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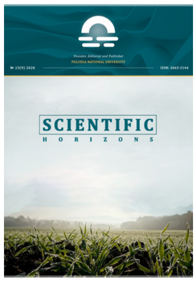

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Climate change and agricultural productivity: Economic implications for food security

Riza Murabildayeva
Master of Sciences, Lecturer
Al-Farabi Kazakh National University
050040, 71 Al-Farabi Ave., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0001-6508-2236

Laila Bimendiyeva
PhD in Economics, Associate Professor
Al-Farabi Kazakh National University
050040, 71 Al-Farabi Ave., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0003-4965-5908

Saltanat Kondybayeva*
PhD in Economics, Associate Professor
Al-Farabi Kazakh National University
050040, 71 Al-Farabi Ave., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0003-3496-3545

Zhanna Yermekova
PhD in Economics, Associate Professor
Al-Farabi Kazakh National University
050040, 71 Al-Farabi Ave., Almaty, Republic of Kazakhstan
https://orcid.org/0009-0009-2224-1239

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Abstract. Since the late 20th century, there has been an increasing focus on the impact of climate change on various sectors, including agriculture. Consequently, it is crucial to assess how the negative effects of climate change can be mitigated to ensure food security. This study evaluated the relationship between agriculture, food security, and CO_2 emissions. In particular, a correlation analysis was conducted between selected indicators for three countries: Kazakhstan, the United States of America, and Germany, as a representative of European Union countries. The study demonstrated that rising temperatures, changes in precipitation patterns, and the increased frequency of extreme weather events significantly disrupt agricultural productivity, posing substantial risks to global food security. These issues were compounded by the need to adapt agricultural methods and technologies to new climatic realities, which often require significant

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**Corresponding author*

financial and human resources, particularly in developing countries with limited resources. Conclusions drawn from statistical data revealed mixed results: for Kazakhstan, the positive impact of agriculture on food security was confirmed, while CO_2 emissions had an ambiguous effect on food security indicators. The findings of this study can be used to inform strategies for future development, both by enterprises and by the state as a whole

Keywords: ecology; CO_2 emissions; agricultural sector; regression models; sustainable development

INTRODUCTION

In the contemporary context of the 21st century, farmers must consider all potential factors that could affect their crops. In recent decades, climate change has become one such factor, gaining increasing relevance due to its impact on agricultural food security. Rising average temperatures, changes in precipitation patterns, the frequency of extreme weather events, and shifts in seasonal patterns are leading to reduced crop yields, deteriorating soil quality, and the depletion of water resources, which are critical for agriculture. These climatic changes also contribute to the increasing number and spread of pests and diseases, which can seriously threaten crop productivity. Therefore, studying the impact of climate change on food security in countries is a pressing issue.

Food security in Kazakhstan has been the subject of numerous scholarly studies. For instance, L. Xuegao and A. Kaiyrbayeva (2024) evaluated the role of innovation in enhancing agricultural productivity. They concluded that continuous innovation is crucial for the country to ensure agricultural development and improve food security over time. Meanwhile, D. Wang *et al.* (2022) identified key climatic factors affecting crop yields and proposed management strategies to mitigate climate-related yield losses, specifically focusing on trends in wind speed and photosynthetic yield in Kazakhstan. The researchers suggested several actions to reduce the negative impact of climate change on crops such as wheat and potatoes. Similarly, S.E. Shmelev *et al.* (2021) investigated the influence of climatic factors on droughts and wheat yields in northern Kazakhstan. Their findings indicated that climate change, particularly droughts, has a detrimental effect on local crops, with a strong correlation observed between wheat yield and factors like soil moisture, June temperature, solar radiation, solar activity, and cosmic rays.

Z.S. Bulkhairova *et al.* (2019) argued that in the current context of climate change, innovation-driven development is paramount for achieving higher levels of food security. Researchers have highlighted that achieving food security hinges on several key conditions: sufficient food availability, innovation-driven production, accessibility for all social groups, and access to food for a balanced diet. They noted that maintaining food security in Kazakhstan requires concerted efforts at all levels of government – national, regional, and district – and across all agricultural sectors. A primary focus should be on enhancing the competitiveness of the agricultural sector, improving production processes, ensuring the quality of agricultural products, and increasing the efficiency of agricultural enterprises. X. Yu *et al.* (2020) examined the role of international agricultural trade as an adaptation strategy to the impacts of climate change on Central Asian agriculture, with a focus on Kazakhstan's grain trade. They found that climatic factors significantly influence grain exports and imports in Kazakhstan. While increases in precipitation and temperature boost wheat and rice exports, higher precipitation levels lead to increased corn imports and reduced wheat imports (Yeraliyeva *et al.*, 2017). These results suggest that international grain trade can help Kazakhstan adapt to climate change by ensuring stable food supplies. However, shifts in Kazakhstan's trade patterns may have implications for global food security, underscoring the need to integrate international food trade into broader climate change adaptation strategies to support resilience in the face of climate challenges.

