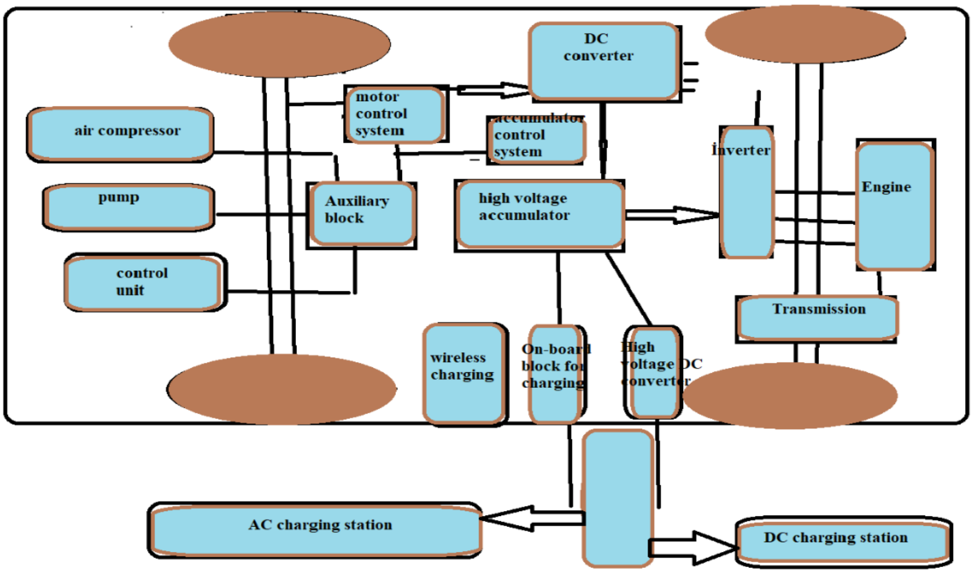

Figure 2. Key nodes for the application of SiC and GaN-based electronic components in an electric vehicle

SiC inverters are ideal for these applications because they can withstand high voltages and temperatures, allowing all other components to be smaller. With 800 V batteries, the required current is reduced and smaller cables can be used, reducing costs, vehicle weight, and electrical system assembly time. This not only improves the range of EVs, but also their efficiency. Charging times for 800 V batteries can be reduced to one-fifth of the time required for 400 V batteries by using powerful SiC DC/DC converters. The former's high efficiency allows the amount of energy delivered to the batteries to be maximized during charging with negligible power losses (SiC and GaN: A Tale of Two Semiconductors, 2021).

The global growth of the BEV market, which meets modern standards for efficiency and CO2 emissions, requires the use of new semiconductor technologies in the drive inverter. The supply voltage of the BEV inverter is in the range of 400–900 V, depending on the drive power, battery type and the presence of a step-up converter. Since the drive inverter controls the motor, its operating frequency is usually less than 20 kHz. The advantage of using higher frequencies here is only to move away from the audible range of audio noise. Therefore, the main losses of the inverter are conduction losses, especially at low BEV loads (SiC and GaN: A tale of two semiconductors, 2021).

Typically, the choice in such cases is a silicon IGBT, but its inherent saturation threshold voltage (due to its "bipolar" structure) at low loads cannot be reduced, even when a large number of IGBTs are connected in parallel. Silicon carbide has an electric field strength 10 times higher (~3 MV/cm) than Si, so the unipolar SiC MOSFET structure is well suited for the implementation of 650, 900 and 1200 V power transistors due to the following main features:
SiC MOSFETs do not have a saturation voltage, unlike Si IGBTs; when paralleling SiC MOSFET chips, the on-resistance can be reduced to ≤ 1–2 mOhm;
SiC MOSFETs can conduct in the third quadrant (unlike Si IGBTs) by using a body diode during the dead time (Tdt is very short for SiC structures) and then turning on the SiC MOSFET channel in the third quadrant, which gives the same low losses in the reverse conduction state as in the forward conduction state. The combination of using a body diode during the dead time and synchronous rectification eliminates the need for an external antiparallel diode, which reduces the size and cost with minimal impact on efficiency at frequencies up to 50 kHz; using SiC MOSFETs can reduce inverter losses in a typical BEV EPA drive cycle by up to ~78%. The basic technology for developing

low-resistance SiC MOSFET power modules can be scaled from 650-900 V to 1200 V by simply modifying the epitaxial drift zone (blocking layer) and edge regions.

The topology remains the same for all devices in the specified voltage range, ensuring easy integration into power modules (GaN Systems listed on 2021 Deloitte Technology Fast 500*)*. Figure 3 illustrates the traditional method of connecting conductors using ultrasonic welding to the top contact surface using the third generation of SiC MOSFET crystals as an example. This technology can be used in 650, 900 or 1200 V modules with a slight change in the chip topology. 900 V crystals with low channel resistance (10 mOhm for the CPM3-0900-0010A) are already available. They were used in the development of a version of the 900 V modules, the static and dynamic losses of which have already been tested.

Conclusion

The rapid growth of the global automobile market with the gradual predominance of the production of hybrid and electric vehicles guarantees accelerated development and further reduction in the cost of semiconductor devices based on SiC and GaN. Assessing the good market prospects of SiC and GaN products, large foreign companies continue to increase investments in their production, as well as in the acquisition of companies developing these products and materials, including for the start of production of new areas of electronic components that were previously absent in these companies (GaN Systems' power transistor prices drop below $1, 2021).

Figure 3. Chips Wolfspeed SiC MOSFET

The development of electronic components based on GaN is evolving from the creation of simpler power discrete components (transistors, diodes, etc.) and control microcircuits (drivers, controllers) to more complex integrated solutions with high energy efficiency, including for use in harsh space conditions. Increasing the diameter of SiC wafers to 200 mm, which will happen in 2022 despite technical difficulties, is the main means that will reduce the cost and price of production of silicon carbide ECs.

The first epitaxial GaN wafers on a silicon substrate with a diameter of 300 mm with high homogeneity and low defects, presented on the market in 2021, will further reduce the cost of production and prices of electronic GaN components. Evolution and progress in the industrial development of the technology of vertical GaN-on-GaN and GaN-on-Si structures for active components with low cost in the future will create competition not only for silicon IGBTs, but also for SiC transistors, diodes in the high-voltage range up to 10 kV.

Recently, much attention has been paid to the sintering technology of SiC chips, which allows eliminating the use of welded conductors during assembly. One of the main advantages is an increase in the so-called intermittent service life (IOL), since fatigue processes in welded conductor joints or crystal connections often cause failures. Other potential advantages include better (two-way) cooling, better heat distribution and higher short-circuit resistance (Quantum physics; Semiconductor; HyperPhysics; YOLE Intelligence).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Tourism Development in Lankaran District and Changes Occurring in Forest Ecosystems

Aynur Heydarova[1], Alibaghish Malikov[2], Tural Huseynov[3*]

Abstract. *In the modern era, the tourism sector plays a special role in the global economy while also being important for the development of socio-cultural relations. In recent years, the successful reforms and infrastructure projects implemented in the Republic of Azerbaijan have created a favorable foundation for the sustainable development of tourism. Our country's natural and geographical location, rich cultural and historical heritage, multicultural values, and hospitable people provide broad opportunities for the rapid development of this sector.*

In our republic, the country's future development is determined by the availability of potential economic opportunities and the expansion of international tourism. The activity of numerous foreign companies reflects the integration of entrepreneurs and businesspeople into foreign economic relations and global tourism. Tourism is one of the main directions of development of Azerbaijan's non-oil sector and makes a significant contribution to the process of economic diversification. The social impact of tourism is also evident in increased employment. Thus, new jobs are created in hotel services, public catering, transportation, and other service sectors.

