# Ecological Assessment of Cotton Cultivation in the Kura-Aras Lowland

**Ulviyya Karimova-Japharova [1], Ramiz Qulamov [1], and Hikmet Ahmadov[1]**

[1]School of Advanced Technologies and Innovation Engineering, Department of Ecology and Environmental Sciences, Western Caspian University, Baku, AZ1072, Azerbaijan.

Received: 07.04.2026 Accepted: 13.05.2026 Published:27.05.2026
https://doi.org/10.54414/JKAW2841

## Abstract

This study investigated the impact of the intensive use of mineral fertilizers in cotton production in the Kura-Aras Lowland of Azerbaijan on the environment. The study focused on the risks associated with the long-term use of nitrogen and phosphorus fertilizers and their impact on soil and water resources. The main aim was the assessment of the environmental impact of these fertilizers by analyzing chemical transport mechanisms, while taking into account the specific agricultural conditions of the study area. To achieve that aim, both field and laboratory experiments were conducted. Soil samples were taken at mid-elevation plots, nitrogen and phosphorus transport rates were determined, and spectrophotometry, colorimetry, and electrochemical analysis methods were used. The studied soil was characterized by low humus content (1.2-1.8%), slightly alkaline pH (7.8-8.3), and overirrigation. Together, these factors significantly alter the storage, transport, and transfer of nutrients, as well as their environmental impacts. The results indicate that the efficiency of mineral fertilizer use in the study area has been decreasing. The use of nitrogen fertilizers at a rate of 180-200 kg/ha leads to a nitrogen deficit of about 90 kg/ha. This means that about 50% of the added nitrogen is not absorbed by plants but instead remains as a mobile compound in the agroecosystem. Most of this excess nitrogen leaks into groundwater, and some of it is also released into the atmosphere. The use of phosphate fertilizers also leads to a nitrogen deficit of about 65 kg/ha in the environment. Over a decade of cultivation, this leads to the accumulation of approximately 650 kg/ha of unavailable phosphate compounds in the soil profile. The data obtained indicate a high risk of groundwater pollution, secondary soil salinization, eutrophication of water bodies, and the accumulation of heavy metals introduced with phosphorus fertilizers. Thus, the study results indicate that current approaches to fertilizer application in cotton production exceed the ecologically acceptable load level for the soil and climatic conditions of the Kura-Aras Lowland and require a transition to more precise and adapted plant nutrition management systems.

**Keywords:** cotton cultivation, mineral fertilizers, Kura-Aras Lowland, soil degradation, groundwater contamination

## 1.Introduction

The current critical state of the global food chain is maintained by a high and nearly metabolic dependence on the use of chemical fertilizers in soil. In agronomic circles, it is known that the abrupt stop of mineral and organic amendments would cause a catastrophic loss of 40-50% of crop production. However, the cost to the environment is high. Self-sustaining soil ecosystems have become open-ended industrial systems, which are releasing nutrients into the environment at a rate that is not sustainable.

The main disruption is due to the amount of chemicals applied being greater than the plants can tolerate. Nitrogen is one such element whose nitrate salts are highly mobile and often pass completely through the root zone to pollute deep aquifers. At the same time, nitrous oxide ($N_2O$) is being released into the atmosphere, which is adding to the depletion of the ozone layer, a phenomenon that has been exacerbated by a focus on increased productivity. However, phosphorus has a special, problematic relationship. It is known to bind to soil particles and is later transported downstream via surface runoff, where it can stimulate the rapid growth of algae that consume oxygen. Residuals from livestock farming, which are frequently touted as being natural alternatives, create their own issues. If not properly treated, manure and poultry litter have the potential to release heavy metals and harmful pathogens into the environment.

The above factors are reflected in the use of encapsulated smart fertilizers and field-specific fertilizer application technologies. The main objective of the study is to balance the economic and biological realities of existing pesticides with the realities of future agricultural practices.

