

Article

Sustainable Trends and Determinants of Wheat Cultivation in Poland (2004–2023): A Spatiotemporal Analysis of Productivity, Resilience, and Climate Adaptation

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Abstract: Wheat farming is of utter importance in every country around the world, since it is a critical crop that contributes to food security and rural development. Given this importance, this research work investigates trends, determinants, and spatial variability in Polish wheat production between the years 2004 and 2023, with a key interest in productivity, resilience, and sustainable farming. This work will apply spatiotemporal analysis, statistical modeling, and ARIMA forecasting in the identification of the environmental, economic, and policy factors that interact with the wheat yield. Determinants include climatic variables, temperature, and precipitation, production costs, and market prices. These results point to great regional disparities in yield; the apparently better regions, such as Opole and Pomerania, enjoy exceptionally good environmental conditions with good access to modern technology, while regions like Podlasie and Subcarpathia are characterized by poor soil quality and a shortage of resources. This paper has pointed out the need for differential intervention policies that could contribute to reducing such yield gaps, increasing resilience to climate change, and hence contributing to sustainable wheat production growth. The stabilized yields projected underline the resilience of the sector to various challenges, from climate variability to market fluctuations. The results also indicate how innovative practices, supported by enabling policy frameworks, are essential in the promotion of wheat production in an environmentally friendly way, such as precision agriculture. The present research work will provide useful tools for policymakers, researchers, and other stakeholders by providing active insights into how to achieve equitable and sustainable agricultural development in Poland.



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1. Introduction

Among the important crops in the world, wheat is one of the most cultivated and consumed cereal crops [1,2]. In most cultures across the world, it still remains a staple food, and that makes its production of importance to ensure food security for nutrition and dietary provisions in several cultural jurisdictions [3–5]. It is also extremely versatile: it finds a place in bread, pasta, breakfast cereals, and a wide range of processed foods in addition to animal feedstock and industrial products such as bioethanol [6–8].

It is grown over, more or less, the most varied climatic regions, from temperate to semi-arid, which is another hallmark of its adaptability and hence its importance as one of

the most resilient crops. Major wheat-producing countries include the likes of China, India, Russia, the United States, and the European Union, all of which take the lion's share in world production together [9–14]. These regions possess very favorable climatic conditions, the most advanced agricultural technologies, and already established infrastructure that contributes to high productivity and great output to international markets [15,16].

Additionally, it is an important driver for the livelihoods and rural development via trade in most of the economies of different countries. Countries with surplus wheat production, like Russia, the United States of America, and Canada, are among the top export categories that form the pivot countries for world wheat demand and supply balances [17–19]. Most developing countries have food security imperatives for wheat importation, either because of small arable land area or less ideal conditions for its growth [20,21].

And yet, this vital grain for the whole world is suffering from a set of serious threats. Major risks include those emanating from climate change, such as rising temperature and erratic rainfall, causing the increased frequency of extreme weather; the degradation of soil and lack of water have risen further, as well as increasing pest and disease pressures [22–25]. Geopolitical events, changes in trade policy, and conflict in key exporter regions cause effects on supply chains and world prices [26,27].

Therefore, against this backdrop, research and innovation are at the very core of wheat production today. Genetic engineering, the development of varieties resilient to climate vagaries, and precision agriculture have all helped raise productivity to its unprecedented high along with enhancing its sustainability. International collaboration via FAO- or CGIAR-supported activities hints towards the dissemination of knowledge and technologies for achieving global food security requirements [28–32]. (See Table 1).

Table 1. Challenges of wheat production.

Challenge	Description
Climate change	Rising temperatures, erratic rainfall, and increasing extreme weather events reduce yields and threaten crop resilience.
Soil degradation	Declining soil fertility and erosion affect productivity and long-term sustainability of farmland.
Water scarcity	Inadequate water supply for irrigation in the main wheat-producing areas keeps the production level inefficient.
Pests and diseases	Increasing infestation and disease incidence, coupled with changing climate conditions, is causing damage to the crops and reducing their output.
Market volatility	Unpredictable global market dynamics and fluctuating prices affect profitability and planning.
Rising production costs	More expensive seeds, fertilizers, and energy erode farmers' margins of profit and reduce their potential for investment.
Land use competition	The conversion of arable land for urbanization or industrial uses diminishes the area available for cultivation.
Geopolitical factors	Trade policies, conflicts, and economic sanctions interfere with supply chains and impact international wheat trade.
Labor shortages	Aging rural populations and a general lack of interest in farming result in labor shortages in key regions.
Technological gaps	Poor access to improved machinery, techniques, and research is holding back productivity improvements.

Source: on basis of [1,4,5,7,9,12–15,22,27,28,31].

Wheat is one of the key economic and agricultural productions in Poland, greatly contributing to the country's food security and rural development. The long-term wheat cultivation in Poland has been subject to a complex mixture of environmental, economic,

and policy-driven factors: the variation of climatic conditions, advancement of agricultural technology, change in land-use practices, and impacts from European Union agricultural policies [33,34].

The period of 2004–2023 is one of the most transformational in the history of Polish agriculture. It was a coincidence that with Poland's joining the European Union, there was increased access to finance, modern agricultural techniques, and export markets. But it has also confronted the country with specific challenges: adapting to climate change, managing production costs, and coping with fluctuations in world wheat prices [35,36]. The dynamics of wheat cultivation understood in this context have gained a pivotal role for the sustainability and competitiveness of Poland's agriculture [37–40].

This paper contributes to the discussion of wheat trends within two decades in Poland, focusing more on the spatial and temporal variability of areas and yields, and the factors that condition such dynamics. The key climatic variables identified in this paper are temperature and precipitation, in addition to the economic factors of cost of production and market price, which were the determinants for wheat productivity through various statistical modeling and sensitivity analyses combined with forecasting techniques. It also allows us to draw conclusions concerning the regional disparities of wheat yield in the country and find the causes of these phenomena by applying the methodology of clustering classification of Polish regions according to the performance of wheat yield.

The results of this study will, therefore, present a good status report on the current wheat production in Poland and its future outlook for policymakers, other agricultural stakeholders, and researchers. The identification of emerging trends and challenges may further contribute to the formulation of targeted strategies toward the improvement of agricultural productivity, adaptation to climate change, and building resilience in the production systems.

In this case, dominant drivers for wheat production will be identified based on various environmental, economic, technological, and policy-related factors from the literature review. These interlinked factors will determine wheat productivity and its sustainability from the regional to the global scale.

Among the environmental factors, temperature and precipitation assume the most crucial role in this regard. The climatic condition for wheat is so critical that it requires optimum temperature with adequate availability of water for high yields [17–23]. On the other hand, extreme weather conditions, such as drought or heatwave, may drastically lower productivity. The second environmental determinant is the quality of the soil. Fertile soils with proper nutrient content are fundamental for maintaining healthy wheat crops. Poor conditions of the soil in some areas give low returns; therefore, there is a need for the management of soil by the use of fertilizers and the rotation of crops [24–29].

Economic factors largely affect wheat production. The price of inputs shows the possible ability of farmers to use resources optimally. In areas with very high prices for inputs, the use of modern technology is reduced and thus reduces profitability [7–9]. On top of this, the prices received from wheat also influence farm decisions of crop allocation and management intensity. Good market prices incentivize investment in inputs as well as progressive farming practices throughout the production process. Conversely, if the market prices are low, it may be underutilized or farmed out less [11–15].

Technological changes are some of the major causes that would explain an increase in productivity more than anything else. With better seed genetics, the high-yielding and climate-resilient wheat varieties bring about improved output. Precise agriculture allows farming through the use of GPS-guided machinery on top of a real-time monitoring system which allow a farmer to shun activities that consume too much money. Irrigation infrastructure again provides the essential means to avert water deficiency [8–12].

The core of wheat production is shaped by policy frameworks and institutional support. Subsidies, agricultural support programs, and trade policies shape the economic climate in which farmers operate. For example, in Poland, the European Union agricultural policy compensation for income and market access has enabled farmers to invest in modernization and raise productivity. These inequalities in resource distribution and support result in regional variation in agricultural performance [16–21].

Other social and demographic aspects influencing wheat production include labor availability and farm ownership structures. For instance, rural aging and a loss of interest in farming result in a shortage of labor and low productivity. Conversely, education and training among farmers enhance skill acquisition and the ability to apply more progressive practices.