Keywords: *forest, tourism, sector, recreation, dynamics, satellite, infrastructure*

Introduction

Azerbaijan's extensive tourism potential is regarded as a factor that stimulates the development of the tourism industry in its natural and economic regions. However, these opportunities are not being fully and effectively utilized. Therefore, studying the domestic tourism potential of individual regions of the country, including the Lankaran–Astara economic-geographical region examined in this research, identifying ways to use this potential efficiently, forming new tourism services, and applying a wider range of tourism types are highly relevant issues. In Azerbaijan, the number of tourism enterprises has increased by an average of 4.5% annually, employment in the tourism sector by 6%, and the number of foreign citizens visiting the country for tourism purposes by 8.5%. An analysis of the structure of foreign investments directed to the national economy in 2015 shows that 11.3% of total investments were allocated to the non-oil sector, one of the leading branches of which is the tourism sector (Aliyev, 2021).

As a result of the purposeful policy pursued by the President of the Republic of Azerbaijan, Ilham Aliyev, a favorable business environment for the development of tourism has been created in the country, and the share of investments allocated to this sector has increased.

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As noted by the President, tourism has been identified as a priority direction in the development of the non-oil sector, which is reflected in two state programs and the Strategic Roadmap adopted in this field. The main objective of the research is to analyze the current state of tourism in the Lankaran region, identify existing problems and opportunities, and determine future development prospects (Ministry of Ecology and Natural Resources, 2020–2023).

Methods

Lankaran district is a unique region located in the southern part of Azerbaijan, rich in relict and endemic vegetation. Hyrcanian-type forests, which survived the glaciation of the Tertiary period, constitute the main natural wealth of this region. However, over the past decade, the rapid development of tourism, the establishment of new recreation centers, and the increase in anthropogenic pressure have caused significant quantitative and qualitative changes in this fragile ecosystem. The development of tourism in Lankaran has both positive and negative impacts on nature; the positive aspects are aimed at the protection, conservation and promotion of nature (e.g. festivals) thanks to agrotourism (tea, tangerine plantations) and health tourism (thermal waters), while the negative aspects include increased construction, infrastructure expansion, increased waste and pressure on natural resources (water, forests), which risks disrupting the balance of reserves and ecosystems (Mammadov & Khalilov, 2005).

Positive impacts:

- Agrotourism: Tours to tea and tangerine plantations aim to protect and promote nature. For example, tours such as "Green Tea".
- Health tourism: Alongside the use of thermal waters, attention to therapeutic natural resources increases, contributing to their protection.
- Festivals and events: Events such as the “Tea, Citrus, and Rice Growing Festival” enhance the attractiveness of nature and promote eco-tourism.
- Environmental protection: Parallel to tourism development, measures are taken to protect nature, particularly along the Lankaran–Lerik–Astara routes.

Negative impacts (Potential risks):

- Construction and infrastructure: The construction of new hotels and recreation complexes may alter natural landscapes and exert pressure on forest areas.
- Waste management: The increase in tourist flow may lead to waste management problems, negatively affecting rivers and forests.
- Pressure on water resources: The growing water demand of recreation complexes and settlements may put pressure on local water sources.
- Ecosystem changes: The development of mountain and extreme tourism (for example, in forest areas) may interfere with wildlife habitats (UNESCO World Heritage Centre, 2023).

The potential opportunities for tourism development in the region include:

1) Increasing the number of foreign tourists;
2) Development of infrastructure and modernization of public utilities;
3) Prioritizing tourism as a key sector in the development of small and medium-sized enterprises;
4) Improving the quality of highways and developing local tourism routes.

Threats to the tourism sector in the region include:

1) High intensity of landslide processes, as the foothills and mid-mountain zones of the Talysh Mountains are prone to landslides;
2) Fluctuations in the Caspian Sea level, which cause greater damage to the infrastructure of Lankaran and Astara districts;
3) Low wage levels;
4) Environmental problems in tourism and recreation centers;
5) Lack of effective coordination among government institutions;
6) The risk of forming a negative image in the long term due to fragmented tourism development;

7) Persistence of bureaucratic barriers to tourism development, resulting in weak growth of tourism entrepreneurship;
8) Failure to ensure sustainable tourism development due to the prioritization of seasonal and short-term tourism.
9) To better understand the impact of tourism, it is essential to analyze the forest cover and infrastructure map of Lankaran. As shown on the map, the main tourism facilities are concentrated around the Khanbulan River reservoir, the Haftoni thermal zone, and along the Lankaran–Lerik highway. These areas are where forest cover is most exposed to fragmentation (WWF – World Wide Fund for Nature, 2023).

Results and Discussion

Statistical Indicators and Dynamics:

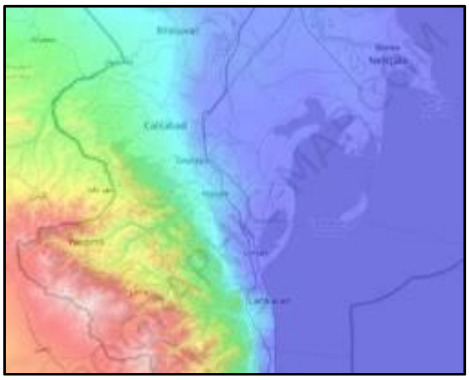
There is a direct correlation between tourist flow and the degradation of forest areas.

Table 1.
Condition of forest cover around tourism centers

Year	Numbers of tourism	Canopy cover (0-1 scale)	Soil compaction (kg/cm^2)
2015	45,000	0.82	1.4
2020	78,000	0.76	2.8
2024	115,000	0.69	4.1

The data show that soil compaction has increased by approximately three times over the past nine years. This leads to the destruction of understory vegetation and young saplings. The dominant forest species of Lankaran—ironwood (Parrotia persica) and chestnut-leaved oak (Quercus castaneifolia)—are particularly sensitive to noise and light pollution generated by tourism facilities (Ministry of Ecology and Natural Resources, 2020–2023).

Comparison with International Experience:
Compared to Germany's Schwarzwald (Black Forest) region, sustainable tourism practices are weakly implemented in Lankaran. In Germany, special suspension bridges and wooden walkways are constructed for tourists to minimize direct contact with the soil. The topographic structure of Lankaran is a key factor determining the degree of tourism penetration into forest areas. The relief map clearly shows that forest massifs extend from the Lankaran lowland (below sea level) up to the ridges of the Talysh Mountains. This is a physical map illustrating relief, river networks, and elevation zones (Map 1).



Map 1. Physical–topographic map of the Lankaran–Astara region (2022–2024)
(Based on satellite imagery)

Hydrographic Network: The valleys of the Lankaran River, Basharu River, and Girdanichay visible on the map are the areas where tourism is developing most actively. The topographic map demonstrates that anthropogenic pressure is concentrated mainly in forested areas along river valley slopes.

Slope Gradient: Tourism roads constructed in areas with slope gradients of 20–30° accelerate erosion processes. The topographic map indicates which forest sections—particularly steep slopes—should be designated as “restricted zones” for tourism.

