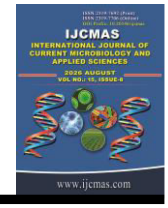
EXCELLENT PUBLISHERS

*Int.J.Curr.Microbiol.App.Sci* (2026) *15*(8): 204-209

*International Journal of Current Microbiology and Applied Sciences*
***ISSN: 2319-7706*** **Volume 15 Number 8 (2026)**
Journal homepage: http://www.ijcmas.com




**Original Research Article** https://doi.org/10.20546/ijcmas.2026.1508.019

# The Effect of Climate Change on Soil Enzyme Activity (A Case Study of Gulistan and Boyovut Districts of Sirdarya Region, Republic of Uzbekistan)

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**Keywords**

Soil, enzymes, biological activity, fertility, microorganisms, soil ecology, organic matter, enzymatic activity.

**Article Info**

***Received:***
10 June 2026
***Accepted:***
28 July 2026
***Available Online:***
10 August 2026

**ABSTRACT**

This article analyzes enzyme activity as an important indicator of biological processes occurring in soil, the mechanisms of its formation, and its significance in assessing soil fertility. Soil enzymes act as important biological catalysts in the decomposition of organic matter, mineralization of plant nutrients, humus formation, and the cycling of nitrogen, phosphorus, and carbon. The dependence of enzyme activity on soil moisture, temperature, pH, organic matter content, microbial activity, vegetation cover, and anthropogenic impacts is described. In addition, changes in enzymatic activity under conditions of soil degradation, pollution, and climate change are substantiated as potentially important indicators for assessing the ecological condition of soils.

## Introduction

In recent years, various changes have been observed in the ecological condition of soils under the influence of waste and climate change. This has resulted in changes in soil properties and a decline in soil fertility indicators. The biological properties of soils are among the main indicators that ensure the cycling of organic matter, soil fertility, and the availability of nutrients. Therefore, studying the processes associated with increasing the number of microorganisms inhabiting the soil and enzyme activity is considered one of the most relevant issues. Consequently, various changes occurring in irrigated agricultural soils require systematic sampling and laboratory analysis. In addition to ensuring the cycling of substances, microorganisms present in soils contribute to improving water permeability and agrochemical properties. Furthermore, soil microorganisms provide plants with nutrients necessary for their growth and development and contribute to improving the ecological condition of various soil properties. Therefore, increasing the number of microorganisms inhabiting soils, reducing risks to their vital activities, improving their ecological condition, and ensuring the stability of their habitat are of great importance.

Climate change directly and indirectly affects biological processes in soil. Increases in air temperature, changes in precipitation patterns, drought, and decreases in soil moisture can affect the intensity of enzymatic processes. Under drought conditions, the activity of soil microorganisms decreases, resulting in reduced activity of certain enzymes. When moisture is restored, enzymatic activity may increase significantly over a short period due to the acceleration of microbiological processes. Such conditions can lead to changes in the cycling of carbon and nutrients in the soil. Determination of soil enzyme activity makes it possible to complement traditional physicochemical analyses with biological indicators. While determining soil pH, humus, nitrogen, phosphorus, and other parameters provides information about the general condition of the soil, enzymatic activity reflects the intensity of biological processes occurring in the soil at a given time.

It has been experimentally observed that soil respiration depends not only on the composition of the various fertilizers applied to the soil, but also on the soil's ability to retain moisture. Many researchers have concluded in their studies that soil respiration and enzyme activity depend on the composition of fertilizers applied to the soil. Soil enzymes are important bioindicators for assessing soil biological activity, fertility, and ecological condition. Climate change, particularly changes in temperature and moisture, affects the activity of enzymes such as invertase, dehydrogenase, urease, and phosphatase. Therefore, studying enzyme activity makes it possible to assess the cycling of carbon, nitrogen, and phosphorus in the soil [1]. According to some studies, soil enzymes play an important role in responding to environmental factors. Climate change, particularly the combined effects of warming and drought, affects soil enzyme activity and biogeochemical cycles. The authors emphasized the need to consider the combined effects of multiple environmental factors when assessing changes in enzyme activity [2].