While much research is occurring globally with respect to wheat, detailed understandings of wheat production in specific national contexts, like Poland, remain unknown. Many of the existing studies are directed toward wider European or global trends and often do not focus on the unique environmental, economic, and policy-related factors that mold agricultural practices within countries. For Poland, accession into the European Union in 2004 brought significant changes in agricultural policies, funding mechanisms, and market access. Few studies so far have investigated the longer-run implications of these changes for wheat cultivation [41,42]. Furthermore, even though new statistical and forecasting techniques have emerged, which can analyze such agglomerative trends in agriculture, few have been integrated for a full-scale analysis in respect to the spatial and temporal variations of wheat production across various regions of Poland. Another related research gap pertains to how climatic variability and economic conditions interact with one another to determine wheat yields. Although there is a significant number of studies that have analyzed either the separate impacts of temperature and precipitation or the contributions of production cost and market price, not many have integrated these into one single analysis framework. More than this, specific regional disparities in yields and wheat cultivation methodologies also remain under analyzed in Poland, raising questions about how environmental and socio-economic factors spur such variation. This understanding is important in elaborating on particular strategies that could strengthen the productivity and resilience of lagging regions.

Wheat is grown to provide a base for food security, economic stability, and environmental concerns that assure the sustainability of food production in the world. Being one of the most widespread cereal crops, wheat takes up a big percentage of human diets that the human race relies on to receive basic nutrition and calories [43–46]. It has varied uses in bread, pasta, cereals, and other food products. It is adapted to all climates and regions, from temperate to semi-arid. The sustainability of wheat production will relate to its capability to answer the challenges imposed by climate change, soil degradation, and water scarcity. Wheat is one of the most resilient crops; on the other hand, increased temperatures and erratic rainfall may pose serious risks [44–46]. These challenges have to be diminished with sustainable practices such as crop rotation, soil conservation, and the development of climate-resilient wheat varieties to ensure long-term productivity [45–53].

Polish wheat output is particularly worthy of study with its European agricultural strategic location, sensitivity to climate change, and the enormous influence of European Union policies on the agricultural sector. As one of the leading Central and Eastern European wheat producers, Poland is a significant regional grain and food security market player. As opposed to Russia [54,55] or the United States [56–64], with their large-scale global production, Poland's agricultural sector is characterized by fragmented land ownership, mean farm sizes, and varied environmental conditions by region. Climate change is an increasing challenge, with rising temperatures, uneven precipitation, and extreme weather conditions affecting the stability of yields and long-term productivity. These climatic al-

terations necessitate adaptation, including improved irrigation facilities, resistant crop varieties, and precision agriculture, so Poland is an appropriate case study in determining the resilience of wheat farming in a temperate climate of Europe.

Poland's accession into the European Union in 2004 brought radical changes to its farm sector, so it is a good example of the role that policy-initiated modernization can have on wheat farming. EU Common Agricultural Policy (CAP) subsidies have encouraged technological transformation, mechanization, and improved farm profitability, but have left regional variations in productivity that reflect the imbalanced distribution of benefits [65,66]. The dependence of Poland on EU subsidies raises serious questions about the long-term sustainability of its agricultural sector in the face of future policy changes and associated subsidy reductions. In addition, with the EU promoting more sustainable farming to reduce the impacts of climate change [66–68], Polish wheat farmers must balance production and ecology, adhering to stricter controls on fertilizers, pesticides, and pollution. To grasp Poland's wheat sector under such stress provides pivotal perspective on the broader issues and possibilities of mid-sized agricultural economies in the face of climate change and shifting policy regimes.

A multivariate approach of spatiotemporal analysis, statistical modeling, and clustering will be implemented to fill the identified gaps in this work. By applying such an integrative approach on wheat cultivation trends within the selected country, namely Poland, over a period between 2004 and 2023, trends and key factors affecting productivity at both regional and sector levels are thoroughly explained, with considerable input toward agricultural policymaking and decisions regarding the sectoral challenges presently encountered due to the prevailing climate and economic scenario.

Therefore, the following research questions were formulated in this paper:

- Q1. What are the main tendencies of wheat cultivation areas and their yield in Poland during the years from 2004 to 2023, and what are the dynamics for two decades?
- Q2. How are the regional disparities within wheat cultivation and productivity developed in Poland, and for what reasons?
- Q3. What are the trends observed? According to which factors will the prospect of further development of wheat production in Poland continue (as calculated with the help of advanced statistical methods represented by the ARIMA model)?
- Q4. How do findings from the clustering analysis of regional data serve to address the targeted interventions necessary for ensuring a potential enhancement in wheat productivity, thus narrowing down the gaps observed between high-performing and low-performing regions?

The objective of this research is to analyze the spatiotemporal trends, environmental and economic determinants, and regional disparities in wheat cultivation in Poland from 2004 to 2023, using statistical modeling and forecasting techniques to assess productivity, resilience, and sustainability in the context of climate change and agricultural policy.

2. Materials and Methods

This paper provides an in-depth analysis of data connected with wheat cultivation in Poland within the period of 2004–2023. The provided data on wheat cultivation areas and yields in Poland from 2004 to 2023, sourced from the Local Data Bank [43], outline the trends, regional disparities, and productivity changes in Polish agriculture over two decades.

Quantitative methods within this study were combined with spatiotemporal analysis and statistical modeling, enabling the establishment of time trends of yields, factors influencing them, and forecasts for further production. Particular attention was given to the variability of areas under cultivation, yields per hectare, and climatic and economic conditions determining agriculture results.

The first stage of the work included an analysis of historical information on areas of wheat cultivation and yields per hectare in different voivodeships. Such information was obtained from official statistical sources [69]. Further, with tabulation, it was possible to analyze temporal trends for two decades: 2004–2013 and 2014–2023. Each decade is characterized by changes in area, dynamics of growth or decline, and regional features conditioned by natural conditions and agricultural policy.

Therefore, the multiple regression statistical modeling was the next step [70–74]. The model proposed investigates environmental factors as well as the economic factors of production costs and wheat price on wheat yield in Poland. In this model, wheat yield expressed in dt/ha was the dependent variable, while independent variables were climatic and economic conditions that may have an impact on the efficiency of production. Regression coefficient estimates and their statistical significance were conducted in order to check which factor exerted the most impact on yield.

Sensitivity analysis of the regression model—the impacts of variation on the value of one independent variable at a time on predicted yields—was considered [75,76]. That is, by manipulating values to change by a certain percentage, say by 10%, a determination of the corresponding change in yield was made. Results of the sensitivity analysis had, therefore, shown quite useful insight into important factors in determining agricultural productivity and pegged temperature as amongst the crucially significant modifying elements for wheat production output.

The ARIMA model was applied since it best fits the analysis of time series data [73,77]. This model extracted the trends from historical data and projected them over five subsequent years. An ARIMA model has three components: autoregression-AR, differencing to secure stationarity of data-I, and moving average-MA. The model best fit the historical data through procedures that minimized residual errors. The forecasted results for the coming years have been stable and thus indicate relatively good health of the agricultural sector in Poland. K-means clustering method is used to group the voivodeships in order to catch the regional variations in wheat production [75–82]. Data for the analysis were the average yields per hectare and standard deviations of yield for the years 2004–2023. This procedure differentiated three groups of voivodships that characterized each of these groups: high, medium, and low yielders. High-yielding voivodships are characterized by stability in production and good environmental conditions, while in low-yielding ones, higher variability and thus technological and investment support was required.

The ARIMA model was selected for the prediction of Polish wheat yield due to the high capability of the model in performing time series analysis in terms of capturing historical trends and temporal patterns. From past research [83], ARIMA models have been found to perform well in modeling agricultural productivity trends as they are capable of handling non-stationary data through differencing and both autoregressive and moving average terms in mitigating prediction errors. This makes ARIMA a good fit for predicting wheat production whose volatility is exposed to uncertainty in climate, market, and policy interventions. Compared to other advanced machine learning or econometric models, ARIMA does not require comparatively more assumptions and can generate plausible short-term predictions using historical data only, thereby being a practical and interpretable instrument for policymakers and agricultural planners. Its application in this study facilitates evidence-based decision-making by providing standardized yield estimates, allowing the authorities to forecast and plan anticipation strategies against expected production trends as well as future climate-related shocks.