The aim of this study was to assess the relationship between the level of food security in Kazakhstan, the development of the agricultural sector, and CO_2 emissions, as well as to compare the results with those of other countries, namely the USA and Germany.

MATERIALS AND METHODS

The study involved an assessment of up-to-date statistical data to determine the existing relationship between agriculture, food security, and climate change. The data obtained was then used for comparative analysis across several countries. For comparison with Kazakhstan, two developed countries were selected: the USA and Germany (as representatives of the European Union). These countries were chosen due to their status as major global economies and their ability to reflect trends observed in their respective regions. For each country, five indicators were calculated: the state of agriculture (a composite score reflecting changes in the level of agricultural development), atmospheric CO_2 emissions, the ratio of the agricultural sector to the total economy (agricultural gross domestic product (GDP) as a percentage of total GDP), the Global Food Security Index 2022 (2023) values, and a food security index constructed based on data from Sustainable Development Goal 2 (Sustainable Development Report, 2024). The time period for all countries was set from 2004 to 2023 (over the past 20 years), as it is sufficiently representative for analysis and the data for this period is publicly available.

To calculate the agricultural sector index for each country, available data on the sector's performance was utilised. The index value for 2004 was set as 1, and subsequent years were indexed relative to 2004. This can be represented by equation (1):

$$I_n = \frac{C_n}{C_1}, \quad (1)$$

where I_n is the index value for indicator n, C_n is the value of the indicator in year n, and C_1 is the value of the indicator in year 1. Thus, the value for year 1 (2004) will be 1, and all subsequent values will indicate how much larger they are compared to the value in year 1.

Subsequently, the geometric mean of all indicators was calculated, resulting in the final index value (2):

$$I = (1 \times I_2 \times I_3 \times \ldots \times I_n)^{\frac{1}{n}}, \quad (2)$$

where I is the index value and n is the number of indicators used in the index.

However, not all indicators were normalised as this was not always meaningful. In this case, it was important to calculate a single index for multiple indicators characterising agriculture. Nevertheless, this was not necessary for the CO_2 emissions indicator, the Global Food Security Index, and the ratio of agricultural output to the total economy. It is also worth noting that the calculation of the Global Food Security Index began in 2012, therefore, the values after 2004 in the model were equated to the 2012 value.

Regarding the food security index based on data from Sustainable Development Goal 2, transformed calculations of the indicators used to assess the Goal were employed. The index calculation was conducted in several steps: initially, 1 was added to all indicators of the Goal, as some indicators had a value of 0, which complicated calculations. Subsequently, for each time series from 2004 to 2023, minimum and maximum values were found, along with the target values for each indicator characterising Goal 2 (for example, for the indicator "Prevalence of wasting among children under 5 years", the target value was 0, which was set to 1 in this calculation). Thus, if the target value was lower than the actual value, the index in a given year was the arithmetic mean of the ratio of the target indicator to the actual indicator and the following equation (3):

$$P_n = 1 - \frac{(C_n - C_{min})}{(C_{max} - C_{min})}, \quad (3)$$

where P_n is the value of the second part of the index in year n, C_n is the value of the indicator in year n, C_{min} is the minimum value of the indicator, and C_{max} is the maximum value of the indicator.

Therefore, the final index value was calculated as the geometric mean of all six index variables. Subsequently, three regression models were constructed for each country. In each model, the variables representing the level of agricultural development and CO_2 emissions served as independent variables, while the dependent variables were, in turn, the indicators characterising food security. Based on the analysis conducted, linear regression models were constructed to describe the relationships between the indicators. The key results of these models are presented in Table 1.