The physical–topographic map of Lankaran (relief and hydrography) clearly reflects the elevation zones in which forests are located and the relief forms (river valleys, slopes) where tourism is geographically concentrated. Analysis of the topographic map shows that tourism infrastructure is mainly concentrated along river valleys at elevations of 0–400 meters above sea level. These areas also represent the most productive and biologically rich forest zones, encompassing lowland and foothill belts. While the complexity of the relief prevents the large-scale expansion of tourism to higher elevations (above 600 meters), it intensifies ecological pressure within the valleys (UNESCO World Heritage Centre, 2023).

This map illustrates the actual health condition of the forest. Dark green colors indicate the densest and most intact forest areas, while lighter shades represent thinned zones affected by tourism and other anthropogenic factors. Overall, the topographic analysis confirms that tourism infrastructure in Lankaran is primarily concentrated along river valleys (Lankaran River and Basharu River) at elevations of 0–400 meters above sea level. As shown on the map, although mountainous relief naturally restricts mass tourism from expanding into higher zones, it transforms forest belts in river valleys into focal points of anthropogenic pressure.

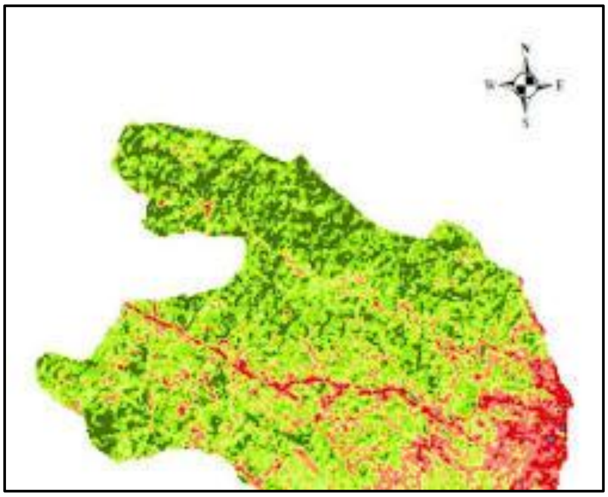
Modern Forest Cover and Vegetation Density of Lankaran
The modern forest map (based on Sentinel-2 satellite imagery) shows that the forest massifs of the district differ sharply in both species composition and canopy density with increasing elevation above sea level (Map 2).

Map 2. Joint satellite imagery map for 2024 by “Azercosmos” OJSC and the monitoring group of the Ministry of Ecology and Natural Resources

Dark Green Zones: Areas with high humidity and minimal human intervention. These mainly include the core parts of Hirkan National Park (reserve zones) (State Tourism Agency of Azerbaijan, 2023). Light Green and Yellowish Zones: Areas close to tourism zones where forest canopy density has decreased. These include forest road edges and newly established cottage-type recreation areas.

Zone A (Coastal and Lowland Forests): The area extending from the Caspian Sea coastline to the main highway. Tourism facilities are most densely concentrated here, and forest cover is highly fragmented.
Zone B (Foothill and Lower Mountain Belt – 200–600 m): This zone includes the main entrances to Hirkan National Park, the surroundings of the Khanbulan River reservoir, and the "Istisu" area. It is considered a "red zone" where tourism causes the greatest physical damage to forests.
Zone C (High Mountain and Reserve Zone – above 600 m): A zone with restricted tourist access, where endemic species—such as the healthiest populations of boxwood and ironwood—are protected (Mammadov, 2007).

The analysis of maps of recreation centers and tourism routes in the Lankaran–Astara economic-geographical region, together with NDVI (Normalized Difference Vegetation Index) values obtained from satellite imagery, confirms that forest canopy density within a 500–800 meter radius of main highways and tourism centers has decreased by 12–15% over the past decade. This clearly demonstrates the fragmentation of the internal forest ecosystem. Satellite imagery enables the measurement of the "greenness" level of vegetation, providing an objective assessment of vegetation health and density (Map 3) (WWF – World Wide Fund for Nature, 2023).



Map 3. Map of Recreation Centers and Tourism Routes in the Lankaran–Astara Economic-Geographical Region

Based on the example of Lankaran district, GIS studies conducted over the past 10 years show that within a 500-meter radius of tourism centers, the NDVI value has decreased on average from 0.85 to 0.70. This indicates forest thinning and a decline in photosynthetic capacity

- Khanbulan Reservoir: Classified as an «ecological stress zone» due to high tourist density
- Lankaran–Lerik Road: Areas where roadside cafés cut through forest belts in a corridor-like pattern.
- Haftoni settlement surroundings: A zone where medical tourism (thermal waters) has altered groundwater levels, affecting forest moisture conditions.
- The development of tourism primarily requires the construction of road and hotel infrastructure. This process has led to the following changes in forests:
- Road construction: New roads built to remote mountain villages of Lerik and Astara have caused fragmentation of forest massifs, affecting migration routes of certain animal species.
- Recreation centers: Cottages and restaurants built on forest fund lands have resulted in a certain reduction in tree density. However, in recent years, the application of "green construction" principles have been observed, integrating infrastructure into forest areas without tree cutting.

Tourism development does not result solely in negative impacts; it has also created new opportunities for forest conservation:

- Ecotourism routes: Tourists now visit forests not only for picnics but also for birdwatching and hiking, increasing interest in preserving forests in their natural state.
- Role of national parks: Enhancing the tourism potential of Hirkan National Park has strengthened state-level oversight. Funding allocated for forest protection and related services has increased.
- Local community income: As tourism develops, local residents become more interested in protecting forests as a "tourism product" rather than cutting trees for firewood (Yusifov & Hajiyev, 2004).

Conclusion

- Although tourism development in Lankaran is oriented toward nature conservation, without continuous planning, ecological monitoring, and the application of sustainable tourism principles, construction and human flow may negatively impact the natural environment.
- Satellite imagery has provided precise evidence of forest thinning associated with tourism development.
- Tourism facilities should be constructed only along forest edges within designated buffer zones.
- A portion of taxes collected from tourism facilities should be allocated to forest restoration.
- Organizing tourist routes based on the region's existing tourism potential allows for attracting more visitors. Therefore, offering ecological, national heritage, and educational tourism routes to visitors in the Lankaran–Astara economic-geographical region is essential.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Efficiency of Fertilizers Under Agricultural Crops in Different Soil–Climatic Conditions of Azerbaijan

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Abstract. *The Republic of Azerbaijan has a very rich natural environment. The geography and relief of the republic, and the formation of manifestations of eleven climatic belts in this territory, have played an important role in the formation of soil–climatic conditions and, overall, of the landscape. For this reason, the soil types formed within the republic are favorable for the development of various branches of agriculture. Under the soil–climatic conditions of the republic, it is possible to develop fruit growing, viticulture, vegetable growing and other agricultural cultivation and obtain high yields from these fields. In the article, the main regularities of fertilizer efficiency under agricultural crops in various soil–climatic zones of Azerbaijan have been investigated. Thus, in the Kura–Araz and Lankaran plains, under different soil–climatic conditions, the characteristics of crop cultivation and the results of scientific research on the efficiency of fertilizer application under cotton and tomato on irrigated meadow-gray and meadow-marsh soils are presented. The scientific analyses carried out show that the effectiveness of fertilizers varies significantly depending on soil texture, humus reserves, soil reaction, and climatic factors. It has been determined that in the irrigated meadow-gray soils of the Mughan–Salyan zone and in the meadow-marsh soils of the Lankaran–Astara zone, the combined application of organic and mineral fertilizers under cotton and tomato has a better effect on increasing soil fertility and crop productivity compared to variants where they were applied separately.*

Keywords: *cotton, tomato, Mughan–Salyan, Lankaran–Astara, meadow-gray, meadow-marsh, fertilizer, crop, productivity, nitrogen, phosphorus, potassium*

Introduction

In the modern period, rapid population growth, increasing demand for agricultural products, and limited land resources have made raising productivity in agricultural production a priority task. In this regard, the scientifically grounded application of fertilizers is of particular importance in increasing the yield of agricultural crops. Fertilizer efficiency is directly and closely related to soil–climatic conditions, agrochemical properties of the soil, biological requirements of the cultivated crop, and the applied agrotechnical measures.