In order to address this critical environmental debt, the present article investigates the intersection of agrochemistry and ecology. The article establishes the theoretical foundations and historical context of the problem and details the methodological framework that was utilised to measure and model nutrient migration. The application of these theoretical models to a specific geographical context – namely, cotton cultivation in the Kur-Aras Lowland – enables the quantification of the precise physical and chemical parameters of nutrient loss.

## 2. Research object and methodology

It is imperative that assessment of agrochemical pollution commences long before any laboratory testing. The study commences with an examination of the spatial geometry of field sampling. The collection of typical topsoil to a depth of 20 cm is not enough for environmental monitoring. Nitrate N has high hydrological mobility, so our protocol requires that deep soil cores to at least 1 m be taken. The avoidance of the critical downward flux of pollutants to the water table is the reason for stopping at the arable layer.

After stabilization, drying, and delivery to the lab, the analytical emphasis is on the determination of the remaining macronutrients. The dangerous over-accumulation of phosphorus is measured by spectrophotometry and target extraction. We separate the 'mobile' phosphates from the soil matrix through the use of certain acidic or alkaline extractants chosen specifically to the natural baseline acidity of the particular plot. We do this for a certain reason. We are not just looking at what is available for plant use, but rather are selecting the plant nutrient fraction most susceptible to surface runoff and thus possible to cause eutrophication in the receiving waters.

The analytical procedure used in the case of Nitrogen is quite different. Nitrates are very soluble in water, so they are removed from the soil samples with a weak salt (saline) solution. This means that during the testing phase, the N is not further biologically transformed. Subsequent analysis – typically using ion-selective electrodes or more sophisticated colorimetric techniques – can give a very accurate measurement of the $N\text{-}NO_3$ concentration.

## 3. Results and discussion

This particular data is used as the baseline for the ecological assessment. The measurement is a direct and quantifiable indicator of the potential for contamination of the aquifer. The utilisation of deep-profile chemical baselines obviates the necessity for subjective estimations when ascertaining the efficiency of fertilisers. These numbers from the extraction data allow us to calculate the actual environmental loss incurred by the farming activity and to see what was left behind after the harvest.

***Table 1.*** *Site-specific extraction reagents and analytical instrumentation*

| Soil Typology / Baseline Acidity | Primary Extractant Reagent | Target Pollutant / Mobile Fraction | Final Analytical Instrumentation |
|---|---|---|---|
| Acidic (e.g., Sod-podzolic) | 0.2M Hydrochloric Acid (HCl) | Phosphates ($P_2O_5$) | Spectrophotometry |
| Neutral to Slightly Acidic (e.g., Chernozems) | 0.5M Acetic Acid ($CH_3COOH$) | Phosphorus Exchangeable Potassium | Flame Photometry |
| Alkaline (e.g., Carbonate soils) | 1%Ammonium Carbonate | Trace Phosphates / Nitrates | Ion-selective Electrodes |
| Deep Profile (All types) | Dilute Saline Solution (1% KCl) | Nitrate Nitrogen (N-$NO_3$) | Advanced Colorimetry |

The selection of the extractant is not an arbitrary choice but is determined with reference to the inherent nature of the soil in terms of its pH and genetic characteristics. The ecological risk assessment of a universal solvent will be totally misinformed if it is conducted on completely different landscapes in a different laboratory. There is a need to ensure that the numbers are representative of real field conditions, and that specific chemical protocols are matched to the specific field conditions. Table 1 decomposes these methodological combinations, which show how we will optimize the extraction process to obtain the most reliable information on remaining contaminants.