***Table 1**. Summary of regression models for Kazakhstan, the USA, and Germany*

Country	**Kazakhstan**		
Indicator	**Ratio of agricultural output to GDP**	**Global Food Security Index**	**Food security index based on data from Sustainable Development Goal 2**
R-square	0.714	0.741	0.866
Adjusted R-square	0.68	0.71	0.85
Significance F	0	0	0
Coefficient C	0.038	23.6	-0.62
Coefficient X_1	0.016	35.3	0.24
Coefficient X_2	0	0	0
P-value for Coefficient C	0	0.012	0
P-value for Coefficient X_1	0	0	0.003
P-value for Coefficient X_2	0	0.276	0
Country	**USA**		
Indicator	**Ratio of agricultural output to GDP**	**Global Food Security Index**	**Food security index based on data from Sustainable Development Goal 2**
R-square	0.189	0.652	0.146
Adjusted R-square	0.094	0.612	0.046
Significance F	0.168	0	0.26
Coefficient C	-1.6	38.9	0.09
Coefficient X_1	0.47	-0.43	0.06
Coefficient X_2	0	0	0
P-value for Coefficient C	0.253	0.027	0.824
P-value for Coefficient X_1	0.185	0.919	0.566
P-value for Coefficient X_2	0.063	0.001	0.136

Table 1. Continued

Country	Germany		
Indicator	**Ratio of agricultural output to GDP**	**Global Food Security Index**	**Food security index based on data from Sustainable Development Goal 2**
R-square	0.868	0.733	0.35
Adjusted R-square	0.853	0.701	0.273
Significance F	0	0	0.026
Coefficient C	0.69	61.2	0.27
Coefficient X_1	-0.52	2.5	-0.011
Coefficient X_2	0	0	0
P-value for Coefficient C	0.241	0	0.498
P-value for Coefficient X_1	0.127	0.628	0.963
P-value for Coefficient X_2	0	0	0.067

Note: *Y is the value shown in the horizontal axis of the table (ratio of agricultural output to GDP, Global Food Security Index, or food security index based on data from Sustainable Development Goal 2); X_1 is the agricultural index; X_2 is the CO_2 emissions; C is the value without the variable*
Source: *compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan (2024), Macrotrends (2024), Statista (2024a; 2024b; 2024c)*

As can be seen from Table 4, all regression models for Kazakhstan were found to be valid, as their Significance F is below 0.05, and the p-values for each variable are also significant. This indicates a clear relationship in Kazakhstan between indicators characterising both the level of agricultural development and CO_2 emissions and the level of food security. The only exception was the model with the Global Food Security Index, which was reconstructed due to the invalidity of one of the indicators, as discussed below. For the USA, only the second model, related to the Global Food Security Index, was found to be adequate, but even in this case, the relationship was determined only between variables Y and X_2, while X_1 was found to be insignificant. As for Germany, only the first and second models were adequate, but for the first one (where Y is the ratio of agricultural output to GDP), the p-values for variables Y and X_1 were insignificant, while for the second model, the p-values for variables Y and X_2 were significant. The general formula for the regression equations described in the study is as follows (4):

$$y = C + x_1 + x_2, \tag{4}$$

where y is the dependent variable; x_1 is the indicator of agricultural development; x_2 is the indicator of CO_2 emissions.

Additional regression equations for the United States and Germany (due to the need to exclude some variables) are shown in Table 2.

***Table 2**. Summary of regression models for the USA and Germany (with one variable)*

Country	Kazakhstan	USA	Germany
Indicator		**Global Food Security Index**	
R-square	0.721	0.652	0.729
Adjusted R-square	0.706	0.633	0.714
Significance F	2E-06	2E-05	2E-06
Coefficient C	16.87	37.5	65.3
Coefficient X_1	31.5	-	-
Coefficient X_2	-	9E-09	2E-08
P-value for Coefficient C	0.0115	3E-04	5E-16
P-value for Coefficient X_1	0	-	-
P-value for Coefficient X_2	-	2E-05	2E-06

Source: *compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan (2024), Macrotrends (2024), Statista (2024a; 2024b; 2024c)*

As can be seen from Table 2, by removing one of the independent variables, the models become adequate and can be considered.

RESULTS

Since the 2010s, climate change has emerged as a significant factor impacting agricultural production in many regions worldwide. These changes include rising average temperatures, altered precipitation patterns and intensity, increased frequency of extreme weather events, and shifting seasonal patterns. These phenomena introduce additional risks to agriculture and necessitate the adaptation of farming practices to new conditions (Kerr *et al.*, 2021; Roy *et al.*, 2024). One of the key manifestations of climate change is rising temperatures, leading to increased evaporation and, consequently, reduced water availability for crops (Abbass *et al.*, 2022). This process is particularly critical for regions with limited water resources, such as the Mediterranean, East and Southern Africa, and parts of South and Southeast Asia. Elevated temperatures have been linked to reduced crop yields, potentially threatening global food security (Shebanina *et al.*, 2024).