All analyses were conducted using statistical software, STATISTICA 13, and spreadsheets, which allowed for the processing of data with high accuracy and the presentation of results in tables and charts. Also, the Python was used to print graphs and some calculations,

and AI-based Chat GPT was used for translation and language improvement. The obtained results form a very sound basis for the formulation of recommendations to policymakers and farmers on wheat production management, investment in modern technologies, and response to climate change and market demands.

The representativeness and validity of the data used in this paper can be presumed as adequate and reliable based on some critical factors.

The data sources are official and reliable and mainly originate from the Local Data Bank, carried out by Statistics Poland (Główny Urząd Statystyczny—GUS). This institution is the national statistical office of Poland, responsible for the gathering, processing, and dissemination of statistical information at the national and regional levels. Official statistics ensure accuracy, coherence, and comparability over time, and their findings are therefore tangible and credible enough for both policy and scholarly purposes. The data extends over a prolonged period of two decades, from 2004 to 2023. The presence of such a long horizon significantly contributes towards the credibility of the results obtained, since the study manages to encompass both short-run volatility and long-run tendencies.

By using data that spans over two decades, the research properly compensates for the effect of any anomalies or outliers that might have arisen due to some events taking place within a specific year. To this end, conclusions drawn from such data are more solid and reflective of general trends that have been observed in Polish wheat production. The geographical scope of the data tremendously increases its representativeness. The data have highly detailed observations across all of Poland's sixteen voivodeships.

This broad regional coverage allows for robust spatiotemporal analysis, not only for discerning national averages but also for important regional heterogeneity and features. As regional inequalities are of elementary importance in agricultural studies—particularly in countries like Poland, with non-uniform environmental conditions and varying economic development—the spatial representation of this database greatly increases the external validity and generalizability of the findings. The factors taken into account for analysis—i.e., climatic (temperature and precipitation), economic (production cost and market price), and wheat yield—are established and methodologically consistent. Climatic conditions are broadly confirmed as significant determinants of the productivity of the farm, with high validity due to standardized procedures of measurement across meteorological stations. Economic variables, such as production costs and the price of wheat, are also generally well recorded and publicly verifiable through agricultural market reports as well as official economic data. Methodological care employed in the validation of data further enhances its credibility. Statistical techniques of multiple regression, sensitivity analysis, and ARIMA forecasting models are correctly used in testing relationships between variables, as well as in testing the robustness of findings.

Sensitivity analysis also ensures that important drivers of wheat yield, like temperature and wheat price, respond sensibly as expected under different scenarios and hence re-enforce the internal validity of model findings. Use of cluster analysis in the identification of high-, medium-, and low-performing regions is also an internal validation procedure by way of the confirmation of spatial pattern consistency and logical coherence of wheat yields.

The choice and utilization of methodologies in this paper are methodologically sound and appropriate, with a solid analytical framework that can cover the research objectives exhaustively. The methodologies used—spatiotemporal analysis, multiple regression modeling, sensitivity analysis, ARIMA forecasting, and k-means clustering—are complementary, established, and tested in agricultural economics, environmental science, and regional analysis. Their use can be justified on many counts.

Spatiotemporal analysis is particularly suited to investigating agricultural productivity over time and across geographic areas. For Polish wheat cultivation, it is necessary to capture spatial and temporal trends given the wide range of variation in climatic conditions, soil fertility, and economic conditions across the voivodeships of Poland. This not only provides an overall view of trends but also delineates regional disparities and their determinants very clearly. This approach is on par with the highest standards of farm geographical levels and is applied widely in research on the complex interactions between environmental factors, agriculture, and economics.

Multiple regression analysis is a highly appropriate and extensively usable statistical method for the identification and measurement of independent–dependent variable relationships. The yield in wheat is a dependent variable induced by climatic variables (precipitation and temperature) and economic variables (production cost and market price). Regression analysis can determine the individual and combined effects of such determinants on yield with easy and interpretable results. Additionally, multiple regression is strict in measuring the significance of each variable statistically and controlling the simultaneous influence of two or more variables, resulting in more reliable and valid findings.

The methodological quality of the study is greatly enhanced through the inclusion of sensitivity analysis. Sensitivity analysis formally addresses the effect of variation in key input variables on the predictions of wheat yield, checking the robustness of the regression model's results under different conditions. The application of this approach is crucial for an estimation of the resilience and vulnerability of wheat production to changes in climatic and economic conditions. It also makes the study more credible by making it clear how sensitive the results are to alterations in the fundamental assumptions, which is regarded as best practice for agricultural and environmental studies.

The use of the ARIMA forecasting method is highly suitable for the aim of short- to medium-term yield prediction. The method has already been firmly established in the application of models to the analysis of time series data, especially in agricultural uses that would entail possible trends and seasonality in yield data. The ARIMA model is convenient in that it does not depend on exogenous assumptions and therefore is well suited to simple but powerful projections that are exclusively grounded in historical yield facts. Its application in this report is stringent due to the proper handling of the problems of stationarity, which ensures that the forecasts generated are statistical and methodological. ARIMA modeling is properly defined, rigorously tested, and validated in farm yield prediction research, which shows its feasibility.

In the Jia et al. [84] paper, the ARIMA model is employed because of its ability to successfully simulate and predict time series data, especially when one has a lot of historical data but lacks clear explanatory models connecting prediction variables to other variables. The ARIMA model is superior to more straightforward techniques, such as linear regression or simple trend extrapolation, since it handles non-stationary data efficiently by differencing, and both autoregressive and moving average processes, hence providing flexibility and accuracy. In our work the ARIMA model is used because of its high applicability in analyzing and forecasting time series data, especially agricultural harvests, where historical trends and temporal relationships need to be captured. ARIMA is able to incorporate non-stationary data using differencing, autoregression, and moving averages and therefore allows accurate short- to medium-term forecasting purely based on past data without complicated assumptions. It is very useful in agricultural research, as the variability of the climate, fluctuations in the market, and policy shocks can influence production. By using ARIMA, this study provides policymakers and agricultural planners with reliable forecasts, aiding informed decision-making aimed at enhancing resilience and sustainability in wheat production.

The use of the k-means clustering approach is methodologically suitable for classifying areas into groups of similarities and differences in wheat yield. Clustering enables the researchers to classify voivodeships objectively into high-, medium-, and low-yield groups, which makes policy interventions and resource distribution easier and more focused. This method is thorough in terms of being able to identify natural clusters in data, unveiling patterns that may not be immediately apparent. Furthermore, the method is valid and has been validated by its continuous application in regional studies and agronomic studies, where clustering based on productivity and variability is important in offering region-specific agrarian policies.

The Fixed Effects Model (FEM) method employed here adds to the literature on the determinants of wheat yields in different Polish voivodeships by addressing unobserved heterogeneity so effectively. The FEM is particularly valuable in the instance of panel data where data are collected on a number of entities (regions) and perhaps across different time periods. By incorporating province fixed effects, the model accounts for the time-invariant individual characteristics of each voivodeship that can exert a strong influence on agricultural outcomes but remain constant over time, e.g., the fertility of soil, land topology, and regional agricultural traditions [85].

In this FEM application, this research explicitly acknowledges the existence of some unmeasured variables with substantial effects on wheat productivity that take on a constant value for every region [86]. Such region-specific variables, possibly unobservable in cross-sectional data, will bias the relations between observable explanatory variables (e.g., rainfall, temperature, GDP per capita, wheat price, and production costs) and wheat yields if not accounted for. By incorporating fixed effects for every province the analysis therefore controls for these unmeasurable aspects, allowing one to more readily identify how observable variables separately influence yields.

The FEM's benefit here is that it can handle omitted variable bias, the common curse of cross-sectional analysis. By accounting for province-specific effects, the model ensures that the estimated effects of independent variables on yields are not biased due to the exclusion of constant regional variables. This enhances the credibility and reliability of the results, so that stakeholders can confidently make decisions and policy interventions based on the results.

