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Analysis of Soil Salinization in the Aghjabadi District Using Various Indices

Garib Mammadov[1], Konul Majnunlu Musabayli[2]*, Rana Hasanova Babazade[3]

Abstract. *This study aims to assess the level of soil salinization in the Aghjabadi district and to analyze the spatial distribution dynamics of salinized areas. Although the Aghjabadi district, located in the Aran region of Azerbaijan, holds strategic importance for agriculture, it faces significant challenges due to soil salinization. Elevated salinity levels contribute to decreased agricultural productivity, degradation of soil fertility, and negatively impact the sustainable use of agricultural lands. Consequently, the application of scientifically grounded approaches is essential for accurate monitoring and effective land management.*

The primary objective of the research is to precisely determine the degree of soil salinization in Aghjabadi, map salinized areas, and compare the effectiveness of various salinity indices. For this purpose, satellite imagery was analyzed using remote sensing and Geographic Information Systems (GIS) technologies. Landsat 8 satellite images were used to calculate several salinity indices, including Salinity Index 1, Salinity Index 2, Salinity Index 3, and the Normalized Difference Salinity Index (NDSI). Each index reflects different aspects of soil salinity, enabling the generation of detailed soil salinization maps for the region.

As a result of the study, the compatibility of different salinity indices with the ecological and climatic conditions of the Aghjabadi district was evaluated, and the most suitable index was identified. This approach contributes to effective soil monitoring, planning of cultivated areas, and the development of soil management strategies. Furthermore, the research holds both scientific and practical significance in terms of ecological sustainability, optimal use of agricultural resources, and the prevention of soil degradation.

Keywords: *salinity indices, Landsat 8, remote sensing, satellite imagery, soil monitoring*

Introduction

Soil salinization is one of the major ecological and economic challenges that reduces agricultural productivity, particularly in arid and semi-arid climate regions (Allbed et al., 2014, pp. 91–102). The accumulation of soluble salts in the soil layer leads to the deterioration of its physico-chemical properties, disruption of soil structure, and a decline in the plants' ability to absorb water and nutrients. As a result, crop yields decrease significantly. This process has long-term consequences, contributing to a decline in soil fertility, salinization of water resources, and degradation of ecosystems (El-Basyoni & Ibrahim, 2018, pp. 104–113; Jones & Pethick, 2006, pp. 1–14).

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[1] Baku State University, Doctor of Science in Biology, Baku, Azerbaijan
[2] Azerbaijan University of Architecture and Construction, PhD student, Baku, Azerbaijan
[3] Institute for Space Research of Natural Resources, PhD student, Baku, Azerbaijan
*Corresponding author. E-mail: konul.majnunlu@azmiu.edu.az
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Although the Aghjabadi district, located in the Aran economic region of Azerbaijan, holds significant importance for agriculture, widespread soil salinization issues are observed in the area. Improper management of irrigation systems, the rise of groundwater levels, and climatic factors are among the main causes contributing to increased soil salinity. Therefore, accurate assessment and mapping of soil salinization dynamics represent one of the essential scientific bases for ensuring the sustainable development of agriculture in the region (Omomov et al., 2022).

In recent years, alongside traditional soil analyses, the application of remote sensing and Geographic Information Systems (GIS) technologies has gained significant momentum in the study of soil salinization. These methods enable the assessment of soil salinity over large areas in a rapid, cost-effective, and highly accurate manner. Various salinity indices derived from spectral data obtained through satellite imagery allow for both visual and analytical evaluation of soil salinity levels (Rana & Mishra, 2014; Scudiero et al., 2014).

In this study conducted for the Aghjabadi district, the assessment of soil salinity levels was carried out using Landsat 8 OLI/TIRS satellite imagery. Four main indices were applied during the analysis: Salinity Index 1, Salinity Index 2, Salinity Index 3, and the Normalized Difference Salinity Index (Scudiero et al., 2014; Xia et al., 2017). The results obtained for each index were compared, and maps reflecting soil salinity distribution were generated accordingly.

The research results indicated that, under the ecological and climatic conditions of the Aghjabadi district, the SI2 and NDSI indices provided more accurate assessments of soil salinity. This confirms the reliability of remote sensing data as a valuable source of information for monitoring and managing soil salinization (Abbas et al., 2013; Rahmati & Nabiollahi, 2020).

The objective of this study is to assess the level of soil salinity in the Aghjabadi district using satellite observations, to analyze the applicability of various salinity indices, and to determine the most effective assessment methodology for the region.

Methods

This study was conducted to assess the soil salinization status in the Aghjabadi district using Landsat-8 satellite imagery. Remote sensing technologies, particularly Landsat 8 OLI/TIRS satellite images, provide high temporal resolution capabilities for large-scale monitoring and mapping of soil salinity conditions. The satellite images utilized in this research were acquired from 2024 and were georeferenced accordingly. Various salinity indices—Salinity Index 1 (SI1), Salinity Index 2 (SI2), Salinity Index 3 (SI3), and Normalized Difference Salinity Index (NDSI)—were calculated from the images. These indices were employed to evaluate the level of soil salinity based on the spectral bands obtained from Landsat 8 satellite imagery (Omomov et al., 2022; Abbas et al., 2013).

Field measurements were conducted within the study area to evaluate soil salinization. Using a Progress 1T device, soil electrical conductivity and temperature were measured, and based on these data, the degree of salinization was determined at three different depth intervals (0–20 cm, 20–50 cm, and 50–100 cm). In total, 214 measurements were taken, which served as the basis for calculating the salinization degree (Tavakkol & Ghorbani, 2021).

Regression analysis was employed to establish correlations between the satellite-derived data and the field-measured electrical conductivity. These equations formed the foundation for generating salinization maps. Using ArcGIS software, salinization maps were produced, and the effectiveness of different salinity indices was compared.

Pixel brightness values and vegetation indicators were calculated from various spectral bands of the satellite images. This process ensured an accurate assessment of salinization and enabled the spatial representation of salinity levels across different areas of the Aghjabadi district on the maps.

Results

The results indicate that soil salinity and salinization risk in the study area were evaluated based on data from 2023. The spatial distribution maps generated using salinity indices reveal five distinct salinity classes, with index values ranging from 0 to 1, representing non-saline to saline conditions (Fig. 1a). The salinity map produced using the alternative SI2 index exhibits a similar classification pattern and value range, confirming the spatial differentiation between saline and non-saline areas (Fig. 1b). The regression models derived from Landsat 8 imagery acquired in 2023 further support the identification of salinity patterns across the study area (Allbed et al., 2014, pp. 91–102; Scudiero et al., 2014). The following map presents the spatial distribution of soil salinization in the Aghjabadi district based on the Salinity Index 1 (SI1) (Figures 1, 2, 3, 4). The salinity levels on the map are classified into five distinct categories:

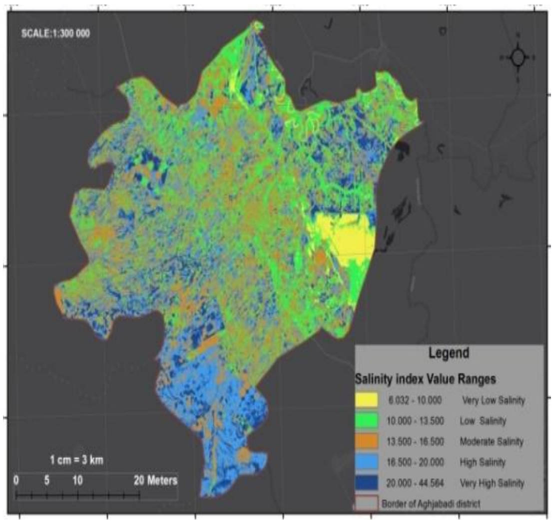

Figure 1. Range of Salinity Index Values (SIVR) in the Soils of Aghjabadi District

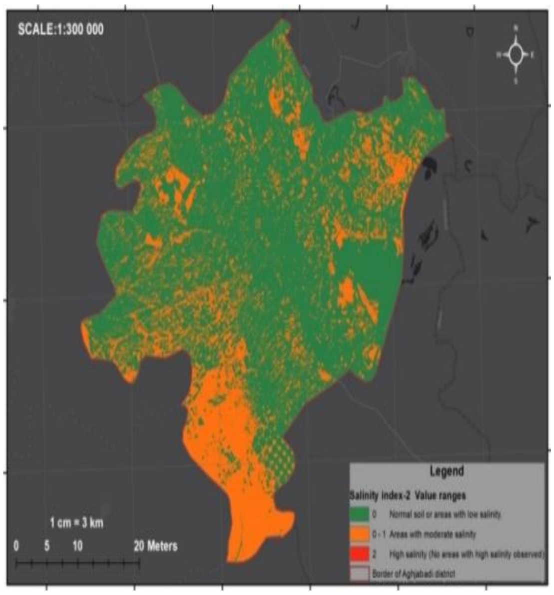

Figure 2. Spatial Distribution of Salinity Index 2 (SI2) in the Soils of Aghjabadi Distric

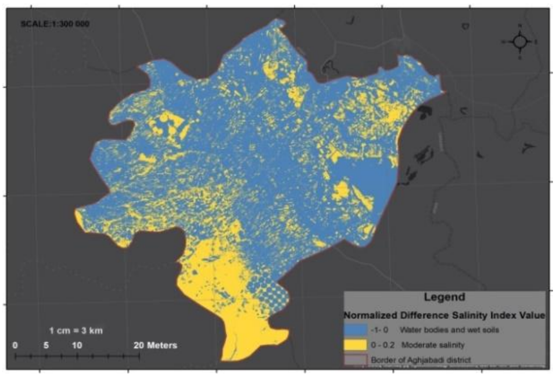

Figure 3. Spatial Distribution of the Normalized Difference Salinity Index (NDSI) in the Soils of Aghjabadi District

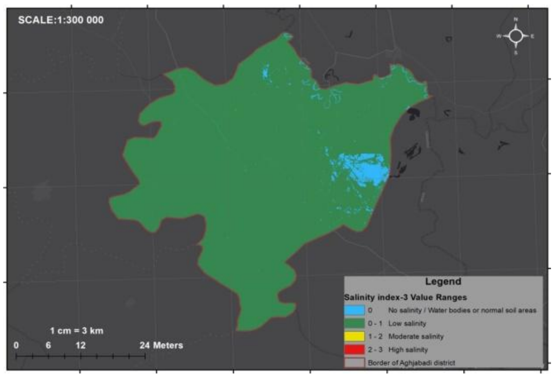

Figure 4. Spatial Distribution of Salinity Index 3 (SI3) in the Soils of Aghjabadi District

The Salinity Index SI-1 map represents soil salinization across five main classes: very low salinity, low salinity, moderate salinity, high salinity, and very high salinity. This map reflects varying salinity levels over a broad range, allowing for a more precise determination of salinization intensity across different areas. In particular, the "very high salinity" class, ranging from 20,000 to 44,584, provides a more complex and detailed differentiation of salinity on the map. The map is designed to identify regions with high salinity over an extensive geographic area, as the very high salinity category (20,000–44,584) covers a large spatial extent (Rahmati & Nabiollahi, 2020; Ismayil et al., 2025).