Changes in the quantity and distribution of precipitation also lead to significant alterations in agricultural ecosystems (Karavolias *et al.*, 2021; Qi *et al.*, 2021). Some regions may experience decreased rainfall, exacerbating drought risks, while others may face more intense rainfall and flooding (Romanenko & Kovalevskii, 2022). Excessive precipitation can cause soil erosion and nutrient leaching, negatively impacting soil fertility. Aa result, farmers find it increasingly difficult to predict optimal planting and harvesting times, reducing agricultural productivity and resilience (Nguyen & Scrimgeour, 2021). Additionally, the increased frequency of extreme weather events, such as hurricanes, cyclones, and storms, leads to substantial losses in agricultural production and infrastructure damage. In particular, hurricanes in North and South America destroy crops and significant economic losses (Buono, 2021). These events pose a serious challenge to agriculture and require substantial effort and investment from farmers for recovery. Climate change also shifts the timing of the growing season, necessitating revisions to crop cultivation methods. Adapting agriculture to new climatic conditions requires the adoption of resilient crop varieties and the development of innovative practices such as agroforestry and drip irrigation (Ismayilzada *et al.*, 2023). However, adaptation is associated with high costs and risks, which is particularly relevant for developing countries where resource constraints may hinder the adoption of new technologies.

The study assessed the impact of indicators describing the level of agricultural development and CO_2 emissions on several variables characterising food security. After calculating all relevant indices, correlation matrices were constructed for each country. A portion of the obtained results is presented in Table 3.

As can be seen from Table 3, Kazakhstan exhibits predominantly positive correlations. Notably, the agricultural development index is strongly correlated with the Global Food Security Index (0.849) and the Sustainable Development Index (0.761), while CO_2 emissions have a moderate correlation with agricultural development (0.531). Data for the USA is presented in Table 4.

Table 3. *Correlation matrix for selected indicators in Kazakhstan*

Indicators	Agricultural development index	CO_2 emissions	Ratio of agricultural output to GDP	Global Food Security Index	Sustainable Development Goalbased Index
Agricultural development index	1	0.583	0.179	0.849	0.761
CO_2 emissions		1	-0.566	0.383	0.879
Ratio of agricultural output to GDP			1	0.138	-0.362
Global Food Security Index				1	0.623
Sustainable Development Goal-based Index					1

Source: *compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan (2024), Macrotrends (2024)*

Table 4. *Correlation matrix for selected indicators in the USA*

Indicators	Agricultural development index	CO_2 emissions	Ratio of agricultural output to GDP	Global Food Security Index	Sustainable Development Goalbased Index
Agricultural development index	1	-0.692	0.001	-0.569	-0.154
CO_2 emissions		1	0.314	0.808	0.359
Ratio of agricultural output to GDP			1	0.363	0.431
Global Food Security Index				1	0.75
Sustainable Development Goal-based Index					1

Source: *compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024)*

Table 4 reveals a more diverse correlation pattern for the USA. The agricultural development index has a negative correlation with the Global Food Security Index (-0.569) but shows no significant correlation with other food security indicators. Data for Germany is presented in Table 5.

***Table 5**. Correlation matrix for selected indicators in Germany*

Indicators	Agricultural development index	CO_2 emissions	Ratio of agricultural output to GDP	Global Food Security Index	Sustainable Development Goalbased Index
Agricultural development index	1	-0.753	-0.786	-0.602	-0.451
CO_2 emissions		1	0.921	0.854	0.591
Ratio of agricultural output to GDP			1	0.738	0.705
Global Food Security Index				1	0.393
Sustainable Development Goal-based Index					1

***Source:** compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Statista (2024a; 2024b; 2024c)*

Table 5 for Germany highlights the ecological and structural transformation of the agricultural sector. There is a significant positive correlation between emissions and the share of agriculture in GDP (0.921), the Global Food Security Index (0.854), and the index based on the second Sustainable Development Goal (0.591). The agricultural development index also shows a fairly high level of correlation with all indicators except the Sustainable Development Goal-based index. Thus, the strongest relationship between indicators was observed in Kazakhstan, while in other countries it was less significant. Based on the obtained data, the resulting regression equations can be described. They are presented in Table 6.