3. Results

3.1. Wheat Cultivation Area in Poland

Tables 2 and 3 present the changes in areas under wheat cultivation in Poland for two successive decades. The data are presented in hectares and differentiated by voivodships: "Wheat Cultivation Area in Poland from 2004 to 2013" and "Wheat Cultivation Area in Poland from 2014 to 2023" [87].

Over the period of 2004–2023, the area under wheat cultivation in Poland demonstrates certain fluctuations, likely influenced by variable climatic conditions, agricultural policy, and the profitability of wheat farming. From 2004 to 2013, the total cultivation area varied from 2.1 million hectares in 2012 to 2.3 million hectares in both 2004 and 2009. In contrast, for the period from 2014 to 2023, slightly higher values are recorded, with a record of 2.5 million hectares in 2022. The overall trend is that the areas allocated for wheat cultivation have remained rather stable, with a slight upward tendency in the second decade.

From the regional analysis, the area of cultivation is visibly differentiated. Voivodeships such as Lublin, Lower Silesia, Kujawy–Pomerania, and Wielkopolskie are constantly ranked among the largest for two decades and have an area up to 300,000 hectares in some years. The voivodeships of Podlaskie and Lubuskie are characterized by the

smallest cultivation areas, the annual dynamics reaching from approximately 40,000 to 70,000 hectares.

Table 2. Wheat cultivation area in Poland (2004–2013) [ha].

Province	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Lower Silesia	282,508	260,859	260,458	259,339	257,134	280,184	258,374	258,373	238,600	262,535
Kuyavia–Pomerania	182,200	180,165	163,239	165,329	191,868	196,409	190,848	194,765	146,352	198,255
Lublin Province	267,373	264,002	261,621	273,082	298,339	303,183	261,865	299,575	277,849	271,603
Lubusz Province	60,715	63,069	60,324	58,414	66,584	62,986	56,514	66,992	62,038	51,301
Lodz Province	89,664	87,777	87,290	84,801	100,420	98,105	90,672	107,593	85,459	103,875
Lesser Poland	111,423	104,648	102,807	102,848	111,462	111,231	86,633	100,529	90,957	87,933
Masovia	134,181	135,477	151,875	129,446	130,492	139,318	127,116	105,529	149,851	143,325
Opole Province	152,595	152,264	147,055	142,560	160,305	158,910	148,619	158,833	145,043	146,224
Subcarpatia	125,030	128,230	123,783	111,373	130,055	135,880	93,494	102,530	107,235	93,237
Podlasie Province	43,217	39,286	39,640	37,021	41,964	42,909	37,614	41,840	42,298	40,271
Pomerania	146,120	132,758	130,800	129,239	128,499	133,978	135,853	132,506	136,392	138,828
Silesia	60,867	62,982	59,045	58,350	62,665	66,931	66,245	69,781	59,824	62,261
Holy Cross	81,851	72,974	73,922	70,241	72,417	77,095	68,973	69,543	71,206	76,750
Warmia–Masuria	157,964	136,232	127,503	122,276	137,797	142,353	143,750	157,659	150,458	127,368
Greater Poland	217,511	193,665	186,232	181,174	200,357	215,217	208,034	211,675	156,093	197,694
West Pomerania	197,523	203,705	200,131	186,489	187,596	181,528	166,939	180,989	157,550	136,408
Polska	2,310,742	2,218,093	2,175,725	2,111,982	2,277,954	2,346,215	2,141,543	2,258,712	2,077,206	2,137,868

Source: on the basis of data from [69].

Table 3. Wheat cultivation area in Poland (2014–2023) [ha].

Province	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Lower Silesia	275,790	277,768	287,350	263,138	249,647	273,256	255,775	248,510	265,880	249,972
Kuyavia–Pomerania	219,576	219,264	219,687	212,427	249,233	220,219	215,300	214,771	227,481	231,150
Lublin Province	281,647	310,011	313,255	322,387	319,654	344,700	325,658	318,209	329,753	313,475
Lubusz Province	57,434	50,028	53,572	56,429	52,105	60,549	49,727	54,203	58,105	55,842
Lodz Province	110,913	119,944	109,348	123,328	110,409	113,904	109,270	112,765	121,528	115,944
Lesser Poland	89,839	94,774	91,662	91,928	96,722	103,091	104,673	90,210	98,687	95,431
Masovia	169,129	180,387	156,697	171,758	172,193	182,416	171,026	170,368	177,071	170,383
Opole Province	150,012	149,151	164,526	151,083	140,470	153,006	152,500	147,569	154,878	155,529
Subcarpatia	98,274	100,057	94,639	97,260	90,799	99,488	103,670	92,957	101,565	93,584
Podlasie Province	46,340	52,680	50,106	54,504	48,624	88,105	48,396	51,364	60,638	61,845
Pomerania	150,623	153,735	154,173	159,952	174,418	165,130	160,689	169,150	166,520	168,683
Silesia	68,500	65,696	67,799	71,482	69,665	68,869	68,659	61,811	66,147	65,373
Holy Cross	79,387	76,856	76,071	85,062	76,843	85,002	92,481	89,675	98,225	95,894
Warmia–Masuria	145,111	150,888	157,885	143,231	156,333	147,440	151,053	180,314	184,478	182,827
Greater Poland	245,367	230,101	220,120	211,454	236,706	233,394	230,641	230,777	248,626	239,144
West Pomerania	150,841	164,111	167,126	176,430	173,406	172,759	151,478	157,871	158,862	154,254
Polska	2,338,782	2,395,451	2,384,016	2,391,853	2,417,227	2,511,328	2,390,996	2,390,524	2,518,444	2,449,329

Source: on the basis of data from [69].

The years 2014–2023 are characterized by more stable and slightly higher values than during the previous decade, which can evidence the better adaptation of agriculture to the challenges connected with the efficiency of production and EU support. Distinctive increases in the areas under cultivation can be seen in voivodeships such as Lublin and

Greater Poland. On the other hand, regions like Subcarpathia and Silesia present stagnation or even slight decreases, which may testify to the marginalization of agriculture for the benefit of other economy branches.

Data on wheat cultivation areas in Poland, for the years 2004 to 2023, reflect interesting trends at both the national and regional levels. At the national level, the first decade shows relative stability of the areas under cultivation, with minor fluctuations between years. Total cultivation ranged between 2.1 and 2.3 million hectares, peaking in the years 2004, 2009, and 2011. The second decade, which involves the period from 2014 to 2023, follows a slightly increasing trend, reaching a record value of 2.5 million hectares attained in the year 2022. Such an increase may be the effect of the increased profitability of wheat production, EU agricultural support, and strategic changes in farming practices due to increasing demand for farm products.

As it can be seen, there are striking regional differences in cultivation areas. The voivodeships such as Lublin, Lower Silesia, Kuyavia–Pomerania, and Greater Poland have appeared at the top of the ranking every year with regard to areas intended for wheat cultivation. The favorable soil and climatic conditions in these voivodeships allow intensive farming there. In the Lublin voivodeship, this dynamic is particularly visible—the areas there exceed 300,000 hectares in every year of the second decade. Voivodeships with more favorable conditions, such as Podlaskie, Lubusz, and Silesia, contribute little to the nationwide production of wheat because of unfavorable natural conditions and also due to the decreased role of agriculture in their economies.

Naturally, within each voivodeship over the years, there are striking fluctuations. An example is the extreme decreases in Lower Silesia and Greater Poland between 2010 and 2012; these may have been influenced by local conditions, such as droughts, plant diseases, or changes in crop structure. In regions such as Lubusz, where wheat cultivation areas are among the smallest, changes within the period of 2004–2023 were not so salient, while the average area oscillated between 50,000 and 60,000 hectares. In Silesia, for example, there is marginal farming activity alongside most other industrial-type activities.

Generally speaking, wheat production in Poland remains the backbone of the agricultural economy and is characterized by large-scale regional diversity. The data underline how local conditions and agricultural policy are fundamental factors in defining the structure and scale of crops produced within the country. In this respect, recent years have shown stability and growth in cultivation areas, underlining increased professionalization within the agriculture sector and reduced risks in crop production.

3.2. *Wheat Yield per Hectare in Poland*

Tables 4 and 5 show the wheat yields per hectare in Poland for the years 2004–2013 and 2013–2023, respectively, with some productivity trends at both the regional and national levels. Yield data underline significant differences among voivodeships and show an upward trend in general during the second decade.