Salinity Index 2 (SI-2): In the Salinity Index 2 classification, salinization is described in only three levels: 0 (normal soils or very low salinity), 1 (moderately saline soils), and 2 (highly saline soils). This index provides a simpler classification by identifying the main salinity levels but does not provide information on higher salinity intensities. Notably, although the "2" class exists on the Salinity Index 2 map, areas of very high salinity are not represented, indicating that the map has more limited capability in depicting zones of high salinity intensity.

Normalized Difference Salinity Index (NDSI): The NDSI map illustrates a narrower range of salinized soils. Values between -1 and 0 on this map represent water bodies or moist soils, while the range from 0 to 0.2 indicates moderately saline soils. The primary focus of this map is on water bodies and moist soils. The NDSI map demonstrates less extensive salinization and a prevalence of water-related soil areas. Since it does not cover a broader range of salinity levels, it provides more limited information confined mostly to water and moist soils.

Salinity Index 3 (SI-3): The SI-3 map displays four main classes of salinity: 0 (normal soils or water bodies), 1 (low salinity), 2 (moderate salinity), and 3 (high salinity).

However, the "3" class is not represented across large areas; only a small region is depicted with the "2" class. This indicates that the SI-3 map provides limited information on high-intensity salinization, with most areas falling into the moderate salinity category.

When evaluating the intensity and distribution of salinization, the Salinity Index 1 map reveals broader and more intensive salinized areas, particularly reflecting regions of very high salinity (20,000–44,584). In contrast, Salinity Index 2 and Salinity Index 3 provide simpler classifications and depict only limited zones of high salinity. The Normalized Difference Salinity Index (NDSI) highlights relatively less extensive salinization and emphasizes the significance of water bodies.

Field measurements and regression analysis used in the study serve as essential tools to enhance the accuracy of the indices. These measurements analyzed soil electrical conductivity and temperature across three different depth intervals, which were then correlated with satellite imagery to generate salinity maps. Data obtained from Landsat 8 satellite images were processed with high precision, especially for salinity analysis. Furthermore, the maps created using ArcGIS software were compared with actual field conditions to assess their reliability. Electrical conductivity measurements provide precise evaluation of salinity levels. For instance, measurements conducted using the Progress 1T device proved highly effective for analyzing soil salinity, and integrating this data with satellite imagery facilitated the production of salinity maps with improved accuracy (Ismayil et al., 2025).

Discussions

Table 1.
Formulas of the Four Salinity Indices Used in the Study

Name	Formula	**Spectral Bands Used**
Salinity index (S1)	$SI = \sqrt{R \times SWIR1}$	Band 4 (Red), Band 6 (Shortwave Infrared 1)
Salinity index (S2)	$SI2 = \frac{SWIR1}{NIR}$	Band 6 (Shortwave Infrared 1), Band 5 (Near Infrared)
Salinity index (S3)	$SI3 = \frac{SWIR1}{G}$	Band 6 (Shortwave Infrared 1), Band 5 (Near Infrared)
Normalized Difference Salinity Index (NDSI)	$NDSI = \frac{(R - NIR)}{(R + NIR)}$	Band 4 (Red), Band 5 (Near Infrared)

According to the table 1, a brief explanation of each index is provided below:

Salinity Index (SI1): $SI = \sqrt{R \times SWIR1}$

- **SI** – Salinity Index, representing the soil salinization index
- **R** – Reflectance of the Red band (Band 4) in Landsat 8 satellite imagery
- **SWIR1** – Reflectance of the Shortwave Infrared 1 band (Band 6) in Landsat 8 satellite imagery

This index is used to measure soil salinity levels based on remote sensing data. The calculation of the salinity index involves the use of the Green (G) and Red (R) bands.

Alternative Salinity Index (SI2):

$$SI2 = \frac{SWIR1}{NIR}$$

- **SI2** – Salinity Index 2
- **SWIR1** – Reflectance of the Shortwave Infrared 1 band (Band 6) in Landsat 8 satellite imagery
- **NIR** – Reflectance of the Near Infrared band (Band 5) in Landsat 8 satellite imagery

This index is used to evaluate the level of soil salinization on the soil surface by analyzing the spectral data from satellite images for the identification of soil salinity.

Salinity Index (SI3):

$$SI3 = \frac{SWIR1}{G}$$

- **SI3** – Salinity Index 3
- **SWIR1** – Reflectance of the Shortwave Infrared 1 band (Band 6) in Landsat 8 satellite imagery
- **G** – Reflectance of the Green band (Band 3) in Landsat 8 satellite imagery

This index is particularly applied for assessing soil salinity, especially to identify areas with high salinity levels.

Normalized Difference Salinity Index (NDSI):

$$NDSI = \frac{(R - NIR)}{(R + NIR)}$$

- **NDSI** – Normalized Difference Salinity Index
- **R** – Reflectance of the Red band (Band 4) in Landsat 8 satellite imagery
- **NIR** – Reflectance of the Near Infrared band (Band 5) in Landsat 8 satellite imagery

Various spectral bands and their corresponding indices play a significant role in environmental monitoring and soil cover analysis. Using satellite data, particularly images from the Landsat series, the condition of soil cover and vegetation is analyzed through different spectral bands (Huang & Li, 2020; Jafari & Fathian, 2019).

Conclusion

This study investigated the effectiveness of various salinity indices for assessing soil salinization in the Aghjabadi district. The analysis revealed that Salinity Index 1 demonstrated the highest sensitivity and accuracy, effectively identifying areas of high salinity intensity and providing a wide range of detailed information. Salinity Index 2 illustrated the overall salinization status but was unable to fully capture areas of high salinity. Salinity Index 3 primarily represented moderately saline zones and provided limited information on high-intensity salinization. The Normalized Difference Salinity Index (NDSI) was particularly useful for identifying water bodies and moist soils, but it had certain limitations in evaluating areas with high salinity intensity.

The results indicate that the Salinity Index 1 (SI1) is considered the most effective indicator for the accurate assessment of soil salinization, as it provides both high sensitivity and a broad range of data.

The study also emphasizes that the SI1 index serves as an important scientific and practical tool for agricultural planning, soil management, and evaluating salinization risks in the region.
Based on these findings, the study presents the following recommendations:

- Salinity maps developed using the SI1 index should be utilized to identify priority areas in soil management and irrigation policy-making.
- Future research should incorporate high-resolution satellite imagery (e.g., IKONOS and Sentinel-2) alongside Landsat 8 to produce more precise and detailed salinity maps.
- Efficient methodologies should be developed for long-term soil monitoring and agricultural planning by combining multiple salinity indices.

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 Effect of Fungi Belonging to the *Trichoderma* Genus on the Biological Productivity of Food Crops

Gulnar Shirinova[1]*, Vusala Suleymanova[1,2], Susan Abdullayeva[3]

Abstract. *The article presents the results of the impact of fungi from the Trichoderma genus on the biological productivity of important agricultural foods. During the research, samples were taken from the relatively clean soils of Absheron, from the rhizosphere of plants there, and from irrigated soils. At the same time, the mycological processes observed in recent years in the transboundary rivers of the Eastern Zangazur economic region (Aras, Okchuchay, Besitchay, Bergushadchay, Agachay), which have been subjected to anthropogenic impacts, have been comparatively assessed in terms of their ecological and biological significance. The conducted studies have shown that the fungal species comprising the microbiota complex formed in soil and water ecosystems are characterized by a high adaptability to the ecological environment, specific associations with the plant rhizosphere, and active metabolic participation in nutrient transformation. In particular, the micromycetes detected in the waters of transboundary rivers (such as* Aspergillus*,* Penicillium*,* Fusarium*, etc.) play a crucial role in decomposition processes, organic matter transformation, and ecosystem self-restoration. Additionally, the characteristics of the species involved in the formation of the microbiota of plants growing there were also determined. Among these microorganisms, both saprotrophic and facultative pathogenic representatives are present, and their balance is considered one of the key factors determining the microecological stability of the plant–soil system. At the same time, in addition to increasing the productivity of plants grown in these soils, they also serve as regulators in the nitrogen and carbon balance of the soils. To optimize plant growth and increase productivity, both biotic and abiotic factors are required. Organic substances influence the life activities of microorganisms present in the soil and plant, and providing these substances to them is considered an essential condition. In addition, the increase in the productivity of areas that are crucial for agricultural purposes can be considered a key indicator, depending on factors such as the interrelations of microorganisms in the soil, the impact of natural climatic and soil conditions on the environment, the rapid progression of microbiological processes, and other factors. When evaluating soils based on microbiological indicators, the main criterion is to assess the microdiversity of the senoz present there, in terms of its species and numerical composition. Taking all these indicators into account, the research has reflected the use of spore suspensions and cultural media obtained from species belonging to the Trichoderma genus to enhance the development ability of various plant seeds and intensify their productivity. Among the species of this genus, strains such as T. harzianum SH-58 and T. asperellum SH-15 can be mentioned as biological control agents, as these strains exhibit antagonistic interactions against several harmful phytopathogens.*

Keywords: *microorganisms, cultural solution, phytosanitary condition, biological productivity, climate-soil conditions*

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[1] Azerbaijan State Oil and Industry University, Doctor of Philosophy in Biology, Baku, Azerbaijan
[2] Doctor of Philosophy in Biology, Baku, Azerbaijan
[3] Ministry of Science and Education Institute of Microbiology, Baku, Azerbaijan
*Corresponding author. E-mail: gulnar.shirinova@asoiu.edu.az
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Introduction

Studies conducted both worldwide and in Azerbaijan have demonstrated that various micromycetes play a significant role in shaping the biological productivity of soils. It should also be emphasized that the biodiversity present in the lower soil layers is richer than that of the upper layers. Thus, when assessing the quantitative composition of soil biota across 20 soil types, it was determined that the number of microorganisms in these soils is three times higher than the total human population on Earth (Boinchan et al., 2016). In the Eastern Zangezur economic region, particularly in the riparian zones of transboundary rivers such as Aras, Oxchuchay, Besitchay, Bergushadchay, and Agachay, studies have shown that the composition of soil and water microbiota in these rivers serves as an indicator of the ecological condition of surrounding areas (Abdullayeva et al., 2025). The micromycetes inhabiting the riparian soils and aquatic systems of these rivers, especially *Trichoderma* strains, play a critical role in maintaining biological balance in the soil and plant rhizosphere. Thus, the rich biodiversity of transboundary rivers in Eastern Zangezur and the application of *Trichoderma* strains interact synergistically, ensuring the optimal sustainability of ecological and biological processes. The activity of microorganisms is directed toward soil formation processes, including the mineralization of plant residues, humification, degradation of various toxic substances present in soil, and the accumulation of compounds with toxic effects. Using these indicators, the determination of biological activity levels of soils and the maintenance of soil fertility are considered essential requirements (Baldrian et al., 2022).