***Table 6**. Regression equations for different countries in the context of their impact on food security indicators*

No.	Country	Indicator	Equation
1	Kazakhstan	Ratio of agricultural output to GDP	$y=0.038+0.016x_1-1.54*(10^{\wedge}(10))$
2		Global Food Security Index	$y=16.87+31.5x_1$
3		Food security index based on data from Sustainable Development Goal 2	y=-0.62+0.24*x1+3.03*(10^(9))
4	USA	Global Food Security Index	$y=37.5+8.88*(10^{\wedge}(-9))x_2$
5	Germany	Global Food Security Index	$y=65.3+2.14*(10^{\wedge}(-8))x_2$

***Note:** the numbering is provided for ease of reference in subsequent text*
***Source:** compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan (2024), Macrotrends (2024), Statista (2024a; 2024b; 2024c)*

As Table 6 demonstrates, the majority of adequate models were found for the Global Food Security Index. A more detailed description of the results obtained from equations 1-5 is necessary to understand their adequacy:

1. For every 1% increase in the agricultural development index, the ratio of agricultural output to GDP improves by 0.016%; for every 1 billion tonnes increase in CO_2 emissions, the ratio of agricultural output to GDP decreases by 0.154%.

2. For every 1-unit improvement in the agricultural development index, the Global Food Security Index improves by 31.5.

3. If the agricultural development index increases by 1, the food security index based on data from Sustainable Development Goal 2 improves by 0.24; if CO_2 emissions increase by 1 billion tonnes, the food security index based on data from Sustainable Development Goal 2 improves by 3.03.

4. If CO_2 emissions increase by 1 billion tonnes, the Global Food Security Index improves by 8.88 units.

5. If CO_2 emissions increase by 1 billion tonnes, the Global Food Security Index improves by 2.14 units.

Considering the described results, it can be concluded that four of the obtained models appear to be inadequate (do not accurately reflect the real situation). The first regression equation and its corresponding results are quite adequate, demonstrating how improvements in the agricultural sector can influence its ratio to GDP (which indirectly indicates a country's ability to ensure food security). However, the remaining four equations raise doubts about their validity, as an increase in CO_2 emissions within a country should not positively impact food security. On the other hand, this could be explained by the fact that the more production a country has (even if it increases CO_2 emissions), the easier it is to ensure food security. However, this could only apply to food processing plants, while overall environmental pollution reduces agricultural efficiency, and therefore the expected impact should be negative. In any case, the obtained results should be further studied in subsequent research.

As part of the study, the impact of individual agricultural indicators on food security in Kazakhstan was also assessed. The first step was to construct a correlation matrix for these indicators to identify those suitable for further analysis (Table 7).

Table 7*. Correlation matrix of agricultural development indicators and food security in Kazakhstan*

Indicator	Food security index based on data from Sustainable Development Goal 2	Gross agricultural output/GDP	Global Food Security Index
Adjusted sown area of cotton	-0.8674	0.4143	-0.576
Adjusted sown area of open-field vegetables	0.8641	-0.0967	0.9015
Adjusted sown area of oilseed crops	0.8807	-0.1967	0.8247
Adjusted sown area of potatoes	0.3684	-0.0483	0.0005
Adjusted sown area of cereals (including rice) and legumes	0.1232	-0.0619	0.2859
Adjusted sown area of sugar beet	-0.1912	0.4834	0.0289
Cotton yield	0.7282	-0.2433	0.6352
Sugar beet yield	0.6149	0.0148	0.8571
Open-field vegetable yield	0.9020	-0.2311	0.8321
Oilseed crop yield	0.7842	-0.043	0.6842
Cereals (including rice) and legumes yield	0.3984	0.2572	0.1125
Potato yield	0.8618	-0.161	0.854
Total adjusted sown area of crops	0.7952	-0.21	0.7601
Gross cotton harvest	-0.5298	0.3047	-0.2452
Gross sugar beet harvest	0.2658	0.246	0.5563
Gross open- and closed-field vegetable harvest	0.8766	-0.1165	0.8929
Gross oilseed crop harvest, thousand tonnes	0.8755	-0.095	0.8338
Gross potato harvest	0.7732	-0.0941	0.5307
Gross grain (including rice) and legume harvest	0.4361	0.2814	0.2031
Gross agricultural production (services)	0.6426	0.1807	0.9467

Source: *compiled by the authors*

Based on the results presented in Table 7, it was decided that only the food security index based on data from Sustainable Development Goal 2 and the Global Food Security Index would be used for further analysis, as they had a sufficient number of variables with a high correlation coefficient with the potential independent variable. In subsequent analysis, indicators were used only if the correlation level between the independent and dependent variables exceeded ± 0.6.