At the country level, yield has increased from 42.8 dt/ha to 53.8 dt/ha between the years 2004 and 2023, respectively. The yields were more irregular during the first decade, mostly owing to adverse meteorological conditions. For instance, in the year 2006, the crop yield went as low as 32.4 dt/ha. Correspondingly, the second decade turned out to be more stable with higher values due to the advance of cultivation technologies, modern wheat varieties, and more effective management of water and fertilizers. Record values in 2023 testified to the growth in the efficiency of Polish agriculture.

Table 4. Wheat yield per hectare in Poland (2004–2013) [dt].

Province	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Lower Silesia	48.7	46.4	35.5	43.4	45.5	45.0	51.3	48.1	44.8	48.6
Kuyavia–Pomerania	45.4	39.7	37.1	43.0	41.6	44.6	44.7	43.4	41.3	48.6
Lublin Province	35.3	33.9	26.3	33.5	38.0	35.0	37.2	36.2	36.1	36.6
Lubusz Province	42.4	37.2	25.1	34.4	32.8	44.6	45.5	34.1	43.2	53.0
Lodz Province	36.5	33.2	27.9	36.4	34.1	37.9	38.5	38.6	33.6	36.6
Lesser Poland	34.0	34.4	25.0	33.3	34.9	32.7	32.0	35.2	36.1	33.7
Masovia	36.1	33.7	27.3	33.1	35.3	34.9	34.6	32.2	35.2	36.6
Opole Province	56.0	52.7	42.1	52.2	58.3	52.4	54.8	58.1	59.7	56.4
Subcarpatia	34.3	30.7	27.4	33.0	34.9	33.1	37.7	32.9	35.2	33.4
Podlasie Province	30.7	30.4	24.5	29.5	31.0	30.8	33.4	30.4	32.6	33.0
Pomerania	47.1	45.0	42.5	45.9	46.3	48.3	47.5	48.1	48.2	52.9
Silesia	42.6	37.0	29.6	38.7	41.3	38.0	35.7	42.2	40.4	41.2
Holy Cross	31.8	30.0	21.9	32.0	35.7	32.8	28.0	31.3	31.4	31.2
Warmia–Masuria	43.3	38.7	36.4	40.8	43.2	41.9	49.0	42.0	44.0	45.5
Greater Poland	48.5	43.8	34.6	43.4	39.0	47.0	45.8	41.1	40.7	48.9
West Pomerania	47.3	42.5	35.9	39.5	40.2	50.1	54.4	41.9	45.7	53.5
Polska	42.8	39.5	32.4	39.4	40.7	41.7	43.9	41.3	41.4	44.4

Source: on the basis of data from [69].

Table 5. Wheat yield per hectare in Poland (2014–2023) [dt].

Province	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Lower Silesia	54.0	51.9	52.7	53.8	45.0	47.1	56.2	52.5	52.2	54.2
Kuyavia–Pomerania	52.4	45.4	43.0	50.2	38.3	44.8	57.4	52.5	56.3	55.5
Lublin Province	45.6	44.1	49.4	52.4	47.1	47.5	57.4	56.6	54.0	57.8
Lubusz Province	54.5	43.8	45.8	48.3	31.1	35.4	47.3	45.5	44.5	46.4
Lodz Province	43.9	36.3	35.2	42.6	34.9	34.6	52.3	45.5	49.9	46.1
Lesser Poland	39.0	35.8	39.4	41.1	38.0	38.5	42.9	42.7	51.1	52.5
Masovia	38.9	32.4	34.7	36.8	32.0	34.9	43.9	43.5	43.3	42.9
Opole Province	65.7	58.4	59.6	62.9	55.7	60.2	62.3	63.1	68.0	71.2
Subcarpatia	37.6	35.5	35.5	38.5	37.3	36.9	39.8	40.7	43.9	47.7
Podlasie Province	36.1	32.6	32.1	34.4	28.7	30.0	44.0	39.8	44.1	43.9
Pomerania	57.6	55.3	48.3	54.4	45.6	52.9	63.1	59.4	58.1	57.0
Silesia	48.4	43.5	47.3	48.2	43.0	42.9	52.0	49.2	50.9	52.3
Holy Cross	37.4	34.5	33.1	36.0	33.9	33.1	37.4	38.2	42.7	45.8
Warmia–Masuria	48.2	49.1	42.1	46.5	38.0	46.1	55.8	48.4	60.1	52.7
Greater Poland	52.1	47.5	46.3	50.5	38.6	41.3	55.1	53.5	55.3	57.1
West Pomerania	59.6	57.5	48.2	52.0	37.2	47.0	52.7	46.2	55.9	52.1
Polska	49.7	45.7	45.4	48.8	40.6	43.9	53.3	50.7	53.4	53.8

Source: on the basis of data from [69].

For example, the yield in Opole increased from 56.0 dt/ha in 2004 to the record figure of 71.2 dt/ha in 2023, placing this region in first place regarding wheat production efficiency. On the other hand, less favorable areas, like Podlasie, Holy Cross, and Subcarpathia, remain on a less advantageous yield level, even though increases are present. Indeed, this is a very good example of Holy Cross as a region where yields in general increased from 31.8 dt/ha for 2004 to 45.8 dt/ha for 2023.

The year-to-year oscillation of yields may be due to different climatic conditions, differential technological availability, or modified agricultural policy. For instance, in 2006 and 2018, due to unfavorable weather conditions, the yield was lower for nearly all the varieties, while growth was observable between 2020 and 2023 despite global challenges linked to the pandemic and climate change—a reflection of the enhanced resilience within the Polish farming sector. In the case of other regions, for example Lublin, Kuyavia–Pomerania, and Greater Poland, the table yield decrease was not indicated within the period in question. Most probably, it is the result of the better adjustment of cultivation technologies and methods to local conditions.

3.3. Additional Data

Table 6 presents the differentiated climatic and economic as well as production cost conditions in the voivodeships that may have an influence on wheat cultivation efficiency. Annual rainfall and average annual temperature present regional variation in natural conditions. At the same time, Lesser Poland and Subcarpatia receive substantially more rainfall in the range of 600–700 mm per year, which, as such, should contribute to agricultural production simply by ensuring water supplies. Somewhat less rainfall reaches no more than 500–550 mm in Kuyavia–Pomerania and Masovia, which can make farming more sensitive to droughts, thus diminishing otherwise possible output.

Table 6. Climate, economic, and production variables by region in 2023.

Province	Annual Rainfall (mm)	Avg. Temperature in During Wheat Cultivation (°C)	Avg. Annual Temp (°C)	GDP Per Capita (EUR)	Wheat Price (EUR/t)	Production Cost (EUR/ha)
Lower Silesia	550–600	14	8.5–9.0	21,111.11	211.11	1777.78
Kuyavia–Pomerania	500–550	13	8.0–8.5	15,311.11	208.89	1755.56
Lublin Province	550–600	13	8.0–8.5	13,822.22	204.44	1733.33
Lubusz Province	550–600	14	8.5–9.0	14,444.44	213.33	1800.00
Lodz Province	500–550	13	8.0–8.5	18,222.22	206.67	1744.44
Lesser Poland	600–700	13	8.0–9.0	17,977.78	202.22	1711.11
Masovia	500–550	13	8.0–8.5	14,622.22	204.44	1733.33
Opole Province	550–600	14	8.5–9.0	14,755.56	211.11	1766.67
Subcarpatia	600–700	13	7.5–8.0	13,444.44	200.00	1688.89
Podlasie Province	500–550	12	7.0–7.5	14,244.44	204.44	1711.11
Pomerania	600–650	13	8.0–8.5	19,022.22	211.11	1777.78
Silesia	550–600	14	8.5–9.0	19,377.78	208.89	1755.56
Holy Cross	550–600	13	8.0–8.5	14,088.89	202.22	1711.11
Warmia–Masuria	600–650	12	7.5–8.0	13,600.00	208.89	1733.33
Greater Poland	500–550	14	8.5–9.0	21,000.00	213.33	1800.00
West Pomerania	600–650	13	8.5–9.0	15,888.89	211.11	1777.78

Source: on the basis of data from [69–72].