As per the strict methodological directions set by the classical agrochemical schools of L.A. Mikhailova and A.Kh. Sheudzhen, the generic categories are highly specific, standardized analytical procedures. For example, the extraction of mobile phosphorus from acidic podzolic soils is performed using the Kirsanov method (based on chemical dissolution of Al and Fe phosphates with 0.2 M HCl), which is chemically formulated to aggressively extract potentially mobile Al and Fe phosphates. The alkaline and often very carbonate-rich soils, such as the sierozems in the Kur-Aras Lowland, are in stark contrast: Here, the Machigin method is strictly prescribed. Using 1% ammonium carbonate solution in this protocol will keep the soil analytical extractant from being neutralized by native soil calcium carbonate. This particular chemical buffer has enabled the very accurate quantification of the calcium-bound phosphate fraction, which represents the main reservoir of long-term eutrophication in this extreme environment. In addition, it is imperative to adhere to physical preparation standards from field collection to laboratory bench to prevent catastrophic data loss. When analyzing raw soil cores, it is necessary to first transform them into a standardized "fine earth", as V.V. Lapa's systemic monitoring framework states. This protocol prescribes air-drying of samples in special chambers away from direct UV radiation and high temperature to avoid thermal degradation of organic matter and artificial volatilization of ammoniacal compounds. After stabilization, the soil is mechanically homogenized and filtered through a standard 2.0 mm analytical sieve to get a soil sample that can be used for analysis (Кротких & Михайлова, 2013, pp. 115-118; Шеуджен et al., 2006, p. 342).

The preparation protocol is even more time-sensitive and stringent, however, for nitrate-nitrogen $(N - NO_3)$ analysis. The soil microbiota, which is naturally alive, can also continue to affect the nitrate levels by ongoing nitrification or denitrification in transit, even after removal from the soil. For deep-profile samples to be analyzed for nitrogen, they must either be processed in a mobile field laboratory or be "frozen" biochemically. This is accomplished by keeping the cores at a constant 4°C to artificially inhibit enzymatic bacterial activity until the 1% KCl extraction can be made. Returning to the spatial geometry of field sampling discussed above, many soils in agriculture are highly micro-heterogeneous, making isolated, single cores too few for statistical considerations (Lapa et al.2009, pp. 22-25).

To remove the random space anomalies (for instance, the core hitting another undissolved fertilizer granule), the protocol requires a "composite sample" to be formulated. One composite sample is created in the polygon from 15-20 individual diagnostic samples collected by the classical “envelope” (grid) trajectory following V.G. Mineev's standards “Ecological Agrochemistry”. Finally, high-precision optical and electrochemical instrumentation is used in the analytical phase of the terminal to assure part-per-million (ppm) accuracy. Nitrate nitrogen is usually measured by sophisticated photocolorimetry. This includes adding certain chromogenic reagents (e.g., the Griess-Ilosvay reagent after the cadmium-reduction of nitrates to nitrites) that result in a specific, colorimetric change that can be detected using a spectrophotometer at particular nanometer wavelengths. These are strict site-specific extraction geometries and highly sophisticated optical verifications that remove statistical noise from the resulting chemical baselines. It is asserted that they provide a mathematically incontrovertible basis for the calculation of the exact ecological debt and the mass balance of pollutants not assimilated (Минеев, 2008, p. 180).

The object of the study is the Kura-Aras Lowland in the Republic of Azerbaijan. Cotton (*Gossypium hirsutum*) is an economically significant crop in the region. However, it imposes considerable ecological stresses on the regional biosphere due to its specific agronomic requirements.