The next step was to construct regression equations. The initial equations were found to be inadequate, primarily due to some dependent variables having high p-values. As a result, inadequate variables were excluded, allowing for the construction of final regression equations. The equation for the independent variable Food security index based on data from Sustainable Development Goal 2 is shown in equation (5):

$$y = -1.61 - 0.001434x_1 + 0.0194x_2 + 0.0113x_3 - (5*10^{-5}) x_4 - (6*10^{-4})x_5 + (8.65*10^{-5})x_6, \quad (5)$$

where y is the dependent variable (food security index based on data from Sustainable Development Goal 2); x_1 is the sown area of cotton; x_2 is the sown area of open-field vegetables; x_3 is the yield of open-field vegetables; x_4 is the total sown area of crops; x_5 is the gross production of open- and closed-field vegetables; x_6 is the gross potato harvest.

In this case, a one-unit increase in the sown area of cotton decreases the index by 0.001434 (a 1% change leads to a 0.288% decrease); a one-unit increase in the sown area of open-field vegetables increases the index by 0.0194 (a 1% change leads to a 5.52% increase); a one-unit increase in the yield of open-field vegetables increases the index by 0.0113 (a 1% change leads to a 5.25% increase); a one-unit increase in the total sown area of crops decreases the index by $5*10^{-5}$ (a 1% change leads to a 2.04% decrease); a one-unit increase in the gross production of open- and closed-field vegetables decreases the index by $6*10^{-4}$ (a 1% change leads to a 4.97% decrease); a one-unit increase of potato production increases the index by $8.65*10^{-5}$ (a 1% change leads to a 0.3% change). Regarding the Global Food Security Index, the following equation (6) was formulated:

$$y = 64.944 + 0.034x_1 - 0.0195x_2 + 0.0703x_3 + (5.9*10^{-6})x_4, \quad (6)$$

where y is the dependent variable (Global Food Security Index); x_1 is the sugar beet yield; x_2 is the yield of open-field vegetables; x_3 is the gross production of open- and closed-field vegetables; x_4 is the gross output of agricultural products (services).

In this case, a one-unit increase in sugar beet yield increases the index by 0.034 (a 1% change leads to a 0.1786% increase); a one-unit increase in the yield of open-field vegetables decreases the index by 0.0195 (a 1% change leads to a 0.7172% decrease); a one-unit change in the gross production of open- and closed-field vegetables increases the index by 0.0703 (a 1% change leads to a 0.431% change); a one-unit change in the gross output of agricultural products (services) leads to an increase of $5.9*10^{-6}$ (a 1% change leads to a 0.17588% increase). Therefore, based on the conducted analysis, different indicators have varying impacts on food security levels in Kazakhstan. However, some overlap, namely the yield of open-field vegetables and the gross production of open- and closed-field vegetables. This may suggest that additional attention should be paid to these indicators to achieve a higher level of food security.

The research has demonstrated the importance of developing policies that address the specific needs of each region, ensuring food security while simultaneously combating climate change. In Kazakhstan, the most effective approach would be to increase investments in sustainable agriculture, improve water resource management, and introduce cleaner technologies to safeguard food supplies in the face of climate challenges. For the United States, reallocating subsidies to promote sustainable farming and implementing carbon-reducing technologies could in turn help reduce inefficiencies and environmental harm. Meanwhile, Germany should prioritise organic and small-scale farming alongside energy-efficient methods to strike the right balance between environmental sustainability and food security.

On a broader scale, countries must integrate food security into their climate action plans, foster global cooperation to share knowledge, and base decisions on sound data. All three countries should work towards the global goal of zero hunger (Sustainable Development Goal 2) while simultaneously addressing the dual challenge of climate change mitigation and adaptation. To achieve real progress, governments should increase funding for programs that help agriculture adapt to a changing climate, especially in the most vulnerable regions, by providing subsidies to encourage the adoption of sustainable practices. By taking these steps, countries can build more resilient agricultural systems, ensure food supplies, and reduce the impacts of climate change. This can lay the groundwork for policy development to design solutions tailored to their unique circumstances, addressing the interconnected issues of agricultural development and food security, alongside climate-related challenges.