Extracellular enzymes released by soil microorganisms play an important role in the decomposition of organic matter and in the global cycles of carbon, phosphorus, and nitrogen, and they also serve as indicators of soil health and fertility. Current studies extensively analyze these microbial populations and enzyme activities in various soil ecosystems and climatic regions, including forests, grasslands, tropical regions, Arctic regions, and deserts. Climate change, global warming, and intensive agriculture are altering soil enzyme activity. Nevertheless, only a limited number of reviews have examined in detail the major enzymes essential for soil fertility and the effects of abiotic factors on their functions [3]. In recent years, research on the stability of agricultural soils under climate change has attracted considerable attention. Studying the thermal stability of soil enzymes during the major growth stages of crops in response to increased $CO_2$ concentration, drought, and warming is important for assessing the effects of climate change on crop production and soil ecosystem stability. Despite its importance, research on the thermal stability of soil nutrient-cycling enzymes remains limited. In one study, a pot experiment was conducted using soil from winter wheat (*Triticum aestivum* L.), one of the major grain crops in China. An artificial climate chamber was used to simulate four growth stages of winter wheat: the jointing stage, flowering stage, grain-filling stage, and maturity stage. By analyzing the temperature sensitivity ($Q_{10}$) of soil enzyme activities associated with carbon, nitrogen, and phosphorus cycling under different treatments, the results showed that doubling the $CO_2$ concentration significantly reduced the $Q_{10}$ of soil carbon-cycle enzymes while increasing the $Q_{10}$ of soil nitrogen- and phosphorus-cycle enzymes. In addition, the $Q_{10}$ of soil carbon-cycle enzymes decreased with increasing temperature, whereas other enzymes showed inconsistent responses [4]. Currently, one of the most important consequences of climate change is drought stress. Drought is one of the significant, concerning, and hazardous abiotic stresses responsible for changes in the soil environment and affects soil organisms, including microorganisms and plants. It alters the activity and functional composition of soil microorganisms responsible for important ecosystem functions and services. These stress conditions reduce microbial abundance, disrupt microbial community structure, and decrease microbial activity, including the production of enzymes such as oxidoreductases, hydrolases, dehydrogenase, catalase, urease, phosphatases, and β-glucosidase, as well as nutrient cycling. This may result in reduced soil fertility, followed by decreased plant productivity and economic losses [5]. Western Jilin Province is one of the three major distribution areas of saline-alkali lands in the world and is an important region for studying global climate change and carbon cycling. Rhizosphere soil microorganisms and enzymes are among the most active components of soil. They are closely associated with soil carbon cycling and can sensitively reflect soil organic carbon (SOC) dynamics. Soil inorganic carbon (SIC) is a major form of the soil carbon pool in arid saline-alkali lands, and its quantitative distribution affects the form of soil carbon accumulation and storage [6]. Soil enzymes occupy a central position in ecosystem processes because they mediate numerous reactions that are important for biogeochemical cycles. However, how soil enzyme activity responds to global warming remains unclear. Studies have concluded that soil enzymes determine the sensitivity of soil carbon to warming; however, the microbial communities and enzymatic characteristics mediating this effect change over time. Long-term studies characterizing a wide range of hydrolytic and oxidative enzymatic properties-including catalytic capacity, kinetics, and inactivation-as well as microbial community responses regulating enzyme synthesis are required to improve the representation of enzymes in soil carbon models [7]. Climate change represents a global threat to food and nutritional security. As greenhouse gas emissions in the atmosphere continue to increase, temperatures are also rising due to the greenhouse effect.