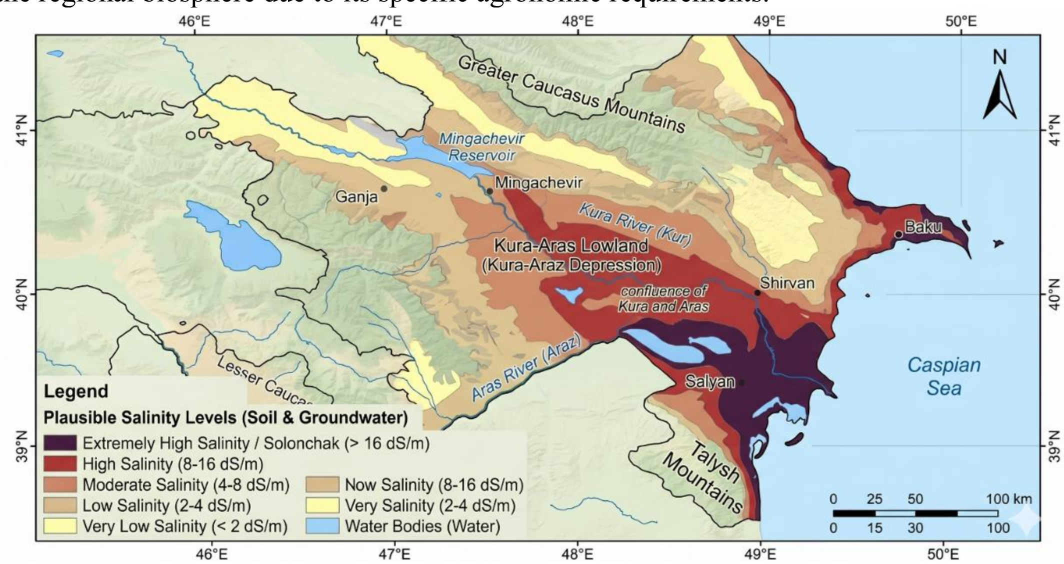


***Figure 1.*** *Soil and Groundwater Salinity Levels*

This map (Figure.1) illustrates the spatial distribution of soil and groundwater salinity levels across the Kura–Aras Lowland of Azerbaijan. The highest salinity levels have been recorded in the southeastern and coastal areas near the Caspian Sea, particularly around Salyan and the Kura-Aras river confluence (see Figure 1). These areas have been identified as those most vulnerable to soil degradation and salinization.

The genesis of the soils in this region is the most significant factor determining the environmental vulnerability of this region. The soil types are mainly irrigated sierozems and meadow-sierozems with a semi-arid climate profile. The extraction procedures were utilised in order to establish our baseline. The chemical composition of these soils is indicative of the risk factors involved. The humus content of the upper horizon of arable soil is found to be generally low, with values ranging from 1.2% to 1.8%. This finding suggests that the biological buffering capacity of the soil is minimal, and the absence of an organic sponge-like material naturally absorbing and retaining excess synthetic nutrients is evident. Due to high calcium carbonate content, the soil pH was found to be highly alkaline (7.8-8.3). This is due to a high calcium carbonate content.

The soils of the Kura-Aras Lowland necessitate the use of large amounts of nitrogenous mineral fertilizers and superphosphates (Бабаев, 1984, pp. 45-48; Mammadov, p. 112). The arid climate of the region requires regular irrigation. Excessive irrigation water leads to an additional increase in nitrates that percolate from soil layers to groundwater through advection. Because of this, irrigation is a major source of groundwater pollution by agricultural chemicals.

The specific physicochemical properties of the soils in the Kura-Aras Lowland largely determine the patterns of nutrient migration and transformation. The serozems of the region are characterized by a slightly alkaline to alkaline soil reaction (pH 7.8-8.3) and a high content of calcium carbonate ($CaCO_3$). Under these conditions, the effectiveness of traditional phosphate fertilizers is significantly reduced due to the chemical fixation of phosphorus. As shown by the studies of L. A. Mikhailova, after the application of water-soluble superphosphates, the dissolved orthophosphate ions quickly combine with calcium in the soil solution. The resulting compounds are poorly soluble. The initially formed dicalcium phosphate is converted into more stable mineral phases, such as octacalcium phosphate and hydroxyapatite, which are not absorbed by plants. As a result of severe phosphorus fixation, the rate of use of phosphate fertilizers is significantly reduced. In order to maintain the required level of productivity, farmers are forced to increase their consumption, thereby compensating for the lack of phosphorus available to plants. As a result, arable land gradually turns into a reservoir for the accumulation of relatively inactive phosphate compounds. This practice not only reduces the profitability of fertilization but also leads to the accumulation of impurities associated with phosphate raw materials in the soil. The gradual increase in the concentration of heavy metals, in particular cadmium and strontium, which are characteristic impurities of industrial phosphate fertilizers, poses a certain environmental threat. Their accumulation in the soil increases the risk of pollution of agricultural ecosystems, reduces the quality of agricultural products, and has a negative impact on the environment.