Alongside chemical protection methods, biological control strategies are also employed to increase plant productivity. Although chemical treatments against pathogenic fungi show strong efficiency, in many cases such applications lead to additional ecological problems, particularly chemical contamination. Taking these factors into account, the application of biological control methods has increasingly been recognized as a more favorable approach in recent years. Based on these premises, studies have shown that species of the genus *Trichoderma* are successfully used as biological control agents and play a significant role in the restoration of soil fertility. Furthermore, experimental results have demonstrated that these fungi synthesize growth-stimulating phytoactive compounds (Jaroszuk-Ściseł et al., 2019). These fungi are especially prevalent in relatively uncontaminated soils characterized by a high abundance of plant debris. It should also be noted that both the biomass of *Trichoderma* strains and the exogenous metabolites released into the culture medium (CM) are utilized (Mironenka et al., 2021). The antibiotic activity of these metabolites plays a key role in defining their application potential. Thus, during the research process, one of the objectives was to determine optimal conditions for obtaining maximum biomass from *Trichoderma* strains. Under optimal conditions, the biomass and culture filtrates of both strains obtained within four days were assessed. This can be explained by the fact that phytohormones, mycotoxins, and metabolites responsible for antibiotic properties are synthesized as secondary metabolites and simultaneously exert external biological effects (Chen et al., 2023). Consequently, these features contribute to enhanced competitive interactions among various microbial species. *T. harzianum* Sh-58 and *T. asperellum* Sh-15 strains were selected as active producers in our study, which is attributed to the high antibiotic potential of their culture metabolites. Various methodological approaches exist for clarifying their mechanisms of action and targeted applications. The strains *T. harzianum* Sh-58 and *T. asperellum* Sh-15 were selected as active producers in our study, which is attributed to their high antibiotic activity in the culture medium.

Materials and Methods

As previously indicated, samples were collected for the study. The isolation of microscopic fungi from the obtained samples was considered a primary requirement. For this purpose, Czapek medium (CM) and malt extract agar (MEA) were used as nutrient media. Prior to transferring the samples onto these media, suspensions were prepared. Serial dilutions were then performed, and inoculation into the nutrient media was carried out using sterile pipettes.

As previously mentioned, samples were collected from the transboundary rivers of the Eastern Zangezur economic region (Aras, Oxchuchay, Besitchay, Bergushadchay, Agachay), including soil and water from the riverbanks. Isolation of microscopic fungi from these samples was considered an initial stage of the study. Using the same nutrient medium, the inoculation of the isolated microscopic fungi was carried out. At the same time, direct placement of the samples onto the nutrient media was also considered appropriate. Incubation was conducted in a thermostat at 27°C for 3–7 days. Consequently, identification of the fungi was performed based on both macroscopic features (colony diameter, surface structure, color, and hyphal appearance) and microscopic characteristics (hyphal structure, conidiophore, conidia size, and shape).

Results and Discussion

The article presents the characteristic features of species belonging to the genus *Trichoderma* and their effects on improving soil sanitary conditions as well as enhancing plant productivity. These characteristics allow *Trichoderma* species to gain a competitive advantage in the rhizosphere and limit the proliferation of pathogenic microorganisms. They help maintain the balance of soil microflora, limit the proliferation of pathogens, and stimulate the plant immune system. All these effects are associated with the antagonistic interactions of *Trichoderma* against plant pathogenic organisms, which is also supported by literature sources (Polyakova et al., 2017).

On malt extract agar (MEA), *T. harzianum* Sh-58 is characterized by colonies with a white margin and a green, sometimes light green, central region (Fig. 1A). This color change does not affect the pigmentation of the colony's reverse side. Both substrate and aerial mycelia contribute to colony formation, while the conidiophores arise from the aerial mycelia. Species of this genus possess branched conidiophores (Fig. 1B), flask-shaped phialides (Fig. 1C), and ovoid conidia. The conidia are smooth-walled, arranged in chains, and produced in abundant quantities, which facilitates their rapid spread in nutrient-rich media and ensures high sporulation capacity. Furthermore, the interaction between aerial and substrate mycelia regulates the overall colony structure and conidial productivity, thereby enhancing ecological adaptation and competitive ability

A B

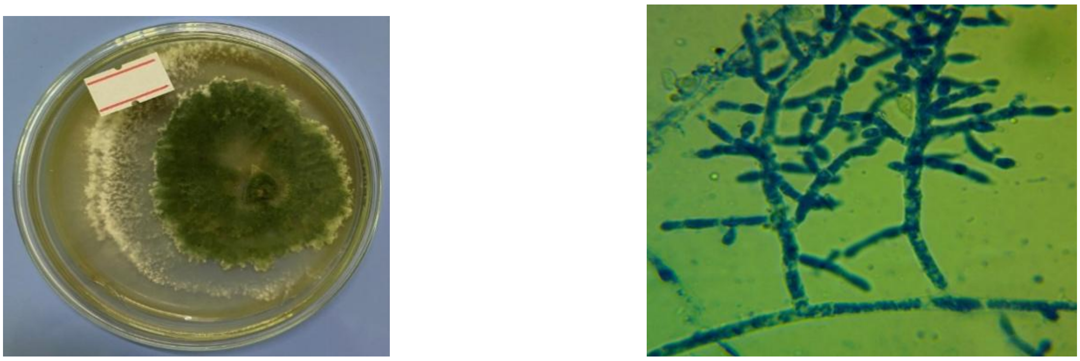

Figure 1. Macroscopic view of *T. harzianum* colony (A) and microscopic appearance of its conidiophores (B)

The use of *T. asperellum* Sh-15 strain in biological control is also appropriate. At the same time, its antagonistic activity against a range of plant pathogenic microorganisms is one of its key distinguishing features. The use of the *T. asperellum* Sh-15 strain in biological control is also appropriate. All these factors make *T. asperellum* Sh-15 strain effective and promising biological control agent and increase its ecological and agronomic significance. Its ecological significance lies in reducing the need for chemical inputs in the soil, limiting the proliferation of pathogenic microorganisms, and maintaining the natural balance of soil microflora, thereby supporting soil health and ecosystem sustainability.

Additionally, research has confirmed that these strains synthesize growth-promoting substances that play an indispensable role in plant development (Kumar et al., 2020). On malt extract agar (MEA), the colony of the fungus initially appears greenish-gray, and after a certain period, the formation of several concentric rings can be observed. A large number of spores are produced. The colony color gradually changes from the margin toward the center, eventually resulting in an aged yellow coloration in the central region (Fig. 2A). A high number of conidia are formed from the phialides (Fig. 2B). This high level of sporulation allows *Trichoderma* species to rapidly colonize nutrient media and promotes the swift development of colonies.

A B

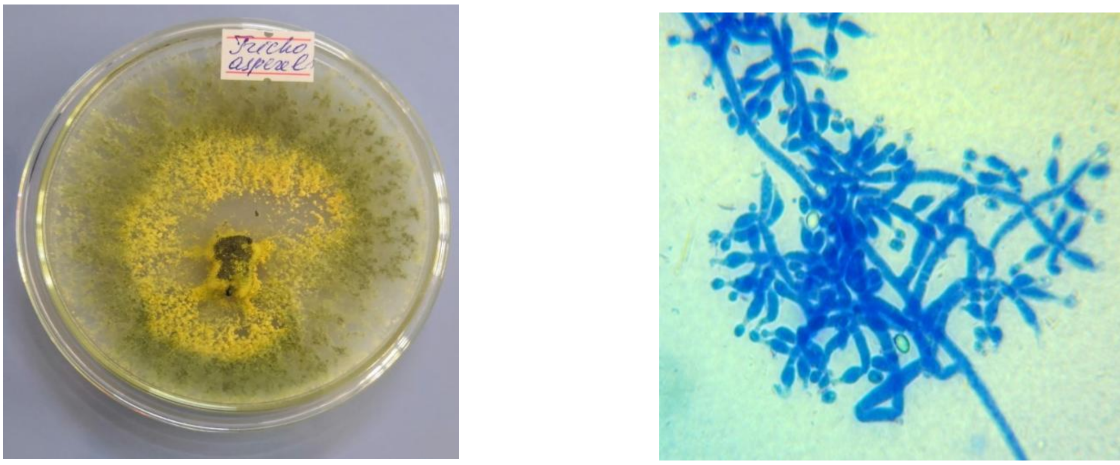

Figure 2. Macroscopic view of *T. asperellum* colony (A) and microscopic appearance of its conidiophores (B)

The cultivation of fungi in an optimized medium, ensuring the formation of a large amount of biomass, was considered a primary requirement based on key indicators. During this period, the growth of the fungi, the macro and microscopic characteristics of the colonies, as well as the intensity of sporulation, were systematically monitored. All these features make the biomass suitable for use in both laboratory and applied settings, serving as a biological control agent and a preparation that promotes plant development. The cultivation period can be considered favorable for these indicators. The use of the biomass and culture medium (CM) of the two strains selected as active producers in this study was deemed appropriate. CM derived from these microbial strains reduces the need for chemical pesticides and fertilizers, preventing soil and environmental contamination. It stimulates plant growth, increases productivity, and improves crop quality.

Table 1.
Optimal conditions required for the cultivation of *T. harzianum* Sh-58 and *T. asperellum* Sh-15 strains

Producent	Carbon source (g/l)	Nitrogen source (g/l)	Breedin g $T^{0}C$	pH	Planting material
T.harzianum Sh-58	$C_6H_{12}O_6$ (24,0)	NH4NO3 (1,7)	$27^{0}C$	5,4	ASSH
T.asperellum Sh-15	$C_6H_{12}O_6$ (27,0)	NH4 NO3 (1,8)	$27^{0}C$	5,4	ASSH

It is also evident from the table that, as a result of medium optimization, the biomass yield of both strains reached its maximum. In addition, it has been noted that the biological active compounds (BAC) synthesized by *Trichoderma* fungi contribute to significant increases in the productivity of agriculturally important crops (Herrera et al., 2020). Specifically, the initial step involved treating the seeds with the culture medium (CM) prior to sowing. Subsequently, the seeds are mixed with the prepared biomass or culture medium (CM) and kept in contact with this medium for a specific period. During this time, the *Trichoderma* strains adhere to the seed surface and establish stable colonization. Occasionally, additional protective measures are applied to the seeds. These experiments were conducted using tomato plants as a model. The results demonstrated that treating tomato seeds with the culture medium (CM) led to significant changes in plant height and flowering time. Moreover, phytohormones and other biologically active compounds synthesized by *Trichoderma* improve nutrient uptake by plants. At the same time, it provides a promising foundation for agronomists and farmers to apply biological agents and disease management tools effectively. Nowadays, by putting chemical control methods in the background, the use of this biological control approach provides ecologically clean, sustainable, and efficient production opportunities for agriculture.