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Aghayev N. A., Ismayilov S. N., Aghayev A. N. (1999, p. 20), in the work “Agrochemical characteristics of some soils in Azerbaijan,” indicate that in order to use soils efficiently it is necessary to increase their potential fertility. Increasing soil fertility can be achieved through the application of organic and mineral fertilizers (Aghayev, 1999, pp. 20–23).

Guliyev A. A. (2015, p. 140) notes that an arid, i.e., dry and semi-desert climate prevails in the lowland zone of our republic, and nitrogen and phosphorus deficiency is observed more distinctly in the soils formed there. However, in the Lankaran–Astara zone there is a humid subtropical climate. In this region, abundant precipitation and the intensity of leaching processes increase fertilizer losses, especially nitrogen fertilizers. In mountainous and foothill areas, the temperature regime, soil reaction, and erosion processes seriously affect the uptake of fertilizers by plants (Guliyev, 2015, pp. 140–148).

Studying fertilizer efficiency under agricultural crops is relevant not only for increasing yield, but also for protecting soil fertility, maintaining ecological balance, and ensuring sustainable agriculture. Excessive or improperly selected fertilizer application can cause soil degradation, pollution of water bodies, and a decrease in the quality of agricultural products. Many studies have led scientists to conclude that applying fertilizers above the norm, or without selecting them according to soil–climatic conditions and also the biological characteristics of the crop, causes the acceleration of a number of negative ecological and agrochemical processes in agroecosystems. Such applications primarily deepen soil degradation by resulting in the disruption of the physical, chemical, and biological properties of soils (Alosmanov, 2022, pp. 225–229).

Excessive application of mineral fertilizers, especially nitrogen-containing fertilizers (Ismayilov, 2018, p. 236), leads to the accumulation of nitrates in the soil solution. As a result, nitrate leaching intensifies and, entering groundwater, causes its pollution. Studies conducted in arid and humid subtropical zones of our republic show that under conditions of intensive irrigation or abundant precipitation, nitrate leaching occurs more rapidly. This is considered one of the factors creating serious ecological risks for both water bodies and drinking water sources (Babayev, 2006). This, studying fertilizer efficiency under cotton and vegetable (tomato) crops on meadow-gray and meadow-marsh soils under different soil–climatic conditions within the Republic of Azerbaijan is an important issue and stands out for its relevance.

Research object and Methodology

Field work was carried out in 2025 in individually owned farms on cotton-growing soils in the territory of Qarabaglar village, Salyan administrative district, and on vegetable (tomato) soils in the territory of Shirinsu village, Lankaran administrative district. In order to study the agrochemical characteristics of the research site, soil samples were taken by the envelope method from depths of 0–20, 20–40, 40–60, and 60–80 cm, and the soil reaction—pH (in a water suspension)—was determined with a potentiometric device; total humus (I. B. Tyurin), total nitrogen (Kjeldahl), total phosphorus (K. E. Ginzburg), and total potassium (P. K. Smit) were determined accordingly. Absorbed ammonium (N–NH4) was determined by D. P. Konev, nitrate nitrogen (N–NO3) by Grandval–Lyaj, available phosphorus (soluble in 1% ammonium carbonate) by Machigin, and exchangeable potassium by the Protasov method in C. Huseynov’s modification. Agrochemical analyses in the soil for both crops were carried out using the following methods:Total nitrogen—I. V. Tyurin; absorbed ammonium (N–NH4)—D. P. Konev; nitrate nitrogen (N–NO3)—Grandval–Lyaj; total phosphorus—A. M. Mesheryakov; available phosphorus—M. P. Machigin; total potassium—P. K. Smit; exchangeable potassium—P. V. Protasov method.

Nitrogen, phosphorus and potassium in plants were determined using the methods of K. E. Ginzburg and Q. M. Sheglova. Mathematical calculation of yield indicators was performed using the method of A. M. Mesheryakov (1972). Field experiments for cotton were carried out in accordance with the accepted agrotechnical rules in the Mughan–Salyan region, in the territory of Qarabaglar village of Salyan district, on irrigated meadow-gray soils, in an individually owned farm. The experiments were conducted in 5 variants, 4 replications, with each plot area being 100 m². Sowing was carried out in the 3rd ten-day period of April (April 23). The first emergence was obtained in early May.

During the experiments, ammonium nitrate was used as a nitrogen fertilizer, simple superphosphate as phosphorus, potassium sulfate as potassium, and cattle manure as an organic fertilizer. As nitrogen fertilizer ammonium nitrate (33.4%), as phosphorus—ammophos (51%), as potassium—potassium sulfate (52%), and as organic fertilizer—cattle manure were applied. Accounting of raw cotton yield was carried out for all replications and variants. In order to determine fiber yield and technological quality of the fiber, before harvesting 20 cotton bolls were collected from each variant and replication. The BO-440 “white gold” cotton variety was used in field experiments. During field experiments, 5 complex cultivation operations and 3 irrigations were carried out.

During yield recording, harvesting was carried out separately for each variant. The accuracy of the obtained yield was calculated by the Mesheryakov method. To study the dynamics of nutrients as a result of applying organo-mineral fertilizers, soil samples were taken from depths of 0–25 and 25–50 cm at the budding, flowering and maturation phases of the crop, and laboratory analyses were carried out. In experiments conducted with tomato, ammonium nitrate (active nitrogen 34%) was used as the nitrogen fertilizer, simple superphosphate (active phosphorus 18%) as phosphorus, potassium chloride (active potassium 52%) as potassium; and as organic fertilizer, semi-rotted cattle manure containing 0.5% nitrogen, 0.3% phosphorus and 0.6% potassium with 65% moisture was used. In the variant with 10 tons of manure + $N_{75}P_{45}K_{90}$ ($N_{75}P_{45}K_{90}$ equivalent to 15 tons of manure), mineral fertilizers were applied in that proportion; in the variant with 20 tons of manure + $N_{50}P_{30}K_{60}$ ($N_{50}P_{30}K_{60}$ equivalent to 10 tons of manure), mineral fertilizers were applied in that amount. The semi-rotted cattle manure applied to the experimental plot was mixed with the soil at sowing time according to variants. Of the annual norm of mineral fertilizers by variants, 50% was applied at transplanting and 50% when 10–15 leaves formed and during the flowering period. Fertilizers were applied by hand, evenly distributed in the experimental plots, then incorporated into the soil and irrigated. All agrotechnical works were carried out in accordance with the agrotechnical rules intended for vegetable cultivation in the republic (except for fertilizer application). To study nutrient dynamics in soil according to the development phases of tomato, soil samples were taken and analyzed during flowering, maturation, first harvest, and last harvest periods. The “Zarrabi” tomato variety was used in the experiment.