At the same time, the low organic matter content of the soil (humus content is only 1.2-1.8%) significantly impairs the agrochemical properties of the soil, in particular, the cation exchange capacity (CEC). According to V. G. Mineev's research on the agrochemical transformation of the soil, the soil adsorption complex is poorly developed in soils poor in humus, which limits their ability to retain and temporarily absorb mobile forms of agrochemical compounds. Under these conditions, the application of high doses of nitrogen fertilizers (including urea and ammonium nitrate) leads to rapid transformation. High summer temperatures in the Kura-Aras Lowland stimulate microbial activity, accelerate the enzymatic nitrification of nitrogen-containing compounds, and increase the formation of mobile nitrate forms that easily migrate in the soil profile. Nitrate ions ($NO_3^-$) formed during nitrification have high solubility and remain mobile in the soil solution due to the lack of sufficient organic matter for adsorption. Soils with low humus content have a very low nitrogen retention capacity, which significantly increases the risk of nitrogen migration beyond the root zone. As previously mentioned, cotton cultivation in the region depends on intensive irrigation, which causes water to flow downwards in the soil profile. This water flow becomes the main transport mechanism for the vertical migration of dissolved substances. In the end, nitrate ions that are not retained by soil adsorption complexes are filtered below the root zone (at a depth of about 1.5 meters) and enter the upper groundwater layer, polluting it (Aliyev, 2009, pp. 15-18; Savci, 2012).

The arid climate further contributes to the soil deterioration in the Kura-Aras region. According to the agroecological studies of A.Kh. Sheudzhen, the combination of the overuse of mineral fertilizers and intensive irrigation creates a complex hydrological regime that contributes to the development of various salt migration processes. Irrigation water initially facilitates the movement of nitrates and other highly soluble compounds through the soil profile. However, during the subsequent dry period, when evaporation predominates, soil moisture rises to the surface by capillary action. This upward flow carries dissolved salts to the upper soil layers. Then, as water evaporates, salts concentrate and crystallize, leading to secondary soil salinization. This process causes changes in soil biogeochemical functions, which ultimately accelerate overall soil degradation.

Thus, the physicochemical characteristics of the soil of the Kura-Aras Lowland show that the use of traditional mineral fertilization systems, developed without considering regional soil-climatic conditions, does not guarantee the efficient use of fertilizers and creates significant environmental risks. The limestone soils of the region are unable to retain existing phosphorus forms for a long time due to strong chemical binding, and the low content of organic matter seriously limits the ability of the soil to retain mobile nitrogen compounds. As a result, the soil cover acts not as a natural reservoir of nutrients, but as a means of facilitating their transformation and active transport, which increases the risk of soil and groundwater pollution. Determining the quantitative characteristics of these physicochemical processes is of great importance for the development of predictive models of the ecological state of agricultural landscapes. In particular, the assessment of parameters describing the delay coefficient of phosphorus compounds and the minimum retention of nitrates in the soil profile allows us to determine the magnitude of environmental deficit (ΔE), calculate the rate of pollutant migration, and predict the potential toxicological load in the regional watershed.