Other economic indicators show big regional differences, such as GDP per capita. The highest values of GDP per capita were recorded by Lower Silesia (EUR 21,111) and Greater Poland (EUR 21,000) which can evidence higher investment potential for agricultural technologies. In contrast, the lowest levels of GDP per capita were registered in Subcarpatia (EUR 13,444) and Lublin Province (EUR 13,822) which can reduce the development of agriculture in the above regions and, in this way, influence the efficiency of production.

Within the voivodeships, wheat prices are rather homogenous, between EUR 200/t in Subcarpatia and EUR 213.33/t in Greater Poland and Lubusz Province. Production costs also remain close, ranging from EUR 1688/ha in Subcarpatia to EUR 1800/ha in Lubusz

Province and Greater Poland. The more intensive farming practices, together with the better financial capability of farmers, could be reflected in the higher production costs in the west.

4. Discussion

4.1. Trend Analysis

The territorial dynamics of change in the areas of wheat crops in Poland within 2004–2023 are presented below by region. In general, wheat is important for the country's agricultural economy, though with different changes in areas across the voivodeships. The voivodeships that are characterized by large cultivation areas and a positive trend of change throughout the analyzed period include Lublin, Kujawy–Pomerania, and Wielkopolska. On the other hand, regions such as Podlasie, Lubusz, and Silesia present relatively small cultivation areas combined with stagnation or even decreases over the last two decades.

The first decade from 2004 to 2013 was a period of relative stability at the national level, while regional differences were pronounced. In some of the strong agricultural voivodeships, such as Lower Silesia and Kujawy–Pomerania, area changes were small, probably because of very good soil conditions and long-lasting traditions in agriculture. In the case of marginal agricultural regions, such as Lubusz and Silesia, decreases in the area of cultivation could be a consequence of poor natural conditions and/or the development of other sectors of the economy.

That upward national trend became more obvious throughout the second decade, from 2014 to 2023, and results from the increased agricultural efficiency relevantly supported by agricultural policy (Figure 1). A high growth dynamic has characterized just these two regions—Lublin and Kujavia–Pomerania—with great increases in the wheat cultivation areas. Of all those above-mentioned voivodeships with area increases over 30,000 ha compared to the beginning of this decade, such a position is held by Lublin. While Lower Silesia and Greater Poland have been dominated in recent years, they present only a moderate decline in the years 2014–2023 which may hence reveal local difficulties or changes within crop structures.

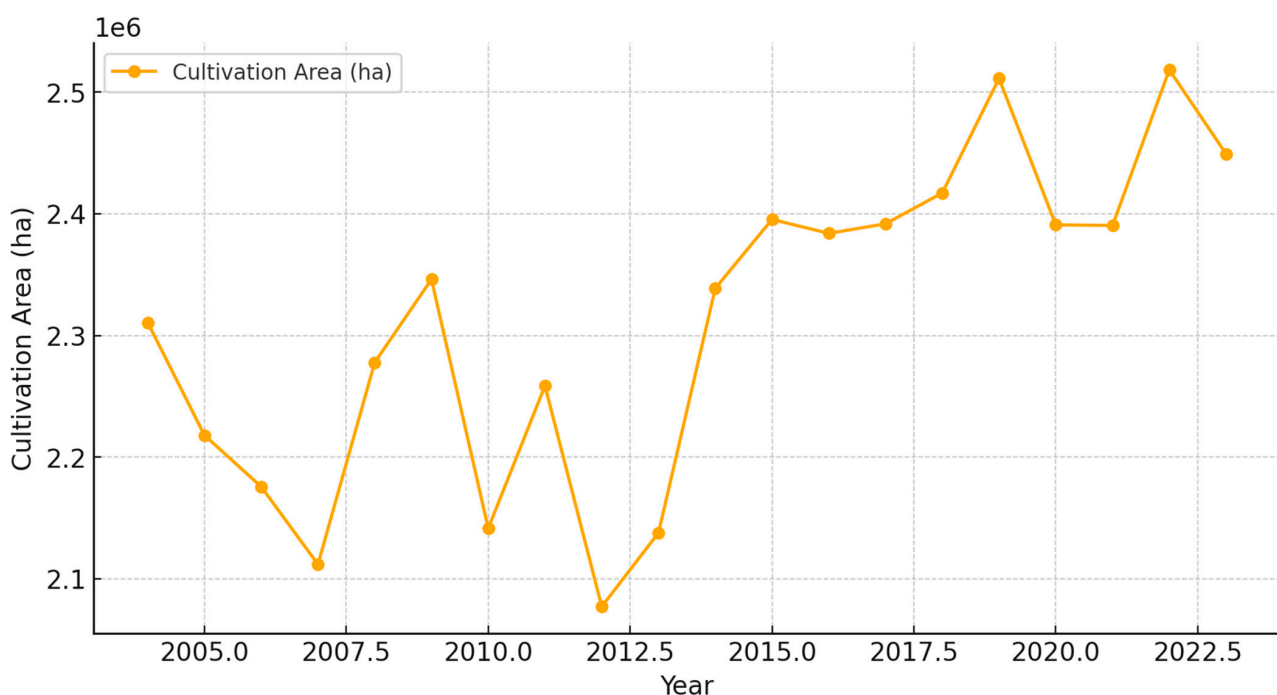


Figure 1. Trends of wheat cultivation area in Poland (2004–2023).

The largest growth in area within the period considered, 2004–2023, occurs in the Kujawsko–Pomorskie and Lubelskie voivodeships, confirming their growing importance in wheat production. This may be due to the exceptionally favorable natural conditions that have occurred along with the introduction of modern agricultural technologies and support by European Union programs. On the other hand, some voivodeships lost a part of their wheat cultivation areas, which confirms the continuing marginalization of agriculture in these regions.

Temporal trends in wheat area and yield per hectare in Poland within the period 2004–2023 may provide insight into the changeability of agriculture based on quantitative and efficiency aspects (Figure 2).

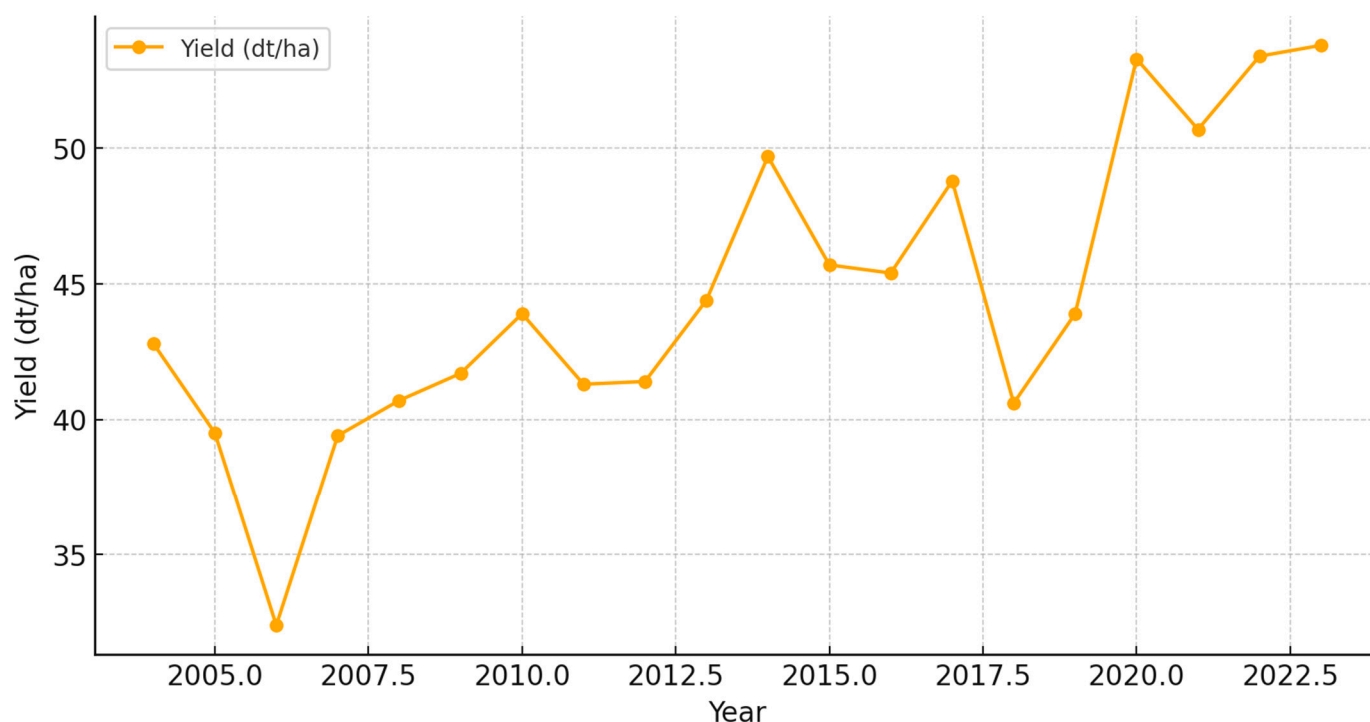


Figure 2. Trends of wheat yield per hectare in Poland (2004–2023).