Analysis and Discussion

Territorial features of the regions: The Mughan–Salyan zone is located in the south-eastern part of Azerbaijan and covers the main part of the Kura–Araz plain. The climate in the zone is dry and semi-desert (arid). The average annual air temperature of the region is +12.5–14.6 °C. According to the temperature regime, being subtropical, the summer is dry and hot, and the winter is mild and with little snow. The low precipitation and high evaporation level make irrigation a main condition of agriculture (Jafarov, 2006).

The soil cover of the Kura–Araz plain mainly consists of gray, gray-meadow, meadow-gray, solonchak, and saline soils. These soils are weakly supplied with humus (1–2%). Carbonate content and salinity are widespread in the soils of the region, and as a result, fertilization and reclamation measures play an important role in agro-production. The natural vegetation cover mainly consists of semi-desert and desert plants. Wormwood, saltwort, ephemeral and ephemeroid plants dominate. In irrigated areas, cotton, cereals, forage crops and vegetable growing are widely developed. The Lankaran–Astara region of our republic, being located on the southern border of our country, covers an area stretching from the Caspian Sea coast to the foothills of the Talysh mountains. It borders Masalli district to the north, the Islamic Republic of Iran to the south, the Caspian Sea to the east, and the Talysh mountains to the west. This geographical position has caused the formation of a specifically natural and climatic environment in the region (Madatzadeh & Shikhlinski, 1968, pp. 16–30). The region is located in Azerbaijan's humid subtropical climate zone. The average annual air temperature is 14–16 °C, and annual precipitation is 1200–1600 mm. Although precipitation falls more in autumn and winter months, humidity remains high throughout the year in the region. Such climatic features generally manifest themselves in the soil-forming processes of the zone. Year-round high humidity creates conditions for intensive development of leaching and gleying processes in soils (Mammadov, 2010, pp. 214–216). Yellow-podzolic, yellow-gley alluvial-meadow, mountain-forest, meadow-marsh and other soils are widespread in the region. The soils are characterized by high moisture, a tendency toward acidic reaction, and humus accumulation mainly in the upper horizons.

Due to its natural soil–climatic conditions, the region differs from other provinces of the republic. The subtropical climate and high precipitation make this region suitable for tea growing, citrus and subtropical crops, and also vegetable cultivation (Alosmanov, 2022). The vegetation cover mainly consists of moisture-loving subtropical forest and shrub plants. Chestnut, iron tree, pistachio, and relict species belonging to the Hyrcanian flora are widely distributed. In agriculture, tea, citrus fruits, rice and vegetable growing are considered the main fields. The soil–climatic conditions and fertility properties of the regions where we carried out the research have been studied by a number of scientists such as Zakharov, Tyuremnov, Volobuyev, M. E. Salayev, M. I. Jafarov, Y. J. Hasanov, Q.Sh.Mammadov, M. P. Babayev, Q. Z. Azizov. According to granulometric composition, the meadow-gray soils of the Mughan plain studied by us are heavy loamy and loamy, while the meadow-marsh soils of the Lankaran zone are light and medium loamy. They contain noticeably soluble salts and are moderately supplied with nutrients (Abdullayev & Gulahmadov, 1956, p. 105).

The Mughan–Salyan and Lankaran–Astara regions are important zones for agricultural cultivation in our country. Studying these soils is among the factors affecting the country's economy and the formation of ecological sustainability policy. Both in the Mughan–Salyan and in the Lankaran–Astara region, investigating, studying and analyzing the widespread soils is a relevant issue for the development of agriculture. Against the background of climate change, obtaining high yields from agricultural crops and at the same time preserving soil fertility is of very great importance. Research shows that applying fertilizers according to normative rates adapted to soil–climatic conditions creates conditions both for increasing productivity and for long-term preservation of soil fertility. F. H. Mishustin and I. V. Moslova, in their studies, note that long-term application of mineral fertilizers under crops accelerates biological and physico-chemical processes in soil. They show that long-term application of mineral fertilizers affects the transition of nutrients from one form to another in soil and also affects the movement of nutrients in the soil. M. K. Daraselja (1953) and M. M. Kononova (1951) state that applying mineral fertilizers affects the biological activity of the soil, and as a result, the decomposition and mineralization of organic matter in soil proceeds rapidly and completely.

During the conducted experiment, the effect of different rates and ratios of organo-mineral fertilizers on the yield of cotton and tomato was studied by us (Tables 1 and 2). As can be seen from the table, in the variant where background + 20 t/ha manure was applied, the yield was higher compared to other variants. Thus, if in the control unfertilized variant the yield was 1785 kg/ha, in the $N_{90}K_{60}$-background variant it was 2342 kg/ha, in the background + N_{120} variant it was 3200 kg/ha, and in the background + N_{30} + 15 t/ha manure variant it was 3488 kg/ha.

When analyzing the table, it is clearly seen that in the variants where mineral and organic fertilizers were applied together, yield was higher. This is explained by the fact that organic fertilizers influence biological activity in the soil. As a result, the process of easier uptake of mineral fertilizers by plants occurs. In heavy loamy soils like meadow-gray soils, organic fertilizers affect soil structure and improve its compaction ability, which results in better development of the plant root system and causes greater uptake of nutrients. In addition, the combined application of organo-mineral fertilizers affects soil microflora, which leads to activation of bacteria functioning in the soil and, as a result, to continuous mineralization of organic matter in the soil. In turn, this increases the soil's moisture retention ability and raises its air capacity, which positively affects plant development.

Table 1.

Effect of different rates and ratios of fertilizers on the yield of cotton

№	Experimental variants	Average number of plants per hectare (pcs)	2025		
			Yield (centner/ha)	Increase	
				c/ha	%
1	Control (unfertilized)	75 000	1785		–
2	$N_{90}K_{60}$-fon	75 000	2342	557	31,2
3	Fon +N_{120}	75 000	3200	1415	79,3
4	Fon+N_{30}+ 15t/ha manure	75 000	3488	1703	95,4
5	Fon+20 t/ha manure	75 000	3963	2178	122,0

Scientific research shows that correct organization of agrotechnical measures has an important impact on tomato yield. Studies have shown that an optimal fertilization system and a correct irrigation regime lead to a 20–35% increase in yield (Mammadov, 2023). Productivity mainly depends on environmental factors. These include the fertilizer and water regime, sunlight, soil type, and so on. In well-cultivated soil, with appropriate fertilization, production increases. Yield begins mainly with seedling planting. Healthy seedlings have healthy roots, which is important for the future development of plants. Researchers note that the most important for yield is correct soil cultivation, subsequence of irrigation, and timely elimination of diseases (Zamanov et al., 2009).

As a result, increasing tomato yield and optimizing production costs makes an important contribution to ensuring economic sustainability in agriculture and strengthening food security. During the study, the yield under tomato when organo-mineral fertilizers were applied together and separately was also studied. During the conducted experiment, it was determined that combined application of organic and mineral fertilizers under tomato was also effective. Analysis of the experimental results shows that the applied fertilizer variants significantly affected tomato yield. In the control (unfertilized) variant, yield was 231 c/ha, which characterizes the natural fertility level of the soil.