To evaluate the observed patterns, the material balance of fertilizers used in the agroecosystems of the Kura-Aras Lowland was calculated. The results allow the comparison of theoretical estimates with real nutrient flows to quantify the efficiency of fertilizers and identify possible impacts on soil and water resources. Aggressive fertilization is playing a big role in the agricultural approach to these areas in order to generate cotton production at higher and higher levels. But when one looks at the biological efficacy of these inputs, one has to admit that there is a huge disconnect between the input and the processing that the plant system can do. The average application rate of mineral nitrogen (N), based on agronomic practices in commercial cotton production under standard regional conditions in relation to irrigated sierozems, is about 180-200 kg/ha per season. We have to compare this huge input with the actual nutrient removal in the harvest by using the mass balance equation derived in Section 2.2. The biological nitrogen requirement is still limited for a representative and optimistic yield of 3.0 tons of seed cotton/ha. Agronomic data show that about 30 to 35 kg of nitrogen is used to produce one ton of raw cotton. Our formula:

$$\Delta E_N = 180 \text{ kg/ha} - (3.0 \text{ t/ha} \times 30 \text{ kg/t}) = 90 \text{ kg/ha}$$

makes for an astounding 50% inefficiency. [8, pp. 34-37; 1, p. 24]

In practical terms, this is equivalent to 90 kg of active nitrogen, which cannot be explained per hectare of cotton grown. However, this surplus is not the same as it was in the past. It is the first "ecological deficit. We need to understand where this 90 kg of 'residual' nitrogen ends up as a threat to the environment. About 25-30% of this loss is volatilized as ammonia and denitrified to the atmosphere each year due to the high mobility of the nitrate form and the very warm summer temperatures in Azerbaijan. This is a direct effect on greenhouse gas emissions. The other 60-70% goes into the downward hydrological flux due to heavy irrigation in cotton. It percolates through the permeable soil column into the shallow, saline groundwater of the lowland. The case of phosphorus $(P)$ is much more complicated and still more harmful to the environment. Cotton has a relatively low P demand to N demand (P: N). Only around 12 to 15 kg of $P_2O_5$ per hectare is removed from the crop for the same yield of 3.0 tons. This has not prevented the application of between 100 and 120 kg/ha of superphosphates as compensation for the "fixation" effect in the soil in accordance with the standard practice in the region. The efficiency is even worse for phosphorus, at 65 kg/ha relative to a potential of:

10 kg/ha: ΔEP = 110" kg/ha − (3.0" t/ha ×15" kg/t) = 65" kg/ha

Phosphorus is not easily leached to groundwater as compared to nitrogen. In the highly alkaline (pH 8.0+) soils of the Kur-Aras Lowland area, however, the excess phosphorus will rapidly retrograde. The 65 kg/ha Deficiency interacts with native calcium, creating very insoluble calcium phosphate compounds. This may appear to be less harmful than groundwater pollution, but may result in a large "Cumulative Ecological Debt". In the course of a conventional 10-year crop rotation period, one hectare of land retains almost 650 kilograms of non-retrievable chemical residues. This man-made storage alters the natural physical soil condition, reduces native soil microorganism activity, and creates a very polluted, eutrophication-causing runoff event when heavy seasonal rains occur. Finally, these quantitative deficiencies are used as the source terms, $S$, in the Convective-Dispersion Equation that we have defined above. They show that the way they are currently being fertilized exceeds the environmental capacity to sustain them in the region, creating permanent environmental problems from agricultural inputs (Кротких & Михайлова, 2013, pp. 90-95; Pimentel, 1996).

To fully grasp the severity of these permanent environmental problems, the quantitative data of the ecological deficit must be analyzed through the advanced toxicological framework established by V. G. Mineev and A.Kh. Sheudzhen. The loss of 25–30% of nitrogen through gaseous emissions—representing nitrogen that was not utilized productively—should be viewed not only as a reduction in fertilizer application efficiency but also as a significant environmental factor. When approximately 90 kg/ha of unassimilated nitrogen is present in the soil, the alternation of irrigation and intense evaporation creates favorable conditions for microbiological denitrification. Through the metabolic activity of facultative anaerobic microorganisms, nitrate ions ($NO_3^-$) are sequentially reduced to nitrites, nitric oxide (NO), and nitrous oxide ($N_2O$). According to current concepts in environmental agrochemistry, nitrous oxide is one of the most significant greenhouse gases, with a global warming potential approximately 300 times that of carbon dioxide.