Table 2.
Effect of cultural medium (CM) obtained from fungi on tomato plant height, flowering time, and overall yield

№	Producent	Plant height (start/end, cm)	Flowering time of the plant (days)	Yield per unit of plant (kg)
1	*T.harzianum Sh*-58	13±1/96±2	30±1	4,5±0,16
2	*T.asperellum* Sh-15	13±1/95±2	31±2	4,8±0,04
3	Control	13±1/86±2	32±1	4,0±0,16

Research findings demonstrate that significant increases were observed in the morphometric parameters of tomato plants compared to the control group. It should be particularly emphasized that the results obtained across all biometric indicators confirm the positive impact of the application of the cultivation medium (CM) derived from the *T. harzianum* strain Sh-58 on the yield potential of the plants. In both settings, the application of CM exhibited similarly positive effects, which were manifested in accelerated vegetative growth, advancement of the flowering phase, and, consequently, an increase in yield parameters. These findings not only demonstrate the high efficacy of the *T. harzianum* strain Sh-58 as a phytostimulator and a potential biocontrol agent but also scientifically substantiate its agrobiotechnological application prospects. The strain also participates in processes such as nitrogen fixation and the coordination of microelements in the soil environment, which enhances the efficiency of nutrient utilization by plants (Crowther et al., 2016). *T. harzianum* Sh-58 synthesizes hormone-like compounds such as auxins, gibberellins, and cytokinins, which strengthen root system development, accelerate vegetative biomass accumulation, and ultimately increase productivity (Li et al., 2017). In addition, studies conducted in the transboundary rivers of the Eastern Zangezur economic region (Aras, Okhchuchay, Besitchay, Bergushadchay, Agachay) have shown that *T. asperellum* SH-15 plays a crucial role in supporting microbial balance in both water and sediment environments (Ismayilov, 2021).

Conclusion

1. The results of the study showed that the application of CM obtained from *T. harzianum SH-58* and *T. asperellum SH-15* strains had a positive effect on the morphometric parameters of plants.
2. Treatment of tomato seeds with CM before sowing resulted not only in significant changes in plant height and flowering duration but also had a notable impact on the yield per plant.
3. Based on the results of the study, it was determined that the CM obtained from *T. harzianum SH-58* and *T. asperellum SH-15* strains had a positive effect on the morphometric parameters of plants. In particular, the application of this CM in agricultural areas surrounding Basitchay and other transboundary rivers in the Eastern Zangezur economic region enhanced plant growth and productivity. This significantly contributes to the preservation of soil and water ecosystem health along the riverbanks and ensures the maintenance of microbiological balance in the plant rhizosphere.

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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Determination of the Optimal Temperature for the Green Synthesis of Iron Oxide Nanoparticles

Vafa Ramazanli

Abstract. *The synthesis of iron oxide nanoparticles depends on several parameters. These parameters significantly affect their structural, morphological, and magnetic properties. One of these parameters is temperature. Temperature directly influences particle size, phase composition, and magnetic properties. This article systematically analyzes the effect of temperature in various synthesis methods and emphasizes the importance of selecting the optimal temperature.*

Keywords: *iron oxide nanoparticles, rosehip extract, temperature, UV-Vis*

Introduction

Iron oxide (Fe–O) nanoparticles are of great importance in the field of nanomaterials because their magnetic, chemical, and biocompatible properties are widely utilized in medicine, catalysis, sensors, and environmental remediation (Laurent, 2008; Wu, 2014). Particularly, during the synthesis of Fe_3O_4 and γ-Fe_2O_3 phases, control over particle size, crystallinity, and morphology plays a crucial role. One of the main parameters regulating these properties is temperature. Changes in temperature directly affect nucleation and growth kinetics, phase composition, and magnetic behavior (Ahn, 2012).

The structural, morphological, and magnetic properties of iron oxide nanoparticles are strongly dependent on the synthesis temperature (Gnanaprakash, 2007). Temperature variations regulate nucleation and growth kinetics, directly affecting particle size, phase composition, and magnetic parameters (Mahmoudi, 2011). Particles synthesized at low temperatures generally have smaller sizes and poor crystallinity, whereas increasing the temperature enhances crystallinity and leads to the formation of a more homogeneous morphology (Thanh, 2014). High temperatures accelerate diffusion, resulting in increased particle size and stronger aggregation.

Temperature also determines the phase composition of synthesized particles—whether magnetite, maghemite, or other oxide forms. Nanoparticles synthesized at optimal temperatures exhibit high magnetic saturation and stable superparamagnetic behavior. Improper temperature control can lead to increased structural defects and uneven size distribution. This article extensively examines the role of temperature in various synthesis methods and its effects on the properties of the resulting nanoparticles. The results indicate that temperature is a key controlling factor in obtaining iron oxide nanoparticles with parameters suitable for target applications (Gupta & Gupta, 2005).

Baku State University, PhD in Biology, Baku, Azerbaijan
E-mail: vefa_ramazanli@hotmail.com
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In “green synthesis” using plant extracts, temperature plays a special role, as high temperatures can cause the degradation of phytochemical compounds. Moreover, temperature also affects the phase transitions between iron oxide phases; for example, the γ-$Fe_2O_3 \rightarrow \alpha$-$Fe_2O_3$ transformation depends on temperature (Bukhari, 2020). Thus, selecting the optimal temperature during green synthesis is crucial for both the chemical process and the preservation of bioactive compounds in the extract (Hajiahmadi, 2019).

Materials and Methods

In this study, Rosa canina (rosehip) fruit extract was used as a natural reducing and stabilizing agent for green synthesis.

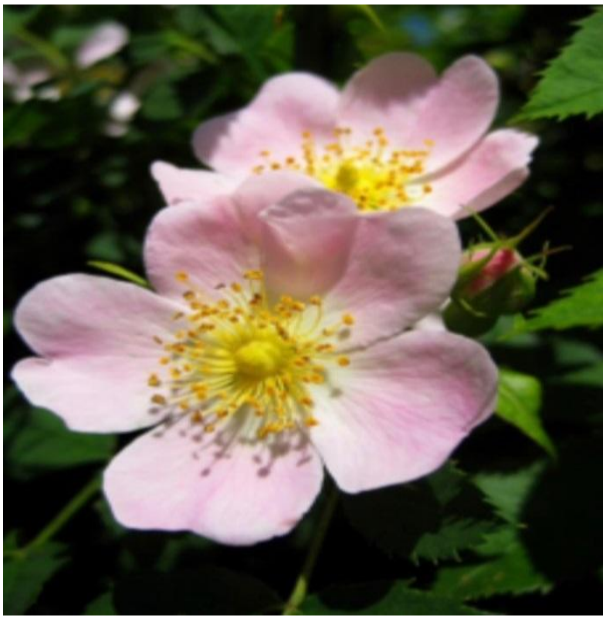

Figure 1. Rosa Canina (Rosehip)

The plant material was collected from local natural areas, dried, and ground into a homogeneous powder. The polyphenols, flavonoids, vitamin C, and organic acids present in Rosa canina fruits play an important role in the $Fe^{3+} \rightarrow Fe^{2+}$ reduction, making this plant widely used for green synthesis. It is known that phytochemical components degrade at temperatures above 40°C. Therefore, two extraction methods were tested:

- **45°C extract:** Rosa canina powder was kept at this temperature for 48 hours, producing a more stable extract with higher reducing ability (Hajiahmadi, 2019).
- **70°C extract:** At higher temperatures, some phenolic compounds were observed to degrade (Patel, 2021).
- **UV-Vis Spectroscopy:** Measurements performed in the 200–800 nm range showed that in the non-boiled extract, the peaks at 280–330 nm were more pronounced, confirming the stability of the phenolic compounds. In the extract prepared at 70°C, the decrease in peak intensity indicated thermal degradation.

Results and Discussion

The study demonstrated that the most optimal synthesis temperature is 45°C. At this temperature, the bioactive compounds in the extract remain intact, and its reducing capability is preserved.

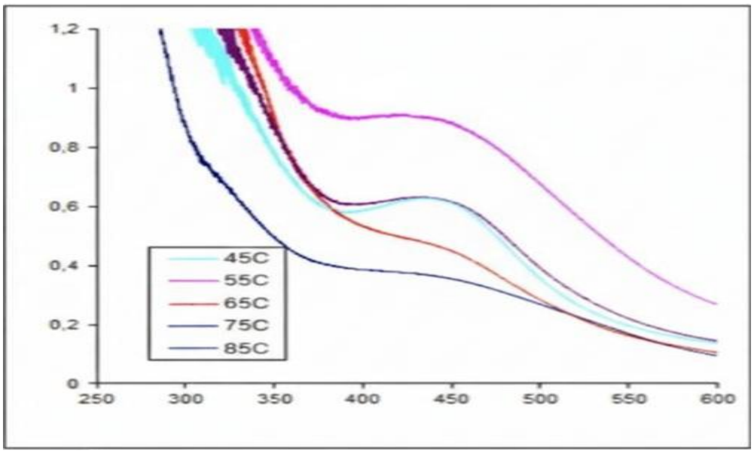

Figure 1. Temperature Dependence

At high temperatures (75°C), phenolic and flavonoid components degrade, weakening the synthesis process. In chemical synthesis methods, increasing the temperature can accelerate diffusion, leading to the formation of larger particles and phase transformations (Teja, 2009). However, in green synthesis, 45°C has been identified as an optimal balance point that ensures both extract stability and appropriate nucleation–growth kinetics.

According to the literature, low-temperature synthesis produces smaller particles, but with poor crystallinity (Cornell & Schwertmann, 2003). Based on our results, 45°C minimizes these negative effects, enabling the formation of high-quality nanoparticles with superparamagnetic properties (Wu, He, & Jiang, 2014).

Conclusion

The results of this study further confirm that temperature is a key controlling factor determining the properties of iron oxide nanoparticles. Preserving the biological activity and chemical stability of Rosa canina extract is crucial in green synthesis. A temperature of 45°C has been selected as optimal for nanoparticle synthesis because it prevents the thermal degradation of bioactive compounds in the extract. High temperatures (75°C and above) significantly reduce the extract's functionality, as confirmed by UV-Vis spectroscopy. With proper temperature control, iron oxide nanoparticles with suitable properties for target applications—high crystallinity, optimal particle size, and stable phase composition—can be efficiently obtained.

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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Reserves and Prospects for the Use of the Medicinally Important Species *Thymus Caucasicus* Wild. Ex Ronniger

Afag Aliyeva

Abstract. *The article provides information on the reserves, prospects for use, and conservation measures of Thymus caucasicus Wild. ex Ronniger, a species distributed in the Ganja–Gazakh region. As is known, the flora of Azerbaijan is remarkable for its rich phytocenoses of medicinally important plants that have no substitutes and are not found anywhere else in the world. Azerbaijan's medicinal plant resources, which possess rich reserves, are exported abroad, where new pharmaceutical preparations are produced and then sold back to us at very high prices. As a result, natural reserves decline and the scope of use becomes limited. Taking all this into account, the species Thymus caucasicus, which is rich in essential oils, has been comprehensively studied.*
The studies were conducted in the Ganja–Gazakh region—specifically in the Dashkasan, Gadabay, Shamkir, and Goygol districts—across various vegetation types at elevations of 700–1900 m above sea level. During our research, Thymus caucasicus was studied within different plant communities, and the reserves of the species were assessed. In the Shamkir and Tovuz districts, the reserves of Thymus caucasicus were very low compared to other districts, whereas in Gadabay, Dashkasan, and Goygol the reserves were satisfactory.
Therefore, implementing conservation measures for the species in the Shamkir and Tovuz districts is an urgent issue. Annual monitoring should be carried out in these areas, and the habitats where the species occurs should be protected. For populations of Th. caucasicus occupying small areas, small protected reserves should be established, and continuous monitoring of the populations should be ensured.