Wheat area cultivation during the first decade, from 2004 to 2013, showed a relatively stable position of the cultivated area, ranging from approximately 2.1 million to 2.3 million hectares. However, there were also fluctuations, likely because of bad weather conditions, changes in agricultural policy, or variability in the profitability of wheat farming in specific years. In the second decade, 2014–2023, the growth became more pronounced and reached a historical height of 2.52 million hectares in 2022. Such a trend could be explained by EU support, improved efficiency in agricultural land management, and a growing demand for wheat both at the domestic and international levels. However, such a decline in 2023 would likely indicate that there are some challenges, such as climate change; thus, a closer look may be warranted.

Yield per hectare also depicts a well-marked upward trend in the past two decades, although with more oscillations in their variation. In the first decade, 2004–2013, average yields reached a high of 4 tons per hectare. The biggest yield oscillations occurred in the year 2006, when the yield dropped to 3.24 tons per hectare, following very bad weather conditions. One can observe a much higher stability in the second decade, with a gradual growth of effectiveness. Record results were achieved during the period 2022–2023 at an average of 5.38 tons per hectare. It certainly reflects the improvement of agricultural

technology, the introduction of varieties of wheat that ensure higher yields, and better management of water and fertilizers.

The latter trends unmistakably show that Polish agriculture is highly enriched in terms of wheat production efficiency. The addition of areas and the increasing yield trends underline the professionalization of agriculture and its modernization to answer current and future challenges. Nevertheless, climate change and/or market volatility remains a possible factor for perturbing this stability in the coming years. Determining the causes for declines in particular years and devising adaptive strategies will be needed to ensure that a positive trend is maintained over the long run.

Variations in the yield of wheat in various regions of Poland are mainly accounted for by climatic, soil quality, and support and technology levels. The regions of Opole, Pomerania, and Lower Silesia always possess greater yields due to their agreeable climatic conditions with mild temperatures and ample rainfall, in addition to the rich soil providing required nutrients to wheat plants for growth. Such regions also have enhanced access to innovative agricultural inputs, efficient farm management practices, and EU subsidies to facilitate investment in precision agriculture and irrigation infrastructure. The concentration of such inputs allows farmers in these areas to achieve consistent yields and deal with climate fluctuation more effectively; hence, they are more productive compared to other areas in the country.

Regions such as Podlasie, Subcarpathia, and parts of the Holy Cross province face more issues with wheat production due to less favorable environmental and economic conditions. Poor-quality soil, with lower organic content and worse water retention capabilities, reduces productivity, and harsher climatic conditions, such as lower mean temperatures and higher susceptibility to extreme weather conditions, lower yields as well. Moreover, the majority of such regions receive less policy attention, lacking adequate investments in new infrastructure related to farming, and enjoy relative policy discrimination from high-performing regions. For farmers in these regions, the limited access to advanced agriculture practices and money hampers their ability to be resistant to climatic risks as well as make crops more stable in terms of output. Synthesizing these differences more naturally captures the manner in which Poland's wheat output is determined by natural and structural factors, calling for targeted interventions for productivity gains in backwater areas.

The trend analysis presented in this paper depicts the dynamics of wheat cultivation in Poland from a sustainability perspective and shows how environmental, economic, and policy factors interact over time. It follows that, while the total wheat cultivation areas have increased slightly, there is considerable regional variation. High-performing regions, such as Opole and Kujawy–Pomerania, enjoy favorable conditions and modern technologies, while regions such as Podlasie and Subcarpathia suffer from unfavorable conditions related both to poorer soil quality and limited access to technological innovations. These regional disparities make strikingly evident the urgent need for proportionate interventions to support those that lag behind and ensure truly equal opportunities for agricultural development—the guarantee of sustainability in food production.

This study underlines that the dual effect of climate change in view of sustainability shows two directions from the environmental perspective: on the one hand, increasing temperatures and precipitation fluctuation bring both positive and negative influences; longer active growth seasons increase production in some places, but result in heat stress in others. All this brings serious challenges that are expected to be answered through sustainable agricultural techniques, such as crop rotation, soil conservation, and the development of drought-resistant varieties. In addition, the enhancement of irrigation systems in susceptible regions would stabilize yield and contribute toward long-term resilience against climate variability.

Economic analysis has underlined the importance of production costs and market prices in determining wheat yields. High costs are a deterrent to adopting advanced technologies, while remunerative wheat prices encourage better resource allocation and productivity. This study urges strategic policymaking aimed at stable market conditions, financial support for modernization, and targeted subsidies for regions with low productivity. Both those, together with several environmental factors, indicate that Poland can encourage a more competitive and sustainable system of wheat production, contributing significantly toward ensuring food security and agricultural resilience.

4.2. Model for Analyzing the Impact of Environmental (Rainfall and Temperature) and Economic (Production Costs and Wheat Price) Factors on Wheat Yields

The multiple regression model applied to analyze the impact of six variables on wheat yield in 2023 demonstrates a moderate ability to explain yield variability ($R^2 = 0.411$).

Interpretation of Regression Results: (See Table 7).

Table 7. Model parameters.

Parameter	Coefficient	Standard Error	t-Value
Intercept	−34.0874	139.012	−0.245
Annual Rainfall (mm)	0.0196	0.045	0.436
Avg Temp Wheat Cultivation (°C)	3.0191	5.687	0.531
Avg Temp (°C)	6.1842	10.045	0.616
GDP Per Capita (EUR)	−0.0002	0.001	−0.185
Wheat Price (EUR/t)	2.8947	1.909	1.516
Production Cost (EUR/ha)	−0.3517	0.286	−1.229

- The intercept (−34.0874)—the negative value suggests that if all explanatory variables were zero, the wheat yield would be negative;
- Annual rainfall (coef: 0.0196)—an increase in rainfall by 1 mm is associated with a slight increase in yield by 0.0196 dt/ha;
- Average temperature during cultivation (coef: 3.0191)—an increase in the average temperature during the growing season by 1 °C increases the yield by 3.02 dt/ha;
- Average annual temperature (coef: 6.1842)—a higher annual temperature may contribute to increased yields;
- GDP per capita (coef: −0.0002)—the surprisingly low impact suggests that the wealth level of a region does not have a significant effect on wheat yield;
- Wheat price (coef: 2.8947)—an increase in the wheat price by 1 EUR/t is associated with a higher yield of 2.89 dt/ha;
- Production cost (coef: −0.3517)—higher production costs are negatively correlated with yields, which may result from more challenging growing conditions in certain regions.

Among climatic factors, total rainfall per year has a very minimal positive impact on yields, i.e., more rainfall may have helped to produce more harvests, but the impact is not statistically significant. Mean temperature during the growing season and mean temperature per year have greater influence but are also not statistically significant. This may be an indication that the impact of temperature on yields is controlled by more complex parameters, such as rainfall distribution or the length of growing season.

In the economic analysis, per capita GDP does not appear to be a significant factor in the determination of wheat yields. This may be because yields are more dependent on technological and natural parameters than on the overall wealth status of a region.

Wheat price, on the contrary, has a positive relationship with yields, which could imply that increased prices will encourage farmers to adopt more intensive farming methods. The relationship is, however, not strong enough to qualify as statistically significant.

There is an inverse relationship between yields and production costs where increased production costs can lead to decreased harvests. Therefore, regions with increased production costs most likely possess inferior soil quality or extremely demanding inputs in the utilization of such lands, leading to less productive farming activities.