The average global temperature is continuously increasing and is projected to rise by 2°C by 2100, which could result in significant economic losses globally. The concentration of $CO_2$, which constitutes a major component of greenhouse gases, is increasing at an alarming rate. Elevated $CO_2$ concentrations have resulted in increased plant growth and productivity due to enhanced photosynthesis; however, rising temperatures offset this effect by increasing crop respiration and evapotranspiration rates, promoting pest proliferation, altering weed flora, and shortening the crop maturation period. Climate change also affects microbial populations and their enzymatic activity in soils [8]. Forests influence climate and mitigate global changes by storing carbon in soils. In turn, these complex ecosystems face major challenges, including increasing carbon dioxide concentrations, warming, drought and wildfires, pest outbreaks, and nitrogen deposition. Forest responses to these changes are largely mediated by microorganisms, particularly fungi and bacteria. The effects of global change differ among boreal, temperate, and tropical forests. The future of forests largely depends on the functioning and balance of fungal symbiotic guilds, saprotrophic fungi and bacteria, and fungal plant pathogens. Drought significantly reduces forest resilience because it promotes adverse processes such as pathogen spread and wildfires, thereby affecting microbial activity and the efficiency of forests in carbon storage and nutrient cycling [9]. Soil microbial carbon use efficiency (CUE) is the efficiency with which microorganisms convert assimilated carbon (C) into their biomass and reflects microbial growth efficiency. Soil microbial CUE is an important physiological and ecological parameter in the ecosystem carbon cycle, affecting carbon retention, turnover, soil mineralization, and greenhouse gas emissions. Soil microbial CUE is generally expressed as the ratio between microbial growth and carbon uptake and can be divided into methods based on changes in microbial growth rate, microbial biomass, substrate uptake rate, and substrate concentration. Its values generally range from 0.2 to 0.8 [10]. Microorganisms are extremely important in terrestrial carbon cycling because their growth, activity, and interactions with the environment largely control the fate of plant carbon inputs and protected soil organic carbon. Soil carbon stocks reflect the balance between microbial decomposition of organic carbon and the stabilization of microbially assimilated carbon. This balance may change under altered environmental conditions, and recent research indicates that understanding microbial physiology may be critical for predicting changes in soil carbon and improving projections of feedbacks to climate change [11]. Climate change is altering the frequency and severity of drought events. Recent evidence suggests that drought can have legacy effects on soil microbial communities. However, it remains unclear whether previous drought events lead to the formation of ecological memory, that is, the ability of past events to influence current ecosystem response trajectories. Some researchers have emphasized that the composition of soil microbial communities changes together with their functioning, thereby affecting soil processes. It has been found that the formation of ecological memory in soils under recurrent drought conditions may increase the resilience of ecosystem functioning to future drought events [12].

## Research Methodology

This study was conducted to assess the biological activity of soils distributed in Gulistan and Boyovut districts of Sirdarya Region, with particular emphasis on the seasonal and spatial variations in enzyme activity. Soil samples were collected from a depth of 0–30 cm under field conditions and subsequently analyzed in the laboratory. The collected samples were transported to the laboratory while preserving their natural condition. The activities of urease, invertase, and catalase enzymes, which characterize the biological activity of the soil, were determined using appropriate analytical methods.

## Analysis and Results

During the study, the activity of enzymes in the soils distributed throughout Gulistan District was analyzed under laboratory conditions. The enzyme activity of the soils distributed in Gulistan District is presented in the following figure (Figure.1).

During the study, soil samples were collected in 2021, 2022, 2023, and 2024 from the northern, eastern, southern, western, and central parts of Gulistan District, and the activities of *urease, invertase,* and *catalase* enzymes in the soil were studied. The results for the four years were analyzed and average values were determined. According to the obtained results, in the northern part of Gulistan District, at the coordinate point 40.629022, 68.747082, urease activity was 18.2 $NH_3$/g soil. In the eastern part, at 40.408028, 69.086713, urease activity was 14.8 $NH_3$/g soil. In the southern part, at 40.490049, 68.822900, urease activity was 19.4 $NH_3$/g soil. In the western part, at 40.507889, 68.731926, urease activity was 24.6 $NH_3$/g soil, while in the central part, at 40.529552, 68.918350, urease activity was 22.8 $NH_3$/g soil. In addition, in the northern part of Gulistan District, at 40.629022, 68.747082, invertase activity was 6.4 mg glucose/g soil; in the eastern part, at 40.408028, 69.086713, it was 4.6 mg glucose/g soil; in the southern part, at 40.490049, 68.822900, it was 6.2 mg glucose/g soil; in the western part, at 40.507889, 68.731926, it was 4.78 mg glucose/g soil; and in the central part, at 40.529552, 68.918350, it was 4.82 mg glucose/g soil. The catalase activity was 9.06 $O_2$/g soil in the northern part of the study area at 40.629022, 68.747082, 8.84 $O_2$/g soil in the eastern part at 40.408028, 69.086713, 10.52 $O_2$/g soil in the southern part at 40.490049, 68.822900, and 9.8 $O_2$/g soil in the western part at 40.507889, 68.731926. In samples collected from the central part of the study area at 40.529552, 68.918350, catalase activity was found to be 10.83 $O_2$/g soil.