DISCUSSION

Thus, the study assessed the relationship between agricultural development, CO_2 emissions, and food security indicators in Kazakhstan, the USA, and Germany. A positive correlation was found between the agricultural indicator and food security in Kazakhstan. However, the relationship with CO_2 emissions was less clear-cut, as varying correlations were observed across countries and indicators. Therefore, further research is needed to more accurately determine the existence of such a relationship. In the current study, a statistical assessment was conducted to evaluate the impact of agricultural development on food security, leading to the conclusion that such a relationship exists, at least in Kazakhstan. However, the influence of climate change on food security was evident in all three countries studied. The impact of climate change on agricultural pests was specifically examined by S. Skendzic *et al*. (2021). Their research highlighted that climate change significantly affects crops and associated pests, although many uncertainties remain. Small-scale climate variability (changes in temperature, precipitation, and humidity) influences insect populations in complex ways, favouring some species while suppressing others (Ivanova *et al*., 2021). These changes affect insect distribution, abundance, growth, and behaviour, which can lead to more frequent pest outbreaks and range expansions, particularly in northern regions. The authors described how climate change may also reduce the effectiveness of current pest control approaches, posing additional risks to food security. Addressing these risks will require proactive, science-based strategies, including improved integrated pest management, monitoring of climate changes, and forecasting of subsequent likely changes in this area.

B. Behera *et al*. (2023) assessed agriculture, food security, and climate change in South Asia, specifically examining the impact of climatic (temperature, precipitation, CO_2 emissions) and nonclimatic (agricultural production, fertiliser use, cereal land) factors on food security in six South Asian countries using data from 2000 to 2019. Their findings indicated that increased agricultural production positively influenced food security, CO_2 emissions had a negative impact on food security, and the interaction between precipitation and temperature negatively affected crop yields, thus harming food security. The level of influence was determined to be "strong", suggesting that a significant portion of food security challenges is attributed to these factors. The researchers also formulated policy recommendations, including training farmers in climate-resilient methods to improve yields and safety, promoting renewable energy in agriculture to reduce CO_2 emissions, and encouraging regional cooperation for comprehensive policies and sustainable food systems. As can be seen, both studies highlighted the negative impact of climate change on national food security. A similar result was obtained in the current study for Kazakhstan, but not for the USA and Germany, which may suggest that the findings for these countries are inadequate.

M. Lupascu *et al*. (2023) explored the challenge of balancing food security, climate change mitigation, and rural livelihoods in the tropical peatlands of Indonesia, carbon-rich areas threatened by agricultural expansion. Using data from various sources, the authors analysed land use trends in Indonesia over the past 30 years, with a particular focus on food crops and monoculture tree crops such as oil palm and rubber. They found that peatland regions contribute minimally to food security but are highly susceptible to land use changes associated with carbon emissions from tree crops. The researchers concluded that integrating climate-smart agriculture, such as paludiculture, could enhance food production and reduce emissions, although peatland conservation should remain a priority. They identified existing challenges such as a lack of comprehensive peatland definitions, varying government sectoral maps, and inconsistent policies that hinder sustainable practices. In this regard, it is important to align food security initiatives with efforts to achieve sustainable development goals. The impact of climate change on agriculture and its mitigation strategies were discussed by G.S. Malhi *et al*. (2021). They noted that growing global populations and climate change are increasing pressures on agriculture to meet food and nutritional needs. Climate change is expected to reduce agricultural productivity through impacts on temperature, precipitation, and greenhouse gases, which affect pest infestations, soil fertility, and plant physiology (Shahini *et al*., 2024). Various strategies can mitigate these effects; the authors argue that their implementation, both by businesses and governments, can alleviate economic losses and increase farmers' incomes while sustaining production. However, a multidisciplinary approach is needed to implement viable, climate-resilient solutions. The other two studies mentioned also highlighted the negative impacts of climate change on agriculture, although the findings of the current study do not entirely align with these. Nevertheless, agricultural development and improved efficiency remain possible under any conditions, including changing climates.

A.A. Chandio *et al*. (2020) examined the short-term and long-term impacts of climate change on agriculture. Their study assessed how climate change affects agricultural production and rural household incomes in China. They found that increasing the area under grain crops, greater fertiliser use and energy consumption positively influenced agricultural value, while changes in temperature and precipitation had a long-term negative impact on farmers. Based on these findings, the researchers recommended adapting irrigation practices to suit current weather conditions. A. Gomez-Zavaglia *et al*. (2020) explored opportunities for mitigating the impacts of climate change. They noted that rising temperatures, changing precipitation patterns, and increased pollution threaten crop yields and nutrient quality, creating a double risk of droughts and floods that damage soil and increase crop water demand. Climate change also promotes the spread of pests and weeds, expanding their impact on agriculture. To enhance resilience, crops resistant to drought and temperature changes should be developed, and irrigation systems and soil management should be improved.