Table 2.
Effect of different rates and ratios of mineral and organic fertilizers on tomato yield on gray-brown soils

№	Experimental variants	2025		
		Yield (centner/ha)	Increase	
			c/ha	%
1	Control (unfertilized)	231	–	–
2	$N_{90}P_{90}K_{90}$	296.3	65,3	28,3
3	Organic fertilizer (manure) 10 t + N75P45K90	373.7	142,7	62,0
4	Organic fertilizer 20 t + N50P30K60	420.7	189,7	82,1

In the mineral fertilizer variant N90P90K90, yield was 296.3 c/ha. Compared to the control variant, this means an increase of 65.3 c/ha or 28.3%. This result indicates that mineral nutrient elements enhanced vegetative development and the formation of generative organs. In the variant with 10 t manure + N75P45K90, yield was 373.7 c/ha, and compared to the control, an increase of 142.7 c/ha (62.0%) was obtained. Improvement of the physical-chemical properties of soil and increased microbial activity by organic fertilizers can be considered the main reason for this result.

The highest yield in the experiment was observed in the combined variant of 20 t organic fertilizer + N50P30K60. In this variant, yield was 420.7 c/ha, yield increase was 189.7 c/ha or 82.1%. This result proves that the complex application of organic and mineral fertilizers shows a synergistic effect and ensures tomato yield at a higher level. During the experiments, the correlative relationship between the selected fertilization scheme and yield was analyzed. Correlation is evaluated only between fertilization system and yield. The analysis of the correlative relationship shows that as fertilization intensity increases, yield rises. This indicates a positive correlation. It is linear in nature and indicates a strong correlative relationship. Scientifically, this relationship is strong, direct, and statistically meaningful in experimentally accepted agronomic terms. The yield increase by variants is consecutive and sharp. The correlation strengthens as one moves from mineral fertilizer to organic fertilizer. Thus, there is a strong positive correlative relationship between yield and fertilization intensity, and the application of organic fertilizers further strengthens this correlation. In soil, organic fertilizers play the main role in increasing soil fertility. The obtained results, having a linear and stable character of yield increase, confirm that the fertilization system was chosen correctly.

Conclusion

In the irrigated meadow-gray soils of the Mughan–Salyan zone and the meadow-marsh soils of the Lankaran–Astara zone, combined application of organic and mineral fertilizers under cotton and tomato, compared to variants where they were applied separately, was found to have a better effect on increasing soil fertility. The highest yield under cotton during the application of organic and mineral fertilizers was obtained in the background + 20 t/ha manure variant, and in the tomato experiments in the variant 20 t organic fertilizer + N50P30K60.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ecological Assessment of Changes in Total Nitrogen in the Soil Profile Under Wheat Cultivation in Irrigated Conditions

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Abstract. *This study was conducted on the basis of soil samples taken from the irrigated wheat field located at the Terter regional experimental station of the Agricultural Scientific Research Institute of the Ministry of Agriculture of the Republic of Azerbaijan. The main objective of the study was to determine the distribution characteristics of total nitrogen (N^t) in the soil profile at different depth layers and to evaluate these indicators from an ecological perspective. According to the results of laboratory analyses, the total nitrogen content was 0.108% in the 0–21 cm layer, 0.105% in the 21–50 cm layer, 0.100% in the 50–88 cm layer, and 0.095% at a depth of 88–122 cm. The results show that nitrogen in the soil profile is higher in the surface layers and gradually decreases with increasing depth. This decrease is mainly due to the greater accumulation of organic matter in the upper layers and the intensive mineralization processes in the surface layers as a result of the activity of microorganisms. At the same time, the movement of nitrogen in the form of nitrate to the lower layers through leaching and infiltration processes under irrigation conditions also affected this distribution. Such distribution of nitrogen in the soil profile is of great importance from an agronomic and ecological point of view. The results of the study indicate that scientifically based application of nitrogen fertilizers, especially fractional application, and optimization of irrigation regime are essential for ecologically sustainable wheat production.*

Keywords: *irrigation, wheat, soil profile, total nitrogen, mineral fertilizer, ecological risks*

Introduction

Wheat is one of the main cereal crops of strategic importance in most arid and semi-arid climate zones, including Azerbaijan. The achievement of high and stable crop yields directly depends on maintaining soil fertility and nutrient supply at an optimal level. Nitrogen plays a special role among nutrients; because it is one of the main regulators of fundamental physiological processes such as protein synthesis, vegetative mass formation, cluster and grain development of wheat plants. Therefore, the application of nitrogen fertilizers in the correct norm and in an efficient manner is considered the main agrochemical measure in achieving high yields.

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Under irrigation conditions, the soil-plant-fertilizer system has a more dynamic and complex behavior. By changing the physicochemical regime of the soil, irrigation significantly modifies nitrogen transformation processes, its movement in the soil solution, and biological activity in the root zone. Under these conditions, the agrodynamics of nitrogen is characterized by a number of important features. First of all, the risk of leaching increases due to the high mobility of nitrate ions, and if the irrigation rate is not selected correctly, nitrates move beyond the root zone, reducing both the supply of plants with nutrients and creating an ecological threat to groundwater. On the other hand, nitrogen in the form of ammonium is nitrated as a result of oxidation processes, and in this case it is possible for it to pass into deep soil layers. Changes in aeration and humidity regimes in irrigated soils increase the intensity of biochemical processes, and as a result, the mineralization of organic matter on the surface is faster.

From an ecological point of view, the most important issue is to keep the sources of nitrogen loss from the soil - leaching, denitrification and volatilization into the atmosphere - at a minimum level. These losses can lead to a decrease in productivity from an agrotechnical point of view, as well as to an increase in anthropogenic pollution in the ecosystem. Thus, managing the nitrogen balance of the soil under irrigation conditions is a strategic task in ensuring the sustainable productivity of agricultural ecosystems (Vəliyev et al., 2016).

The main objective of this study is to study the variability of total nitrogen at different depths of the soil profile in an irrigated wheat field and to scientifically evaluate the factors affecting the vertical distribution of nitrogen. Determining the dynamics of nitrogen along the profile allows for a more accurate understanding of the transformation processes taking place in the soil, optimization of irrigation and fertilization systems, as well as the development of an ecologically based fertilization model. The research results serve to clarify the behavioral characteristics of nitrogen under irrigated conditions and to formulate scientific and applied recommendations aimed at both increasing productivity and ecological protection of soil and water resources (Hacıyev et al., 2012).

Materials and Methods

The materials used in the research and the applied methodology were carefully selected for the purpose of assessing the agroecological condition of the soil in irrigated wheat crops and determining the amount of total nitrogen at different depths of the soil profile. Soil samples were taken in the wheat crop field formed under long-term irrigation of the Terter regional experimental station of the Agricultural Scientific Research Institute of the Ministry of Agriculture of the Republic of Azerbaijan. The research area is located in the arid-subtropical climate zone in accordance with natural conditions and is distinguished by the intensity of soil-plant-irrigation relations. The use of the field in the wheat-alfalfa rotation cropping system in previous years was taken into account as one of the important factors affecting the level of soil organic matter and nitrogen turnover (Əliyev et al., 1986).