The second study area was Boyovut District. During the study, soil samples collected in 2021, 2022, 2023, and 2024 were analyzed under laboratory conditions to determine enzyme activity in the soils distributed throughout the district. The average data obtained for the study years are presented in the following figure (Figure.2).

During the study, soil samples were collected in 2021, 2022, 2023, and 2024 from the northern, eastern, southern, western, and central parts of Boyovut District, and the activities of *urease, invertase,* and *catalase* enzymes were studied. The results for the four years were analyzed and average values were determined. According to the obtained results, in the northern part of Boyovut District, at the coordinate point 40.295540, 69.020017, urease activity was 12.2 $NH_3$/g soil. In the eastern part, at 40.280874, 69.044393, urease activity was 8.8 $NH_3$/g soil. In the southern part, at 40.257625, 69.016069, urease activity was 14.4 $NH_3$/g soil. In the western part, at 40.287422, 68.994611, urease activity was 21.6 $NH_3$/g soil, while in the central part, at 40.276553, 69.023965, urease activity was 20.8 $NH_3$/g soil. Furthermore, in the northern part of Boyovut District, at 40.295540, 69.020017, invertase activity was 4.4 mg glucose/g soil; in the eastern part, at 40.280874, 69.044393, it was 3.2 mg glucose/g soil; in the southern part, at 40.257625, 69.016069, it was 4.2 mg glucose/g soil; in the western part, at 40.287422, 68.994611, it was 4.42 mg glucose/g soil; and in the central part, at 40.276553, 69.023965, it was 6.82 mg glucose/g soil. The catalase activity in the northern part of the study area at 40.295540, 69.020017 was 7.06 $O_2$/g soil; in the eastern part at 40.280874, 69.044393, it was 6.84 $O_2$/g soil; in the southern part at 40.257625, 69.016069, it was 8.52 $O_2$/g soil; and in the western part at 40.287422, 68.994611, it was 6.4 $O_2$/g soil. In samples collected from the central part of the study area at 40.276553, 69.023965, catalase activity was found to be 8.83 $O_2$/g soil.

According to the research results, it was determined that the increasing influence of climatic factors on soils from year to year directly affected enzyme activity. In particular, it was observed that warming resulted in reduced accumulation of vegetation cover in soils. In addition, an increase in soil salt content had a negative effect on enzyme activity. As a result, the activity of soil microorganisms and enzymes decreased, which was considered to contribute to various ecological problems.

The results of the study demonstrate that the biological activity of soils distributed in Gulistan and Boyovut districts varies considerably depending on the geographical location and ecological conditions of the area. Based on soil samples collected from the northern, eastern, southern, western, and central parts of the study areas during 2021–2024, the average activities of urease, invertase, and catalase enzymes were analyzed. A comparative analysis of the results obtained from the two study areas showed that enzymatic activity was relatively higher in Gulistan District than in Boyovut District, particularly in terms of urease and catalase activity.