CONCLUSIONS

Thus, the correlation and regression analyses presented in this study reveal the complex interplay between agriculture, CO_2 emissions, and food security indicators in Kazakhstan, the USA, and Germany. Kazakhstan exhibited the strongest and most positive correlations among the variables examined, suggesting that investments in agricultural development and effective environmental management can significantly enhance food security. In contrast, the USA and Germany displayed more diverse and intricate relationships, reflecting structural and ecological transformations in their agricultural sectors. These findings indicate that the impact of agricultural and environmental policies on food security varies considerably across countries, depending on their specific socioeconomic, climatic, and institutional contexts. While regression models confirm the relationship between key variables, their limitations in certain contexts, such as the USA and Germany, highlight the need for further methodological refinements and the inclusion of additional factors. The study also identified specific agricultural indicators that exert a stronger influence on food security within each country.

The study highlighted the critical importance of integrating climate resilience into agricultural policies and practices. Developing innovative approaches, such as using climate-resilient crop varieties, sustainable irrigation systems, and precision agriculture, is essential to mitigate the adverse effects of climate change. Furthermore, fostering international cooperation and knowledge sharing can accelerate the adoption of effective strategies, particularly in regions most vulnerable to climate impacts. The findings also underscore the need for robust policy frameworks that align agricultural development with sustainable practices and address the dual challenge of enhancing food security while minimising environmental degradation. Future research should focus on identifying specific government actions that can be taken to bolster food security, especially in Kazakhstan.

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CONFLICT OF INTEREST

None.

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Зміна клімату та продуктивність сільського господарства: економічні наслідки для продовольчої безпеки

Різа Мурабілдаєва
Магістр, викладач
Казахський національний університет ім. аль-Фарабі
050040, просп. Аль-Фарабі, 71, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0001-6508-2236
Лайла Бімендієва
Кандидат економічних наук, доцент
Казахський національний університет ім. аль-Фарабі
050040, просп. Аль-Фарабі, 71, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0003-4965-5908
Салтанат Кондибаєва
Кандидат економічних наук, доцент
Казахський національний університет ім. аль-Фарабі
050040, просп. Аль-Фарабі, 71, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0003-3496-3545
Жанна Єрмекова
Кандидат економічних наук, доцент
Казахський національний університет ім. аль-Фарабі
050040, просп. Аль-Фарабі, 71, м. Алмати, Республіка Казахстан
https://orcid.org/0009-0009-2224-1239

Анотація. З кінця XX століття дедалі активнішими стали обговорення з приводу змін клімату та їхнього впливу на різні сфери діяльності, зокрема й сільське господарство. У зв'язку з цим, проведення оцінки з приводу того, яким чином негативний вплив на зміну клімату може бути знижено для забезпечення продовольчої безпеки, є актуальним. У рамках цього дослідження було проведено оцінку в контексті існування взаємозв'язку між сільським господарством, продовольчою безпекою та викидами CO_2. Зокрема, проводився кореляційний аналіз між обраними показниками для трьох країн: Казахстану, Сполучених Штатів Америки та Німеччини, як представника країн Європейського Союзу. У роботі було показано, що підвищення температури, зміна характеру опадів і збільшення частоти екстремальних погодних явищ істотно порушують продуктивність сільського господарства, створюючи істотні ризики для глобальної продовольчої безпеки. Ці проблеми поглиблюються необхідністю адаптації сільськогосподарських методів і технологій до нових кліматичних реалій, що часто вимагає значних фінансових і людських ресурсів, особливо в країнах, що розвиваються, де такі ресурси обмежені. Висновки на основі статистичних даних засвідчили неоднозначні результати: для Казахстану позитивний вплив сільського господарства на продовольчу безпеку було підтверджено, тоді як викиди CO_2 мали неоднозначний вплив на показники продовольчої безпеки, результати, отримані в рамках дослідження, можуть бути використані для формування стратегій подальшого розвитку як з боку підприємств, так і держави в цілому

Ключові слова: екологія; викиди CO_2; аграрний сектор; регресійні моделі; сталий розвиток