Keywords: *medicinal plant, plant grouping, reserve, conservation measures*

Introduction

The nature of Azerbaijan is fascinating and, at the same time, highly valuable. Its diverse forests, steppes, lakes, rivers, valleys, and mountains are exceptionally beautiful. Particularly impressive are the rich phytocenoses of medicinally important plants in the flora of Azerbaijan, many of which have no substitutes and are not found anywhere else in the world. Azerbaijan's medicinal plant resources, which possess abundant reserves, are exported abroad, where new pharmaceutical preparations are produced and then sold back to the country at very high prices.

In addition, it is regrettable to note that, during the transition period, "a group of profiteers" have acted ruthlessly toward nature, harvesting rare and valuable medicinal plants in a destructive manner without following any collection regulations and bringing them to markets for personal gain.

Ganja State University, PhD in Agricultural Sciences, Ganja, Azerbaijan
E-mail: aliyevaafaq87@gmail.com
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Taking all these factors into account, it is considered appropriate to study the reserves and prospects for the use of *Thymus caucasicus* Wild. ex Ronniger, a species distributed in the Ganja–Gazakh region.

Methods

The studies were conducted in the Ganja–Gazakh region across various vegetation types at elevations of 700–1900 m above sea level. The systematic position of the species was determined according to generally accepted principles, including APG IV (www.worldfloraonline.org), World Flora Online (Botanical Journal of the Linnean Society, 181(1), pp. 1–20), and The Euro+Med PlantBase (http://ww2.bgbm.org/), through which the taxonomy and nomenclature of the species were clarified.

In studying the bioecological characteristics of the species, the following sources were used: *Flora of Azerbaijan*, *Flora of the Caucasus* (Grossheim, 1945; Flora of Azerbaijan, 1952), E.M. Gurbanov's *Systematics of Higher Plants* (Gurbanov, 2009), A.M. Asgarov's *Plant World* (Asgarov, 2016), Volume III of *Conspectus of the Flora of the Caucasus* (2012), as well as works by N.N. Portenier (2012) and other scientists.

Geobotanical studies of the plant communities (cenoses) in which the studied species occurs were carried out according to generally accepted methods in geobotany (Pedrotti, 2013). The structure and composition of the vegetation, the number of species present, as well as the edificator and dominant species—in other words, the floristic and geobotanical characteristics of the study areas—were examined, and floristic richness was assessed using Drude's five-point scale (Drude, 1887; 1906). In each district, focal plots were established, and natural reserves were calculated using experimental methods for geobotanical indicators and Yaroshenko's mathematical calculations (Yaroshenko, 1946–1967).

Materials and Discussion

The research material used in this study was *Thymus caucasicus* Wild. ex Ronniger (Caucasian thyme). The investigations were carried out in the Ganja–Gazakh region, specifically in the Dashkasan, Gadabay, Shamkir, and Goygol districts. *Thymus caucasicus* Wild. ex Ronniger is a semi-shrub plant reaching 9–17 cm in height (Fig. 1). Its leaves are ovate or ovate-triangular, and its flowers are capitate, rarely elongated-capitate in form. The species was first described from the Caucasus. It is distributed in the lower, middle, and upper mountain belts (1200–2800 m), inhabiting dry gravelly and sandy stony substrates, rocky outcrops, steep cliffs, screes, and stony dry-grass slopes.

During our investigations, *Thymus caucasicus* was studied within various plant communities, and the reserves of the species in the studied area were assessed. Based on literature data, the antimicrobial properties of *Thymus caucasicus* have also been identified. The aqueous extracts and essential oil of this species exhibit stronger bactericidal properties compared to other species (Bakhshaliyeva & Jalilova, 2018).

The leaves are used in the spice industry and in the preparation of various beverages. Infusions are also used in the treatment of different diseases. Due to its high essential oil content, *Thymus caucasicus* is considered promising for use in the treatment of respiratory tract diseases and has expectorant properties. In addition, it is a valuable melliferous (honey-producing) plant.

Figure 1. *Thymus caucasicus* Wild. ex Ronniger

Traditionally, in folk medicine, infusions are used, and the powdered form is applied as a compress for inflammation of the sciatic nerve. An infusion prepared with honey or in the form of an ointment is believed to "cleanse the chest and lungs," facilitate the expulsion of sputum, and relieve pain. Thyme aids digestion. Thyme baths are beneficial for nervous disorders, radiculitis, rheumatism, skin rashes, as well as joint and muscle diseases. For external rubbing, mixtures containing thyme essential oil are used. Studies were conducted to determine the natural distribution of *Thymus caucasicus* in different areas, as well as its variability, biological and phytocenological characteristics, productivity, and other features.

The meadows of the Gadabay district are mainly used extensively as pastures and hayfields. In winter, due to sharp temperature fluctuations, anthropogenic impacts are reduced to almost zero. In these areas, dark mountain-meadow soils are more widely distributed compared to other districts. Such soils are highly resistant to erosion. As shown in Table 1, the productivity of *Thymus caucasicus* in this area was within normal limits. Up to 80 species of flowering plants were recorded in the plant communities of the area. In plant communities formed by species such as *Rumex acetosa*, *Senecio othonnae*, *Alopecurus laguroides*, *Dactylis glomerata*, *Campanula latifolia*, *Trifolium pratense*, *Poa bulbosa*, *Cerastium purpurascens*, *Minuartia arenaria*, and others, the abundance of *Thymus caucasicus* was assessed at 2 points.

Figure 2. The status of *Thymus caucasicus* within plant communities in the Gadabay district

In the Goygol district, *Thymus caucasicus* occurs sporadically and individually in small patches on steep slopes within formations dominated by variegated fescue. In this association, the diameter of the turfs of the studied *Thymus caucasicus* reaches 20–25 cm. The soil of the experimental site consists of mountain-meadow soil with a pH of 5.0–5.5 and a humus content of 10–20%. A total of 20–25 species were recorded in the association, with *Carex tristis* and *Festuca rupicola* among the dominant species. The abundance of *Thymus caucasicus* was assessed at 1 point.

In the Dashkasan district, the species is more widely distributed, mainly across mountainous areas. The study of the phytocenological characteristics and reserves of *Thymus caucasicus* was conducted in the area of Khoshbulag village. Research was carried out in steppe and petrophytic vegetation types. Within the fescue–thyme formation group (*Festucetum–Thymusosum*), the associations *Festucetum valesiaca* (valesian fescue–hill thyme) and *Festucetum ovina–Thymusosum collinus* (sheep fescue–hill thyme) were identified. Overall, 25 species were recorded within this formation group. The abundance of hill thyme (*Th. collinus*) was assessed at 3–4 points, while the subdominant species, valesian fescue (*F. valesiaca*), was assessed at 2 points. The abundance of *Th. caucasicus* in this plant community was assessed at 2 points.

In petrophytic vegetation types, *Thymus caucasicus* participates in communities together with drought-resistant species such as *Thymus collinus* Bieb., *Th. kotschyanus* Boiss. et Hohen., *Th. fominii* Klok. et Shost., *Stachys inflata* Benth., *S. aspera* Michx., *S. arvensis* L., *Cousinia macroptera* C.A. Mey., *Ziziphora tenuior* L., *Z. turcomanica* Juz., *Teucrium polium* L., *Amygdalus communis* L., *Atraphaxis spinosa* L., and other drought-tolerant plants. Based on data obtained during expeditions, the technical significance and productivity of *Thymus caucasicus* were studied using various methods. The species was investigated in three replicates on 10 m² sample plots. The number of individuals, fresh biomass, average weight per individual, and productivity per hectare were determined. For example, in the Gadabay district, an average of 5–6 individuals per 1 m² was recorded, the weight of a single individual ranged from 480 to 860 g, and productivity was calculated at 30–31 tons per hectare.

Based on the obtained data, the biological reserves, exploitable reserves, and annual allowable harvest volume of *Thymus caucasicus* were determined.

Table 1. *Regional reserves of Thymus caucasicus*

№	Districs	Total area, ha	Average weight per plant,g	Number of plants per hectare	Yield, ha/kg	Natural reserves, t		
						Biological reserves	Exploitable reserves	Annual allowable harvest
1	Gadabay	1132	68	2780	189,04	213,99	85,60	21,40
2	Dashkasan	1025	59	3900	230,10	235,85	94,34	23,59
3	Shamkir	43	370	595	215,4	119,45	73,61	6,25
4	Tovuz	259	473	2423	1190, 58	686,4	371,85	37,15
5	Goygol	1058	70	3827	267,89	283,43	113,37	28,34

As can be seen from table 1, the reserves of *Thymus caucasicus* in the Shamkir and Tovuz districts are very low compared to other districts. In contrast, the reserves in the Gadabay, Dashkasan, and Goygol districts are satisfactory. Therefore, the implementation of conservation measures for the species in the Shamkir and Tovuz districts is one of the most urgent issues. For this reason, annual monitoring should be carried out in these areas, and the sites where the species occurs should be protected. For populations of *Th. caucasicus* occupying small areas, small protected reserves should be established, and continuous monitoring of these populations should be ensured.

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 Nature of the Doppler Effect

Gunay Dadashzade

Abstract. *This text explains the physical nature of the Doppler effect, its classical and relativistic manifestations, and its practical applications in science. The longitudinal and transverse effects, their differences, and experimental confirmations are discussed. The historical milestones of the discovery and confirmation of the effect are described, as well as its significance for astrophysics and the theory of relativity. The Doppler effect is a change in the frequency and wavelength of waves recorded by a receiver due to the movement of the source and/or receiver.*

Keywords: *electromagnetic, Doppler effect, partticles, waves, observation*

Introduction

One of the most interesting, unusual, and optically beautiful phenomena, yet underrepresented in school physics, is the Doppler effect. The Doppler effect describes the change in wave frequency due to the relative motion of a source or observer. A study of popular science literature and online sources revealed that this effect plays a key role in radio engineering, medical devices, and optical systems. In today's world of progressive technological advancement, this effect is used not only to optimize existing technologies but also to create new, more efficient engineering systems. Therefore, I believe that studying the Doppler effect is an important and relevant research topic. The effect is most clearly evident when a car with a siren passes by: the pitch increases as it approaches, and decreases as it recedes. For sound waves, motion relative to the medium is taken into account, while for light, only the relative motion of the source and receiver is considered. The effect was first described by Christian Doppler in 1842.

Methods

The relativistic Doppler effect is explained by both the classical change in frequency and time dilation. At low speeds, the relativistic formula coincides with the classical one. The longitudinal Doppler effect (motion along the line of observation) is used in astrophysics to analyze the motion of celestial bodies based on the shift of spectral lines. The transverse Doppler effect (motion perpendicular to the line of observation) is a purely relativistic phenomenon, confirmed by the experiments of Ives and Stilwell in 1938, providing evidence of time dilation in moving frames of reference (Yavorsky, 1981, pp. 43–47).

This phenomenon is characteristic of all types of waves and particle flows, but Doppler arrived at this discovery while studying the properties of sound waves. Indeed, the Doppler effect is most often encountered in acoustics. It is known that the frequency of sound vibrations is perceived by the human ear as pitch (Arkhangelsky, 1975, pp. 57–59).