The soil sample for the study consisted of four genetic-agronomic layers and covered the part of the soil profile from 0 to 122 cm. Samples were taken from depths of 0–21 cm, 21–50 cm, 50–88 cm and 88–122 cm. Samples were taken from several points at each depth and homogenized to prepare an average sample. This approach allowed us to accurately reflect the real variability in the distribution of nitrogen throughout the soil section. The samples were transported to the laboratory in plastic containers, dried, sieved and prepared for analysis. The determination of the amount of total nitrogen in the soil was carried out according to the Kjeldahl method. This method involves the conversion of organic nitrogen into a mineral form and subsequent determination of its amount by titration. The analysis process was carried out in a standard laboratory mode, and technical procedures in accordance with internationally accepted FAO and ISO requirements were applied at the distillation and titration stages. In order to ensure the reliability of the study, each sample was analyzed twice, and the results obtained were presented as an average (Xudayev, 2012; Seyidov and Ağayev, 2005).

The applied methodology allowed us to obtain scientific conclusions on the ecological assessment of the distribution of nitrogen at different depths of the soil profile, as well as on the transformation, displacement and potential losses of nitrogen under irrigation conditions. When evaluating the results obtained, the analysis was carried out based on the accepted normative indicator for the level of total nitrogen in the soil, which is 0.090–0.170% interval. The aforementioned normative interval was taken as the main criterion for assessing the degree of nitrogen supply to the soil at an ecologically safe and agronomically optimal level. The use of normative indicators is of great importance not only for the protection of soil fertility, but also for determining the potential impact of nitrogen leaching in the soil profile and environmental components. In order to assess the intensity of nitrogen changes in depth in the soil profile and its vertical distribution characteristics, the 0–21 cm layer was adopted as the main (reference) layer. This layer, being the most biologically active part of the soil, is characterized as the accumulation of organic matter, the intensity of microbiological processes and the main distribution zone of the plant root system. Comparison of other depth layers with this reference layer allows us to determine how nitrogen is distributed in the soil profile under ecological balance conditions and its trends in depth.

Relative Retention Indicators of Total Nitrogen (0–21 cm = 100%)

During the calculations, the 0–21 cm layer of the soil profile was taken as the main (reference) layer, and the amount of total nitrogen determined in this layer was considered as 100%. The relative proportion of total nitrogen in the other depth layers was calculated using the following formula:

$$N_{\text{relative}}(\%) = \frac{N_{\text{layer}}}{N_{\text{reference}}} \times 100$$

where:

- $N_{\text{reference}}$ – total nitrogen content in the 0–21 cm soil layer, %
- N_{layer} – total nitrogen content in the soil layer under comparison, %

The proposed calculation method allows quantitatively assessing the relative change in nitrogen depth in the soil profile, and is also a convenient tool for analyzing the ecological behavior of nitrogen. The gradual increase in the percentage of reduction indicates that nitrogen is more concentrated in the surface layers, and gradually decreases towards the deeper layers, which is consistent with the vertical structure of the distribution of organic matter and microbiological activity in the soil.

From an ecological point of view, this approach is of particular importance, since under irrigation conditions, the migration of nitrogen, especially nitrate forms, to the lower layers is considered a potential risk factor for soil and groundwater. Calculations of the relative reduction by depth allow us to determine that nitrogen is distributed in the soil profile not at the level of uncontrolled leaching, but in conditions of ecological equilibrium. If the percentage of reduction were sharp and disproportionate, this could indicate intensive leaching of nitrogen and disruption of the ecological stability of the agroecosystem (Əliyev et al., 1981).

Thus, the applied formula and comparative approach allow for the assessment of the vertical distribution of total nitrogen in the soil not only from an agrochemical but also from an ecological perspective, and for the scientific explanation of the sustainability of soil fertility and the formation of a nitrogen regime that is safe for the environment.

Results of the Calculations

- **0–21 cm:**

$$\frac{0.108}{0.108} \times 100 = 100.0\%$$

- **21–50 cm:**

$$\frac{0.105}{0.108} \times 100 = 97.2\%$$

- **50–88 cm:**

$$\frac{0.100}{0.108} \times 100 = 92.6\%$$

- **88–122 cm:**

$$\frac{0.095}{0.108} \times 100 = 88.0\%$$

As a result of the calculations, it was determined that the relative decrease in total nitrogen compared to the 0–21 cm base layer is 2.8% in the 21–50 cm layer, 7.4% in the 50–88 cm layer, and 12.0% in the 88–122 cm layer. These indicators demonstrate a gradual, consistent and proportional decrease in nitrogen in the soil profile from the surface to the deeper layers. Such a distribution is consistent with the natural mechanisms of substance circulation in soil ecosystems and is considered one of the main indicators of ecological stability. The gradual decrease in nitrogen with depth is closely related to the concentration of organic matter in the soil mainly in the surface layers, the high concentration of humus in the upper layers, and the more intensive course of microbiological processes — especially ammonification, nitrification and immobilization reactions — in this zone. The weakening of biological activity in deep layers leads to a decrease in both the reserve and turnover intensity of nitrogen, which is confirmed by the observed percentages of decrease. The results obtained from an ecological point of view are particularly important, since in irrigated agroecosystems, the leaching of nitrogen, mainly nitrate forms, to the lower layers is considered a potential source of risk in terms of groundwater pollution. However, the relative reduction indicators determined in this study indicate that nitrogen does not migrate sharply in the soil profile, but rather is retained in association with the soil matrix and organic matter. This proves that the nitrogen buffering capacity of the soil is high and that ecological balance is maintained even under irrigation conditions. The fact that nitrogen remains above the normative minimum even in the deepest layer of 88–122 cm indicates that the nitrogen reserve in the soil profile is at an ecologically safe level. This can be assessed as an important ecological advantage in terms of both preserving the productivity potential of the soil and preventing nitrogen pollution of groundwater resources (Ağayev et al., 1989).

Thus, the increasing but balanced nature of the relative reduction rates indicates that the nitrogen cycle in the soil–plant–water–microorganism system proceeds in ecological balance. This is considered an important scientific result in terms of ensuring the long-term ecological sustainability of the agroecosystem, as well as maintaining soil fertility in irrigated wheat crops.

Features of nitrogen distribution along the profile under irrigation conditions

The results of the conducted research show that the distribution of nitrogen in the genetic profile of the soil is sharply heterogeneous and the irrigation regime has a significant impact on this process. According to the data obtained, the highest amount of nitrogen was recorded in the surface horizon of the soil profile. This phenomenon is assessed as a natural result of aboveground and underground ecological-biochemical processes. The accumulation of organic matter in the surface layer and more intensive decomposition of plant residues here lead to a high humus reserve of the soil in this zone. As a result of the decomposition of humus, the formation of mineral nitrogen forms occurs mainly in the surface layers, which creates conditions for a relatively high total nitrogen content.

The activity of soil microorganisms is also one of the factors that directly affects the distribution of nitrogen. Since the zone where temperature, humidity and oxygen exchange are most optimal is located in the interval of 0–20 cm, microbiological processes are more active here. These conditions accelerate the transition of organic forms of nitrogen to mineral forms, and as a result, a high nitrogen concentration is observed in the surface layer. A sharp decrease in nitrogen was recorded in the deeper layers of the soil profile - especially in horizons below 50 cm. This decrease is explained by the natural pedogenetic properties of the soil, as well as by the physicochemical transformations caused by irrigation conditions. During irrigation, the nitrate form in the soil solution has high mobility and can be washed out and migrated to lower horizons. However, due to the lack of organic matter in the deep layers, poor mineralization and a significant decrease in the activity of microorganisms do not allow nitrogen to accumulate in these zones. Thus, the nitrogen level observed in the deep layers is more likely due to the displacement of nitrates, and this amount is not at a level that can seriously affect plant nutrition.