A large part of the nitrogen is transported downwards into the groundwater at a rate of about 54-63 kg/ha each year. Calculations based on the convective dispersion equation (CDE) model show that the long-term maintenance of current fertilization and irrigation practices can lead to an accumulation of nitrates in the aquifer. Mathematical modeling shows that the concentration of nitrates in drinking water is likely to exceed the World Health Organization limit of 50 mg/L and put the quality of groundwater and the health and safety of rural areas at severe risk.

Another equally important environmental aspect is the accumulation of significant amounts of residual phosphorus in the soil. In a ten-year crop rotation, this amount can reach about 650 kg/ha. According to the fundamental research of L. A. Mikhailova, commercial phosphate fertilizers, including superphosphates, contain not only the main active substance but also trace element impurities and xenobiotics obtained from natural phosphate raw materials (apatites and phosphate rocks). The precipitation of poorly soluble calcium phosphates in the alkaline environment of calcareous sierozems is accompanied by the simultaneous immobilization of several heavy metals such as cadmium (Cd), lead (Pb), and strontium (Sr). Among them, cadmium poses the most environmental risk, since the similarity of its ionic radius to that of calcium facilitates the isomorphic substitution of the latter both in the mineral structure of the soil and in the physiological mechanisms of nutrient absorption and transport in plants. Cadmium can bioaccumulate, increasing the risk of contamination of agricultural produce and negatively affecting ecosystems and population health.

According to V. G. Mineev, these changes result in the depletion of the soil at a biogeochemical level. If these conditions keep persisting, the agricultural system gradually loses its ability to self-regulate, and soil fertility becomes increasingly dependent on the continuous use of mineral fertilizers.

Therefore, a quantitative assessment of the ecological deficit of particulate matter ($\Delta E_n$) and phosphorus ($\Delta E_p$) allows for determining the degree of nutrient loss and evaluating the environmental impact of current fertilization practices in the Kura-Aras Lowland. The results show that a significant part of the applied fertilizer is not used by plants. On the contrary, it participates in migration and transformation processes and has a negative impact on terrestrial and aquatic ecosystems. The determination of the amount of pollution, including about 90 kg/ha of unproductive waste and 65 kg/ha of phosphorus converted into less absorbable forms, provides the basis for a comprehensive ecological and economic assessment of the efficiency of fertilizer use. The results can be used to calculate economic losses, develop environmental regulation mechanisms, improve state regulation of the use of natural resources, and justify environmental protection measures. The modeling results show the urgent need to transition to science-based and sustainable agricultural management (Минеев, 2008, pp. 312–315).

## 4.Conclusion

In conclusion, it becomes apparent that currently applied agricultural practices in the Kura-Aras cotton production are not sustainable and do not consider the natural properties of the soil. Low humus content, soil alkalinity, and overirrigation increase nutrient mobility and reduce the efficiency of fertilizers, causing significant harm to the economy and environment.

The results show nutrient deficits of approximately 90 kg/ha for nitrogen and 65 kg/ha for phosphorus. Unabsorbed nitrogen leads to groundwater pollution and greenhouse gas emissions, including nitrous oxide. Long-term accumulation of phosphorus residues leads to an increased risk of eutrophication and the disruption of natural biogeochemical cycles. The accumulation of heavy metals associated with phosphate fertilizers creates additional ecological problems.

The study confirms the urgency to improve the situation by transitioning to science-based methods of plant nutrition management that consider the soil properties and climatic characteristics of the Kura-Aras region. The implementation of monitoring, modern fertilizer technologies, and consideration of the spatial heterogeneity of soils and their agrochemical characteristics will increase the efficiency of nutrient use, reduce fertilizer losses, and reduce the anthropogenic load on soil and water ecosystems. This will contribute to the long-term preservation of soil fertility in the Kura-Aras Lowland, increase the sustainability of agroecosystems, and ensure the continuation of cotton production.

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