Azerbaijan State Pedagogical College, Baku, Azerbaijan
E-mail: gunay_dadaszade@mail.ru
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Doppler discovered that as a sound source approaches an observer (the receiver of the sound waves), the pitch of the sound will appear higher than if the same source were emitting the sound at rest. Conversely, as the sound source moves away from the observer, the pitch of the sound waves will decrease. One of the most widely known applications is determining the speed of moving objects using velocity sensors. Radar signals are reflected by vehicles and returned. The frequency shift with which the signals return is directly related to the vehicle's speed. By comparing the speed and frequency change, speed can be calculated (Gorokhov, 1990, pp. 94–97).

Findings and Discussion

The Doppler effect is widely used in medicine. It underlies the operation of ultrasound diagnostic devices. There is a separate ultrasound technique called Dopplerography. The Doppler effect is also used in optics, acoustics, electronics, astronomy, and radar. The discovery of the Doppler effect played a crucial role in the development of modern physics. One of the confirmations of the Big Bang theory is based on this effect. How are the Doppler effect and the Big Bang related? According to the Big Bang theory, the universe is expanding (Landau, 1988, pp. 158–159).

When observing distant galaxies, a redshift is observed—a shift of spectral lines toward the red end of the spectrum. Explaining the redshift using the Doppler effect leads to a conclusion consistent with the theory: galaxies are moving away from each other, and the universe is expanding. Radio navigation devices based on the Doppler effect are widely used to solve a number of basic navigation problems. These radio navigation devices, known as Doppler radio navigation devices, are designed to determine the components of the aircraft's velocity vector relative to a surface reflecting electromagnetic vibrations. They are considered autonomous radio navigation devices, as they do not require additional ground equipment to form a measurement channel.

The aircraft's total velocity vector is the sum of the aircraft's airspeed and wind speed vectors (Andreev, 1960). This vector characterizes the aircraft's speed relative to the earth's surface. In what follows, when describing the Doppler radio navigation system, we will use a rectangular coordinate system in which the Ox-axis coincides with the aircraft's longitudinal axis, the Oz-axis is perpendicular to it, the Oxz-plane is horizontal, and the Oy-axis is perpendicular to the Oxz-plane (Fig. 1). $W = V_r + U_x$

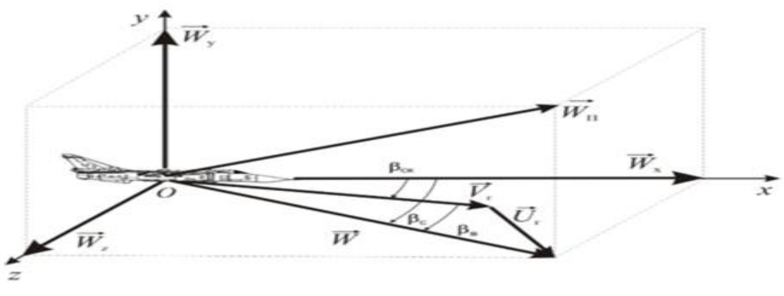

Figure 1. Aircraft Velocity Vector Components

Generally, all three vectors in this coordinate system can have both horizontal and vertical components. Let's denote by the letters W, Vr, and Uг, respectively, the projections of the total speed, airspeed, and wind speed vectors onto the horizontal plane (Golyamina, 1979). These projections, in turn, form a navigational velocity triangle, for which the following relationship holds (Fig. 1). The horizontal component of the aircraft's total speed vector is called the ground speed vector, since it is this component that is taken into account when calculating the aircraft's distance along the Earth's surface. From now on, the vector's magnitude will be referred to as ground speed (Hawking, 2017, p. 232).

Depending on the number of components of the aircraft's total velocity vector that can be measured by a given device, a distinction is made between Doppler total velocity vector meters and Doppler ground speed and drift angle meters. Doppler total velocity vector meters are used for flight control in the vertical and horizontal planes. They are primarily used on helicopters. Some types of these meters also measure the aircraft's true altitude (Effect of Doppler).

Doppler ground speed and drift angle meters measure the aircraft's horizontal velocity vector or the longitudinal components of this vector. They are most commonly used on aircraft, where they serve as the primary sensor in an autonomous dead reckoning navigation system (Wave length and speed). Doppler meters operate in either continuous or pulsed wave modes. Continuous unmodulated or frequency-modulated wave modes are the most common.

Components of the total velocity vector in the horizontal coordinate system; - ground speed vector; - horizontal components of the aircraft airspeed vector and wind speed vector; bc – drift angle; bск – sideslip angle; bв – wind drift angle. In most cases, DISS are used to solve navigation problems in conjunction with an analog or digital navigation computer. In this case, the computer is additionally fed with airspeed data from the airspeed sensor and aircraft heading data from the course system. Such equipment complexes are called autonomous Doppler navigation systems (Golyamina, 1979).

The navigation computer is pre-loaded with the coordinates of the route checkpoints (including the initial and final route points), the values of the specified course angles, and other data. Based on this initial data, the output data of the Doppler meter, and other sensors of the system, the navigation computer solves the following problems: determines the course to the selected route point; Determines the aircraft's current coordinates (geographical or orthodromic); calculates course corrections; the remaining distance and flight time to the selected point, etc. This information is displayed on the corresponding indicators. If necessary, the navigation computer can generate control signals sent to the autopilot to automatically maintain the aircraft on the specified route. In the simplest case, the navigation computer displays ground speed and drift angle values on the corresponding indicators (Andreev, 1960, p. 664). Regarding the change in the oscillation frequency at the receiver, the following explanations are known:

1. When the wave source moves toward the observer, each subsequent wave crest emerges from a position closer to the observer than the crest of the previous wave. Therefore, the distances between crests will be smaller than for a stationary source. This means that the wavelength of the waves arriving at the observer decreases, while their frequency increases (Landau & Lifshitz, 1988).
2. Since the source shifts in the medium over time t = To, by a distance Vu * To, where Vu is the source velocity, the wavelength increases by this amount, and therefore each subsequent wave will need less time to reach the observer.

Consequently, the time between the arrival of successive crests decreases, causing an increase in frequency. Both the first and second explanations involve a change in wavelength, which is unacceptable: classical wave theory allows for changes in wave parameters if the characteristics of the medium in which it propagates have changed (Golyamina & Isakovich, 1979). Furthermore, it was shown above that the Doppler effect does not change wavelength. The author believes that the change in wave frequency at the observer (receiver) can be explained as follows: a moving source imparts additional velocity to the wave (carries it along with its motion), thereby increasing the number of oscillations reaching the observer (receiver) per unit of time. This is similar to how a gramophone record plays out of tune when played at too high a speed, even though the waves recorded on it remain unchanged (Hawking, 2017).

Thus, if the number of incoming waves at the observer (receiver) increases compared to a stationary source, then the source and observer (receiver) are moving closer together. If the number decreases, then they are moving further apart.

The Doppler effect also occurs when waves pass from one medium to another. Let's assume that the wave propagation velocity changes from V1 to V2 during the transition. And at the receiver, N1 and N2 oscillations are received per second, respectively. Then the speed of each oscillation will be:
V1 / N1 and V2 / N2.
Taking the ratios of the velocities, we get:
V2 / V1 = N2 / N1.
Since N2 / N1 are frequency ratios, we can write V2 / V1 = F2 / F1.
This means that a change in wave velocity leads to a change in their frequencies according to the given formula. Thus, the following conclusions can be drawn:

1. With the Doppler effect, the waves do not undergo any changes.
2. The effect is caused by an increase or decrease in the number of waves arriving from the transmitter to the observer (receiver).
3. A change in wave velocity causes an equal change in frequency at the receiver.

Conclusion

The Doppler effect was comprehensively examined during this study. The theoretical part of the work established that the Doppler effect is a universal phenomenon characteristic of all types of waves and particle flows. The discoverer of the effect, Austrian physicist Christian Doppler, first described it while studying sound waves, which was subsequently confirmed in other areas of physics. The practical significance of the study is confirmed by the wide range of applications of the Doppler effect in modern science and technology:

- In radio engineering and communication systems for determining the velocity of moving objects
- In medical diagnostics, particularly in Doppler ultrasound
- In astronomy for studying the motion of stars and galaxies
- In security and speed control systems

The study also focused on the practical application of the effect in medicine. In astronomy, the Doppler effect has become a key tool for studying the motion of celestial bodies and a confirmation of the Big Bang theory. Prospects for further research lie in expanding the application of the Doppler effect in new fields, including quantum technologies and space exploration. Constant technological advances are opening new horizons for the practical use of this fundamental physical phenomenon. Thus, the Doppler effect is not only an important physical phenomenon but also a powerful tool for scientific knowledge, playing a key role in the development of modern science and technology.

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 Influence of Abiotic Factors on Plant Growth and Development

Afag Mammadova

Abstract. *The habitat is the part of nature in which an organism lives. Living organisms are inextricably linked to their environment; they influence each other in a wide variety of ways. Environmental components that influence an organism are called environmental factors, or ecological factors. Inanimate factors, or physical factors (abiotic factors), include light, humidity, heat, wind, rain, hail, and the salt and gas composition of soil and water—to name just a few. Environmental factors are extremely diverse. The responses of living organisms to their influence are equally diverse. Light is a crucial factor for most plants and animals. Light is one of the most important abiotic factors, especially for photosynthetic green plants. Photosynthesis, the most important process in the biosphere, occurs only in the presence of light. Light influences the rate of plant growth and development and the intensity of photosynthesis.*

Keywords: *plant, growth, water, soil, light*

Introduction

Let's imagine there were no plants left in the world. What would happen then? The fact that it would be unsightly is only half the problem. But the fact that we couldn't live without plants is truly a disaster. After all, plants have a very important secret. Amazing transformations occur in plant leaves. Water, sunlight, and carbon dioxide—the gas we exhale—are converted into oxygen and organic matter. Oxygen is necessary for us and all living things to breathe, and organic matter for nutrition. So, one could say that plants contain a veritable chemical laboratory for the production of vital substances (Artamonov, 1991).

Plants are used by humans not only as a source of food but also as raw materials for various industries: food, textile, paper, chemical, and others. Since the importance of plants for human life is so essential, it is crucial that crop yields be consistently high. Taking into account all of the above and having defined the current research problem, we wanted to analyze how external conditions (light, heat, moisture, and air) influence plant growth and development, and, consequently, yield increases. The objects of the study were bean seeds and sprouts, potato tubers, and onion bulbs. The subject of the study was the influence of external conditions on plant growth and development. We set ourselves the goal of studying the conditions for plant germination and development using onions, potatoes, and beans as examples (Baturitskaya, 1991).