Ecological risks of nitrogen under irrigation

Irrigated soil systems face different ecological risks compared to other agroecosystems, and one of the main sources of these risks is nitrogen leaching. The fact that the nitrogen levels determined in the study are close to the lower limit of the normative indicators indicates that it is necessary to increase nitrogen reserves in the study area from the outside in the form of fertilizers. A more important point is the possibility of nitrates moving beyond the root zone as a result of irrigation. This process both weakens the plant's nitrogen nutrition and creates a risk of pollution for hydrological systems.

The fact that nitrates are detected to some extent in deep layers indicates that they move dynamically downward. This fact can be assessed as a potential threat from the point of view of the ecology of the soil-water system, since excessive leaching of nitrates can result in groundwater pollution. Changes in irrigation intensity, amount of precipitation, soil texture characteristics, and water-air regime are the main factors shaping the amplitude of nitrate leaching. This risk is particularly high in sandy and light soils, although the study area is dominated by medium and heavy soils, and there are results indicating that leaching occurs.

In this context, it is important to develop an ecologically sound fertilization strategy. It is known that excessive or inappropriate application of nitrogen fertilizers has a negative impact not only on productivity but also on the ecological balance of the soil. Therefore, nitrogen fertilizer management under irrigated conditions requires a more precise and dynamic approach. Assessment of plant nitrogen nutrition Wheat is one of the cereal crops that requires a sufficient amount of nitrogen from the soil to achieve high productivity. The 0.108% nitrogen content measured in the surface layer of the study area can be characterized as a “medium” provision of the soil. However, it can be concluded that this indicator is not enough to achieve high productivity. Therefore, it is important to consider the physiological needs of the plant during the vegetation period when applying nitrogen fertilizers. Efficient absorption of nitrogen is closely related to the characteristics of the root system of wheat, the structural condition of the soil, and the rate and timing of irrigation. In this regard, optimizing the irrigation-fertilization relationship is one of the main determinants of productivity in the agroecosystem of the study area.

The following table shows the variation of total nitrogen at different depths in soil samples taken in an irrigated wheat field:

Table 1.
Distribution of Total Nitrogen in the Soil Profile

Soil depth (cm)	Total nitrogen (%)	Standard requirement (%)	Evaluation
0–21	0.108	0.090–0.170	Adequate
21–50	0.105	0.090–0.170	Adequate
50–88	0.100	0.090–0.170	Adequate
88–122	0.095	0.090–0.170	Adequate

Note. The total nitrogen content in all soil layers falls within the recommended standard range, indicating an adequate nitrogen status of the soil profile under irrigated wheat cultivation.

Results

The results of the study show that the total nitrogen content in the soil profile of irrigated wheat fields decreases consistently with depth. The highest nitrogen content was recorded in the 0–21 cm surface layer (0.108%), while in deeper layers the indicator decreased to 0.095%. This decrease is associated with a greater accumulation of organic matter and plant residues on the soil surface, as well as active mineralization activity of microorganisms (Zayev et al., 1966).

Nitrogen variation in the range of 0.095–0.108% indicates that the soil is “medium-sufficient” in nitrogen. The available nitrogen reserves of the soil are not considered sufficient to achieve high yields in crops with high nitrogen requirements, such as wheat. In this regard, it is considered more appropriate to apply nitrogen fertilizers in stages – in 2 or 3 fractions – during the growing season.The study also shows that under irrigation conditions, nitrate nitrogen can move deeper into the soil profile, which can lead to both nitrogen deficiency for the plant and environmental risks (leaching, groundwater pollution). Based on these risks, it is recommended to use ammonium nitrogen fertilizers, fertilizers stabilized with nitrification inhibitors, and avoid high-dose nitrogen applications before heavy rainfall/irrigation periods. At the same time, foliar nitrogen fertilization is considered an effective and loss-minimizing method to eliminate nutrient deficiencies during critical plant phases (Məmmədov, 2007).

Discussion

The soil ecosystem has a complex and multilayered structure. The amount and distribution of nitrogen in the soil layers (profile) directly determines its biological functions, productivity and ecological stability. Therefore, the ecological grouping of soil layers based on total nitrogen indicators is of great importance for both agrobiological and ecological assessment. In the conducted study, the total nitrogen content of the 0–21 cm soil layer was taken as a 100% base, and the ecological functions of different depth layers of the soil profile were grouped according to the relative nitrogen indicators as follows (Məmmədov et al., 2010).

Ecological group I – Biologically active and main nitrogen storage zone (≥95 %)

This group includes the 0–21 cm and 21–50 cm soil layers. The relative nitrogen levels are as follows:
• 0–21 cm: 100.0 % • 21–50 cm: 97.2 %
These layers are considered the central zone of biological activity in the soil ecosystem. Here, the accumulation of organic matter is intensive, microbiological activity is at a high level, and nitrogen turnover — mineralization and immobilization processes — are actively taking place. The main food reserves of plants are formed in these layers, and the productivity potential of the soil is directly related to these layers (Fətəliyev, 2013).
Ecological and agroecological significance:

- Maintaining a high level of nitrogen in biological forms as a center of biological turnover of the soil.
- Ensuring the main food supply of plants.
- The intensity of the turnover of organic matter as a result of the active activity of soil microflora and fauna.

For this reason, the 0–50 cm layers are considered the main nitrogen supply zone in terms of both productivity and ecological sustainability (Məmmədov et al., 2010; Məmmədov, 2009).

II ecological group – Transition and buffer zone (90–95 %)

This group includes soil layers of 50–88 cm:
• 50–88 cm: 92.6 %
This layer plays the role of a "buffer" between the surface biologically active zones and deep layers in the soil profile. Although the amount of nitrogen here is slightly reduced compared to the surface layers, it is still maintained at a high level. This indicates that the nitrogen retention capacity of the soil continues to the depth.

Ecological and agroecological significance:

- Prevents uncontrolled migration of nitrogen to the lower layers.
- Regulates the structure of the soil profile and nitrogen cycle.
- Prevents the downward loss of microelements and organic nutrients, despite the weakening of biological activity in the deep layers.
- Provides a reserve source of nitrogen for the root system of plants in irrigated wheat crops.

The ecological function of this zone is to maintain a stable nitrogen balance in the soil-plant-water system and prevent the risk of washing out the deep layers.

Ecological group III – Deep accumulation and ecological safety zone (<90 %)

This group includes the soil layers of 88–122 cm:
• 88–122 cm: 88.0 %
This layer is a zone in the soil profile where biological activity is further weakened, but nitrogen still remains above the regulatory minimum level. Nitrogen here is not subject to intensive leaching in nitrate forms, therefore it does not pose an ecological risk.

Conclusion

1. The decrease in total nitrogen in the soil from the surface to the lower layers reflects the natural profile characteristics and potential nitrate leaching due to irrigation.
2. The "medium" level of nitrogen supply is not optimal for wheat and requires proper planning of the fertilization strategy.

3. From an ecological point of view, the main goal of nitrogen management is to minimize leaching losses and provide nitrogen in accordance with the real needs of the plant.
4. The phased application of mineral nitrogen fertilizers, the use of stabilizers, as well as the addition of foliar nutrition were determined as the most effective approach under irrigated conditions.

These results serve to scientifically determine the ecological basis of the strategy of nitrogen fertilizer application under wheat plants under irrigated conditions and serve as a baseline for future research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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