**Figure.1** Data on enzyme activity in the soils distributed in Gulistan District

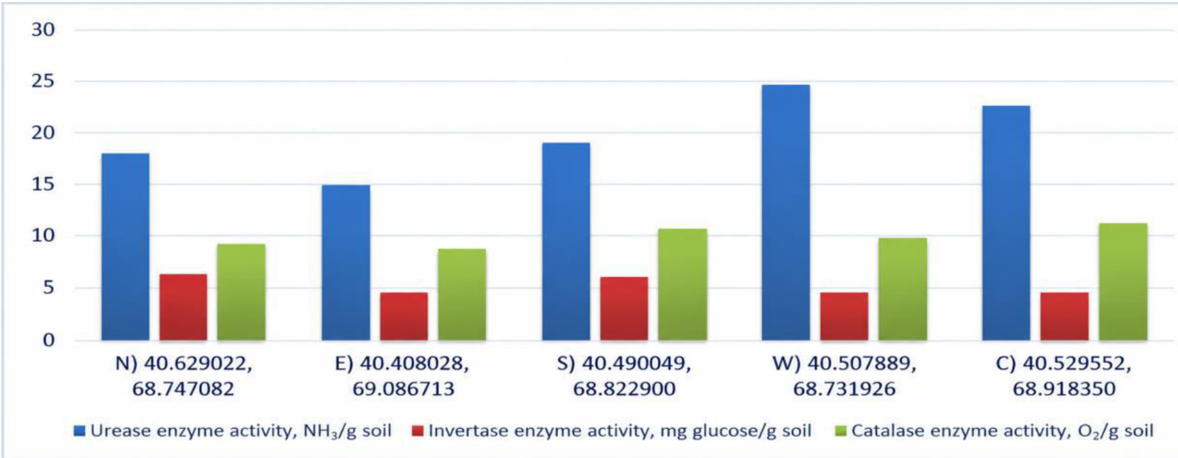
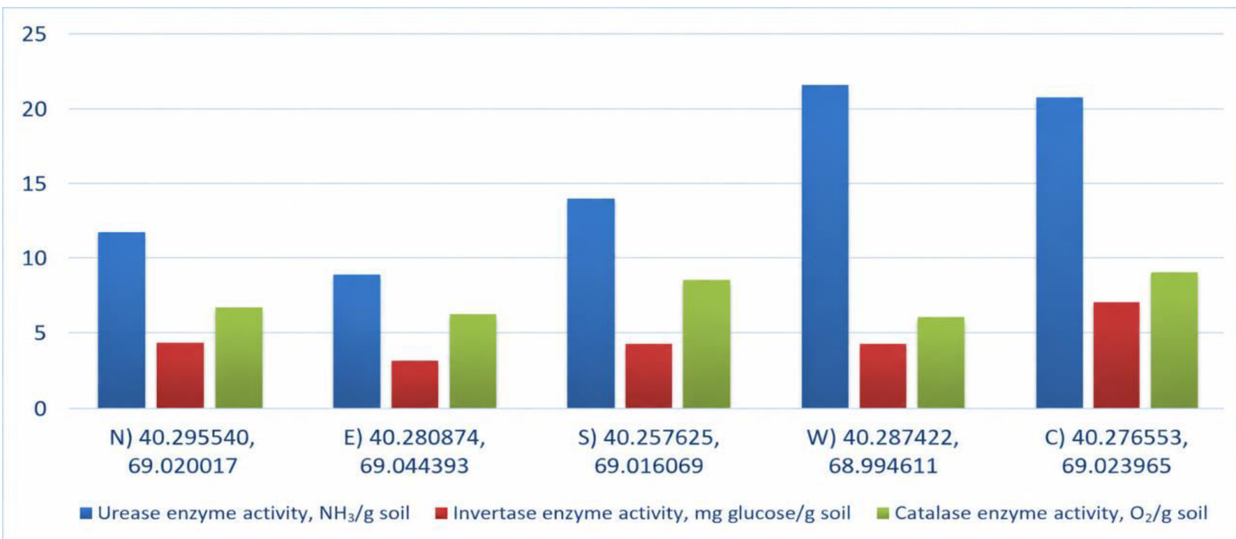



**Figure.2** Data on enzyme activity in the soils distributed in Boyovut District




This difference may be explained by variations in soil and reclamation conditions, moisture regimes, organic matter content, vegetation cover, microbiological activity, and salinity levels between the two areas. In conclusion, the activities of urease, invertase, and catalase can be used as effective indicators for assessing the biological condition of soils in Gulistan and Boyovut districts. Regular monitoring of these indicators makes it possible to detect biological changes occurring in soils under the influence of climate change, salinization, and other anthropogenic factors at an early stage. Based on the obtained results, it is advisable to develop agroecological management measures aimed at preserving soil fertility, supporting microbiological activity, reducing salinization processes, and adapting agricultural practices to climate change.

## Author Contributions

Dilnoza TOYMBAYEVA: Conceptualization, methodology, data curation, supervision, writing—reviewing the final version of the manuscript.

## Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethical Approval** Not applicable.

**Consent to Participate** Not applicable.

**Consent to Publish** Not applicable.

**Conflict of Interest** The authors declare no competing interests.

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**How to cite this article:**

Dilnoza TOYMBAYEVA. 2026. The Effect of Climate Change on Soil Enzyme Activity (A Case Study of Gulistan and Boyovut Districts of Sirdarya Region, Republic of Uzbekistan). *Int.J.Curr.Microbiol.App.Sci.* 15(8): 204-209.
**doi:** https://doi.org/10.20546/ijcmas.2026.1508.019