Azerbaijan State Pedagogical College, Baku, Azerbaijan
E-mail: elmitexnikisobe@mail.ru
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To achieve this goal, we set the following objectives:
1. To practically identify the influence of external conditions (lack of light, moisture, and air) on seed germination and plant growth.
2. To study information on the influence of external conditions on plant growth from literary sources.
3. To analyze the results and draw conclusions.
Light has a profound effect on plants. Without sunlight, no plant can survive; it is essential for normal development. Under the influence of light, various chemical reactions called photosynthesis occur in the leaves. During this process, the plant absorbs carbon dioxide and water from the air and returns oxygen (Zanina, 2005, p. 64). This carbon dioxide allows the plant to form new tissue. Without photosynthesis, plant growth is impossible. Furthermore, light is needed to generate energy (Ivanov, 2001, p. 144)

Some plants adapt very quickly to low light. However, symptoms indicating a lack of light still appear. When a plant lacks light, growth slows. Leaves stretch upward and stems elongate. The distance between shoots and leaves increases, and the stem becomes thinner (Lebedev, 1988). If new leaves appear, they are much smaller than they should be. Lower leaves turn yellow and die. But the worst thing is that the plant will bloom little, the flowers will be paler, and the buds will develop poorly and fall off (Medvedev, 2004).

Methods

We decided to test how the presence of water affects bean seed germination. We took three containers, placed several bean seeds in them, and filled them with varying amounts of water. In the first container, the seeds were left without water, in the second, we placed a damp bandage and wrapped the seeds in it, and in the third, the bean seeds were completely covered with water. We observed the seeds daily. In the first container, which contained no liquid, the beans remained unaffected. In the second container, the bean seeds began to germinate on the second day. In the third container, filled with the largest amount of water, the beans failed to germinate; on the fourth day, an unpleasant odor developed, and the water became cloudy. The seeds in the second container continued to grow (Maksimov, 1966).

Thus, we can conclude that plants require water for germination, but only in a specific quantity. After confirming that plants require water, we decided to find out what kind of water is suitable for them. To do this, we conducted a second experiment. We took two jars, lined the bottoms with cotton wool, and planted onion bulbs in them. We watered one bulb with tap water, and the other with melted snow (Polevoy, 1989). After a week, we saw that the bulb planted in the jar with melted snow showed more vigorous root and leaf growth, as this water was natural and contained the necessary nutrients for growth. The tap water was likely chlorinated, which is why the bulb sprouted less well (Reinhold, 1987).

The Effect of Light on the Growth and Development of Bean Sprouts

Light is another crucial abiotic requirement for plant life. It is necessary for photosynthesis. If there is too little light, the plant is doomed to die, as the chlorophyll will rapidly degrade, leading to yellowing of the leaves and further deterioration of the plant itself. If natural light is insufficient, artificial light can be substituted (Tompkins, 2006).

We decided to conduct an experiment. Sprouted bean seeds were planted in two cups. We placed one cup in a dark place (a cabinet), and the other on a windowsill, and observed the results. Changes were noticeable after three days. The plants in the dark place developed poorly, while those receiving sufficient light grew strong, with large, green leaves.

We can conclude: when a plant lacks light, growth slows, the leaves stretch upward, and the petioles elongate. The distance between the shoots and leaves increases, and the stem becomes thinner. If new leaves appear, they are much smaller than they should be. The lower leaves turn yellow and die. The next important abiotic factor is air. Air plays a vital role in plant life. Oxygen is vital for all living things. Plants cannot germinate without oxygen (Tretyakov, 1990, p. 271). Roots, leaves, and stems all require this element. Is it true that plants need air? For our experiment, we took two flasks and half-filled them with water. We placed bean sprouts in them. One flask was left untouched, while sunflower oil was added to the other flask on top of the water. The beans in the flask with oil began to wilt after five days. This occurred because a film formed on the surface of the water, blocking oxygen from reaching the roots. The beans in the water without oil received oxygen and therefore remained alive and continued to grow. Studying Tropisms in Different Plants. We noticed that plants can move individual body parts throughout their lives. For example, houseplants turn their leaves toward the light. In science, such movements are called tropisms. Tropisms are cell orientation responses, that is, the direction of cell growth or movement relative to a stimulus. We decided to study tropisms such as geotropism, hydrotropism, and phototropism (Appendix 5).

Experiment 1. Geotropism

We took containers and filled them with soil. We planted sprouted bean seeds: one with the root facing up, the second with the root facing down, and the third with the root facing horizontally. All three roots grew downward, and all the stems grew upward. Conclusion: This means that the root exhibits positive geotropism, and the stem exhibits positive phototropism.

However, it can be seen that plants developing from seeds whose roots initially faced down and the stem upward grew and developed faster. The seedlings whose roots faced up did not sprout immediately; their growth was slow and they did not look as healthy as the previous ones.

Experiment 2. Phototropism

A potato tuber was placed in a maze (a shoebox with a hole on one side and partitions inside). After a month, the potato stems could be observed reaching toward the light and navigating around the maze's obstacles.

Experiment 3. Hydrotropism

Sprouted bean seeds were placed along the edges of a saucer using plasticine. Water was poured inside, and observation was made. After three days, the roots began growing toward the water. This demonstrated that the root also exhibits positive hydrotropism.

Findings and Discussion

The results of the first experiment showed that water is essential for plants from the moment a seed germinates and throughout its lifespan. Meltwater from snow and tap water have different effects on plant growth and development. Meltwater is absorbed by plants faster than tap water, and plants develop more rapidly. The second experiment demonstrates that plant growth is directly dependent on sunlight. The less light a plant receives, the less it grows. Plants follow the light, and leaves reach toward the light source.

The third experiment clearly demonstrates that plants require air for normal growth. If plant roots do not receive sufficient air, the plant becomes ill and cannot develop normally. The experiment also revealed the ability of plant parts to grow in a specific direction. These phenomena are called tropisms. For example, the plant root exhibits geotropism (regardless of the seedling's position in space, the main root always bends downward), while the stem exhibits phototropism (it reaches toward the light). Cell growth by elongation occurs intensively in the dark, resulting in long, elongated, pale-colored stems. The stems, which are horizontal and downward, change their growth direction in the dark (growing upward). In the light, cell elongation is inhibited, so the stems grow less in the same amount of time than in the dark. Exposure to sunlight causes the stems to acquire a bright color. Conclusion: no matter how the plant is positioned, its stems invariably grow upward.

This attraction to the sun allows the plant to more fully utilize the energy of sunlight, so essential for photosynthesis (Yakushina, 1993).

Conclusion

The importance of water in plant life cannot be overstated, as it is an essential component of cells. It turns out that tap water and snow water have different effects on plant growth and development. A bulb germinated in melted snow water grew significantly faster, likely due to the greater penetration of moisture into plant tissue. Tap water contains substances added to preserve pipes and disinfect water, which have an adverse effect on plants. Melt water stimulates growth because it contains more dissolved salts, essential for plants.

It is interesting to note that Russian farmers have used melt water for soaking seeds since ancient times. For example, it was recommended to sow beans only after soaking them in "winter water," obtained by melting March snow collected in May from forest ravines. To summarize our work, we can say that our goal and objectives have been achieved. We came to the following conclusion: for the best growth and development of plants, a combination of external factors (light, heat, moisture, atmospheric oxygen, mineral salts) is necessary.

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 Impact of Modern Agrotechnical Practices Based on Intelligent Agriculture Systems on Plant Quality Indicators

Ali Muradli

Abstract. *Within the framework of agronomic approaches, digital tools such as GPS, drones, and high-resolution satellite imagery play a crucial role in the zonation of plantations and in the management of fields according to their microeconomic characteristics. Modern IoT-based smart gateway systems facilitate the collection of environmental data including solar radiation, temperature, relative humidity, and other factors through integrated ecological sensors and monitoring devices. By leveraging "EDGE Computing" technologies, these systems enable on-site preliminary processing of collected data, ensuring its rapid transmission via wireless communication and accelerating decision-making processes. Consequently, agricultural enterprises gain the capacity for more precise and flexible control over production processes. For the storage and processing of collected data, cloud-based storage solutions and virtual server infrastructures are employed. This technological framework allows for the analysis of large datasets, thereby supporting the comparative study of the growth environments of various crops, including grapevine varieties.*

Keywords: *ıntelligent agriculture, agronomic practices, GPS and drone technologies, fertigation, artificial intelligence, morphometric, photosynthetic*

Introduction

In the contemporary period, enhancing product quality in the agricultural sector and ensuring the sustainability of production emerge as key indicators of competitiveness (FAO, 2022; World Bank, 2021). To this end, alongside traditional agrotechnical measures, the application of intelligent agricultural systems has gained particular relevance (Wolfert et al., 2017). Approaches based on digital technologies, automated monitoring mechanisms, and analytical processing of data enable more precise regulation of plant growth and development stages. The quality attributes of plant-derived products are directly dependent on the effective planning of agrotechnical measures, accurate assessment of soil and climatic conditions, appropriate selection of crop varieties, and the implementation of vegetation and harvesting stages at optimal times (Liakos et al., 2018). In this context, modern intelligent systems and agrotechnical practices play a crucial role in the process of crop cultivation. However, despite the growing application of intelligent agricultural technologies, their integrated impact on the quality indicators of perennial crops under specific agro-ecological conditions has not been sufficiently investigated. Therefore, the present study aims to evaluate the effect of intelligent agricultural systems combined with modern agrotechnical measures on selected quality parameters of perennial plants. The findings of this research are expected to contribute to the optimization of sustainable agricultural practices and the improvement of product quality (FAO, 2022).

Azerbaijan Cooperation University, Master student, Baku, Azerbaijan
E-mail: muradli.eli53@gmail.com
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Materials and Methods

Within the framework of agrotechnical approaches, digital tools such as GPS technologies, unmanned aerial vehicles (drones), and high-resolution satellite imagery play a significant role in the zoning of plantations and the management of agricultural fields according to their micro-environmental characteristics. Modern IoT-based smart gateway systems enable the collection of data on solar radiation, temperature, relative humidity, and other environmental parameters through the use of ecological sensors and monitoring equipment (Fig. 1) (Adamu, 2024).

Through the implementation of edge computing technologies, these systems perform preliminary on-site data processing, thereby facilitating the rapid wireless transmission of information and accelerating decision-making processes. As a result, more flexible and precise control over production processes is achieved in farming operations.

For the storage and processing of the collected data, cloud-based data storage solutions and virtual server infrastructures are employed (Fig. 2). This infrastructure enables large-scale data analysis, allowing for comparative assessment of the growth environments of various crops, including different grapevine varieties. Topographic and agro-ecological mapping of vineyards is conducted, enabling detailed analyses of key parameters such as soil structure, moisture levels, temperature variations, and the spatial distribution of solar radiation (GIGABYTE, 2019).

Figure 1.

Figure 2.

Within the framework of the development of modern agricultural technologies, the “GIGABYTE Smart Farming System – IoT Gateway”, and particularly its component “IoT Eco Box”, plays a significant role in ensuring optimal growth conditions for plants (Fig. 3). This system is equipped with integrated sensors and actuators that enable real-time monitoring and control of environmental factors. Through artificial intelligence–based sensors embedded in the “IoT Eco Box” system, key ecological parameters such as light intensity, humidity, and temperature are continuously measured (GIGABYTE, 2019).

Each sensor is linked to specific operational processes; for instance, the light sensor regulates the lighting system, while the temperature sensor controls the activation of ventilation units. Communication between the sensors and the “GIGABYTE IoT Gateway” is established via the ZigBee protocol, and the collected data are transmitted to a cloud-based database through the internet. The system can be remotely managed via a mobile application or a computer interface. Users are able to monitor environmental parameters in real time, access live camera feeds, and perform relevant operational tasks. These functionalities enable farmers to supervise plant growth processes from any location and at any time. Consequently, the “GIGABYTE Smart Farming System – IoT Eco Box” technology contributes not only to the improvement of product quality but also to the promotion of environmentally friendly and safe food production that supports a healthy lifestyle (Fig. 4).

Equipped with artificial intelligence capabilities, the system represents not only a technological innovation but also a key driver of sustainable development in the agricultural sector (Consumer Technology Association 2020 CES.)

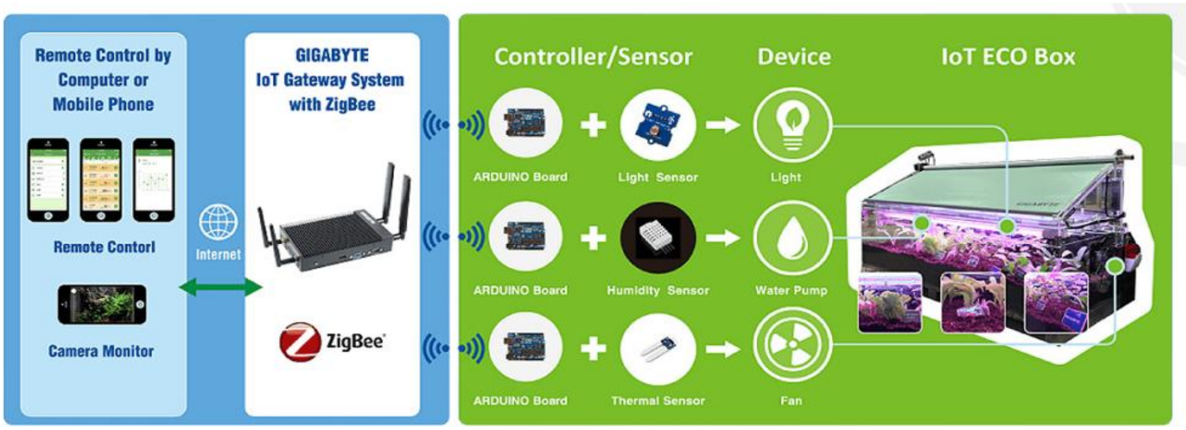

Figure 3.

Figure 4. CES 2020 Exhibition of Artificial Intelligence, Cloud Solutions, and Smart Applications

Results

The results of the conducted studies indicate that the agrotechnical care measures applied during 2024–2025 had a positive impact on both the morphometric and technological parameters of the “Madrasa” and “Khindoghni” grape varieties. In particular, an increase in berry and cluster weight was observed for both varieties in 2025. In this regard, the “Khindoghni” variety demonstrated superior performance, with an average cluster weight of 159 g and a berry weight of 1.8 g, surpassing the “Madrasa” variety. Analysis of technological parameters revealed that the “Khindoghni” variety maintained a stable sugar content of 16.4% compared to the previous year, while titratable acidity showed a slight decrease. This trend can be attributed to the relatively earlier achievement of technological ripeness under the regional warming conditions. For the “Madrasa” variety, although an increase in berry and cluster size was noted in 2025, the sugar content remained stable at 19.9%, while acidity exhibited a declining tendency. These observations indicate that the variety possesses relative biochemical stability and exhibits moderate sensitivity to climatic factors (Table 1).

Overall, the results demonstrate that agrotechnical approaches integrated with sensor technologies, digital monitoring, and drip and fertigation irrigation systems have a tangible and positive effect on enhancing both the production and quality potential of agriculture.

Table 1.

Indicators	**2024 Madrasa**	**2025 Madrasa**	**2025 Khindoghni**
Cluster weight, g	256	271	355
Cluster width, cm	13.5	14	11
Cluster length, cm	19	18	16
Number of berries per cluster, pcs	201	152	223
Berry weight, g	2.31	2.2	2.7
Berry width, mm	11	14.3	15.9
Berry length, mm	11	14.6	16.6
Weight of 100 berries, g	134	189	175
Volume of 100 berries, ml/cm³	195	275	270
Juice yield per cluster, ml	110	147	153
Juice yield per 100 g of berries, ml	47–59	60–105	45–81
Seed weight, g	12	15	13
Residual pulp and seed weight, g	98	81	143
Weight of 100 seeds, g	5	6	4
Sugar content, %	20.4	19.9	16.4
Titratable acidity, g/dm³	6.9	11.2	9.09

The application of soil and climate sensors enables the collection and processing of data in real time. Based on this information, irrigation and fertilization activities can be carried out on a demand-driven basis and at optimal dosages, thereby ensuring both the efficient use of resources and stress-free plant growth. According to records obtained using the PIX4Dfields software, areas within vineyards exhibiting lower photosynthetic activity (marked in blue) have been identified (Fig. 5) (Guebsi et al., 2024). Additionally, the DJI Mavic 3 Multispectral drone represents a modern unmanned aerial technology utilized for capturing high-resolution imagery of vineyards (Fig. 6) (Pix4D 2020 July 22)

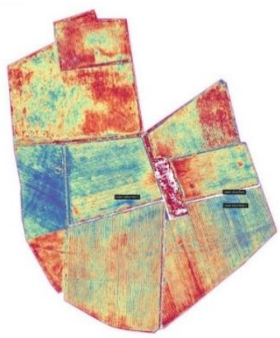

Figure 5.

Figure 6.

Among agrotechnical practices, canopy management holds particular importance. Through leaf thinning and proper formation of shoots, the exposure of grape clusters to sunlight and the level of ventilation are enhanced (Van Leeuwen & Seguin, 2006). This, in turn, promotes increased photosynthetic activity in the berries, consequently facilitating the accumulation of sugars and the intensified synthesis of anthocyanins (Reynolds, 2010). High concentrations of anthocyanins serve as one of the key quality indicators of grape-derived products, influencing both color intensity and phenolic content (Bably & Rana, 2025).

Regulation of the irrigation regime is also a critical factor in maintaining and improving fruit quality in vineyards. Irrigation should be conducted according to the phenological stages of the plants: typically once every 7–10 days during early developmental stages, and 4–5 times throughout the vegetative period during fruit set and ripening stages. In this context, drip irrigation ensures the efficient use of water resources, maintains soil moisture balance, and supports optimal root system development.

Fertilization practices directly affect the biochemical composition of plants. Periodic soil loosening, weed removal, and structural improvement throughout the vegetative period expand the nutrient availability to the root system. Applying nitrogen-based fertilizers in early spring and phosphorus- and potassium-based fertilizers in autumn helps maintain an optimal balance between vegetative growth and the formation of generative organs. Moreover, pruning is an essential agrotechnical practice for the proper formation of grapevine shoots and regulation of yield. The application of both short and long pruning methods facilitates optimization of shoot load, enhances the quality attributes of berries, and ensures uniformity of the harvest.

The application of subsurface (injection) irrigation and fertigation technologies in the Ganja-Dashkasan economic region, as well as in other areas with high viticultural potential, has demonstrated significant results. Fertigation, which involves the direct delivery of fertilizers to the plant root zone through irrigation water, ensures substantial savings in both water and agrochemical resources. For comparison, traditional irrigation methods consume 2–3 times more water and require approximately 60% more fertilizers than subsurface irrigation systems (Mirsalahova, 2024).

The automation of irrigation and fertilization processes is carried out through modern sensors and transmitters, allowing for more precise and sustainable management of agrotechnical practices. Observations conducted in experimental plots indicate that the application of these technologies has positively influenced yield. For instance, grape varieties “Madrasa” and “Khindoghni” exhibited yields of 183–195 centners per hectare, reflecting an approximate 20–25% increase in productivity. In addition, economic efficiency has significantly improved. The implementation of fertigation and injection irrigation technologies enabled a net income of 245.7 thousand AZN per hectare. Furthermore, these technologies help prevent soil erosion, minimize water losses, and reduce the environmental impact of viticultural practices (Mirsalahova, 2024).

Discussion

The findings of this study demonstrate that the integration of intelligent agriculture systems with modern agrotechnical practices has a significant and measurable impact on plant quality and productivity, particularly in perennial crops such as grapevine. Improvements in morphometric, biochemical, and yield parameters confirm that digital monitoring and sensor-based decision-making enhance the precision and efficiency of crop management. A key outcome of the research is the 20–25% increase in yield and improved berry quality observed in the “Madrasa” and “Khindoghni” grape varieties. These results are consistent with previous studies indicating that sensor-driven irrigation and fertigation optimize water and nutrient use, reduce abiotic stress, and support balanced vegetative and generative growth. The higher productivity recorded in experimental plots is primarily attributed to demand-based irrigation scheduling and precise nutrient delivery enabled by real-time soil and climate monitoring. Increases in cluster and berry weight indicate that optimized canopy management, irrigation regulation, and nutrient availability collectively enhanced photosynthetic efficiency and assimilate distribution.

The use of multispectral drone imagery and NDVI-based analysis enabled early identification of zones with reduced photosynthetic activity, allowing targeted interventions that represent a clear advantage over uniform management practices.

The relative stability of sugar content and titratable acidity further demonstrates the effectiveness of intelligent agrotechnical management. Differences observed between varieties confirm that crop response to digitalized management systems is genotype-dependent. Fertigation and subsurface irrigation significantly improved resource-use efficiency, reducing water and fertilizer consumption while maintaining or enhancing product quality, in line with sustainability objectives.

From an economic perspective, the reported net income of 245.7 thousand AZN per hectare highlights the practical feasibility of intelligent agriculture technologies. Reduced input costs, lower water losses, and improved yield stability contribute to overall economic sustainability. Nevertheless, the study underscores the need for long-term monitoring and multi-year datasets to evaluate the stability of quality indicators under changing climatic conditions. Overall, the results confirm that intelligent agriculture systems integrated with scientifically grounded agrotechnical practices provide an effective and scalable approach for improving crop quality, resource efficiency, and economic performance in modern agriculture.

Conclusion

The conducted study demonstrates that the application of modern agrotechnical practices based on intelligent agriculture systems is highly effective in improving productivity and quality indicators across agricultural crops. The integration of IoT sensors, digital monitoring, drone technologies, and data-driven management enables irrigation, fertilization, and cultivation practices to be implemented in accordance with the actual needs of plants. The results indicate that this approach ensures efficient resource utilization, reduces plant stress factors, and enhances morphometric and biochemical quality parameters. Moreover, the adoption of intelligent agricultural systems contributes to lower production costs, increased economic efficiency, and reduced environmental impact. Overall, intelligent agriculture technologies represent a promising and sustainable approach for ensuring resilient agricultural production systems and improving product quality in modern agriculture.

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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CONTENTS

Editorial address
AZ1073, Baku,
Matbuat Avenue, 529,
"Azerbaijan" Publishing House, 6th floor
Phone: +994 99 805 67 68
+994 99 808 67 68
e-mail: nature.science2000@aem.az

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e-mail: zengezurda1868@mail.ru