The sensitivity analysis tests how the changes in individual parameters affect the estimated 2023 wheat yield changes (Table 8). Initially, the outcomes took into account yearly precipitation, mean temperature during the wheat growing season, mean temperature, GDP per capita, wheat price, and production cost. All of these have been subjected to -20% , -10% , 0% , $+10\%$, and $+20\%$ changes to determine the effects on projection yields.

Table 8. Sensitivity analysis.

Variable	Change (%)	New Value	Predicted Yield
Annual Rainfall (mm)	−20	462.5000	49.932641
Annual Rainfall (mm)	−10	520.3125	51.066321
Annual Rainfall (mm)	0	578.1250	52.200000
Annual Rainfall (mm)	10	635.9375	53.333679
Annual Rainfall (mm)	20	693.7500	54.467359
Avg Temp Wheat Cultivation (°C)	−20	10.4	49.560568
Avg Temp Wheat Cultivation (°C)	−10	11.7	50.880284
Avg Temp Wheat Cultivation (°C)	0	13.0	52.200000
Avg Temp Wheat Cultivation (°C)	10	14.3	53.519716
Avg Temp Wheat Cultivation (°C)	20	15.6	54.839432
Avg Temp (°C)	−20	6.2	49.035734
Avg Temp (°C)	−10	7.0	50.617867
Avg Temp (°C)	0	7.7	52.200000
Avg Temp (°C)	10	8.5	53.782133
Avg Temp (°C)	20	9.2	55.364266
GDP per capita (EUR)	−20	13,488.8889	52.203690
GDP per capita (EUR)	−10	15,100.0000	52.201845
GDP per capita (EUR)	0	16,711.1111	52.200000
GDP per capita (EUR)	10	18,322.2222	52.198155
GDP per capita (EUR)	20	19,933.3333	52.196310
Wheat Price (EUR/t)	−20	166.6667	50.621051
Wheat Price (EUR/t)	−10	187.5000	51.410526
Wheat Price (EUR/t)	0	208.3333	52.200000
Wheat Price (EUR/t)	10	229.1667	52.989474
Wheat Price (EUR/t)	20	250.0000	53.778949
Production Cost (EUR/ha)	−20	1386.6667	53.071846
Production Cost (EUR/ha)	−10	1560.0000	52.635923
Production Cost (EUR/ha)	0	1733.3333	52.200000
Production Cost (EUR/ha)	10	1906.6667	51.764077
Production Cost (EUR/ha)	20	2080.0000	51.328154

The research shows that an increase in rainfall by 20% per annum leads to a rise in the estimated yield from 52.2 dt/ha to 54.47 dt/ha while a decrease in rainfall by 20% drops the estimated yield to 49.93 dt/ha. This is indicative of a positive, though relatively small,

effect of rainfall on yield. Similarly, a 20% rise in the mean temperature of growth (from 13 °C to 15.6 °C) raises the yield estimate to 54.84 dt/ha, while a 20% fall in temperature lowers the yield to 49.56 dt/ha, showing that temperature during the growing season is a significant determinant of wheat yields.

Mean annual temperature also affects yields, though less than rainfall. A 20% increase increases the yield to 55.36 dt/ha, while a 20% reduction lowers it to 49.03 dt/ha. This may be due to a longer growing season in a warmer climate. On the other hand, GDP per capita does not play any meaningful role in affecting the yield because a 20% increase or decrease only brings about negligible changes in the estimated yield, thus showing that local prosperity is not a crucial determinant in wheat production efficiency.

Wheat price is positively related to yields—a 20% price rise leads to an expected yield of 53.77 dt/ha, while a 20% price fall reduces it to 50.62 dt/ha. This is an indication that higher prices could encourage farmers to adopt more intensive methods of production. Production expenses act in the opposite direction—a 20% price rise reduces yields to 51.32 dt/ha, while a 20% price fall increases yields to 53.07 dt/ha. This would imply that higher costs are more likely to result in less production or more stressful growing conditions.

MANOVA was initially contemplated to determine the determinants that significantly affect wheat yield per hectare. As MANOVA requires a number of dependent variables and wheat yield was the only dependent variable in this study, another technique incorporating one-way ANOVA was utilized to determine the determinants of yield variation. The results of the ANOVA tests are revealing in determining which independent variables play a significant role in wheat production in Poland.

The ANOVA result (Table 9) shows that wheat price has the highest value of F-statistic, i.e., wheat price is the most influential variable to explain variations in yield. A high value of F-statistic means the differences in wheat yield between different categories of wheat price are significant statistically. The *p*-value is very small for wheat price, which confirms the relationship is extremely significant. This finding implies that increased wheat prices can prompt farmers to practice improved agriculture, purchase good-quality seeds, fertilizers, and other inputs, thus raising output. Alternatively, wheat price can be a proxy for the overall market conditions influencing farm profitability and investment in productive capacity.

Table 9. ANOVA analysis.

Variable	F-Statistic	<i>p</i> -Value
Annual Rainfall (mm)	2085.1746	2.749×10^{-29}
Avg Temp Wheat Cultivation (°C)	487.9836	4.111×10^{-20}
Avg Temp (°C)	619.9970	1.356×10^{-21}
GDP Per Capita (EUR)	581.2333	3.417×10^{-21}
Wheat Price (EUR/t)	5749.8003	7.743×10^{-36}

Annual rainfall is another major determinant of wheat yield. The F-statistic for this factor is similarly high, but not as high as that for wheat prices, reflecting a strong though slightly lessened effect. This positive correlation indicates that higher amounts of rainfall will most likely lead to better yields of wheat. This relationship can, however, conceivably not always be linear, such that too much rain can likewise lead to the erosion of soils, nutrient leaching, and increased susceptibility to disease in plants. Therefore, whereas precipitation is paramount, precipitation distribution and intensity also play a huge role. Other research can also explore whether or not there is any threshold rate at which increasing rain is not beneficial or worse, becomes counterproductive.

Mean temperature during the wheat growing period and average yearly temperature also exert a significant statistical influence on the yields of wheat. F-statistics on these variables are of a form in which warmer temperatures are linked to greater yields but perhaps nonlinearly. More warmth can stimulate vegetative growth and lengthen the growth season, but excessive heat stress will damage grain development and the plant as a whole. With Poland's climatic variability, there may be significant spatial variation in the temperature effect so that wheat farming practice will need to adjust to local conditions. Follow-up research can ascertain whether such a temperature effect actually varies significantly by soils and production practices.

The per capita GDP was also discovered to be an important variable affecting wheat yields, although its impact is less so than climatic and price variables. Higher GDP per capita can represent the greater availability of farm infrastructure, high-technology farming, and subsidization of R&D in farming. However, the relatively lower F-statistic of GDP per capita compared to other variables does reveal that the economic growth of a nation is no guarantee for its higher wheat productivity. Agricultural policy, technology uptake, and investment in precision agriculture practices can be more pivotal in dictating levels of productivity than regional prosperity.

The hectare unit cost of production was statistically related to wheat production, yet its F-statistic was smaller than the F-statistics for wheat price, rainfall, and temperature readings. This implies that even though increases in costs sometimes occur as a consequence of more intense and technologically advanced methods in agriculture, they do not automatically lead to corresponding increases in the yield. At times, cost increases may also be indicative of inefficiencies or the use of expensive but poor-quality inputs. The economies of scale may also affect the cost of production and the yield of wheat because bigger farms will likely have reduced costs per unit but varied results in yield based on the scale of management.

4.3. Forecasting Yields per Hectare Using the ARIMA Method

The ARIMA model was developed using the average wheat yields in Poland from 2004 to 2023. The input data contained a single time variable, yield in dt/ha, and respective years. The model was meant to capture the trend and temporal dependencies of the data and predict yields for the next five years: 2024–2028. It applies because the ARIMA model can analyze time series data through autoregression, integration, and moving average.

The configuration of the ARIMA model applied in this paper has, in order, one autoregressive component, one differencing step, and one moving average component while trying to model or describe it. In practice, a statistical method is used to fit the model on historical data such that the residual errors are minimal. Such an approach might result in model parameters reflecting historical data the best, along with good prediction capabilities.

This forecast was obtained for five years, considering the continuity of prevailing trends. The numerical and graphical results from the model facilitate easier interpretation and comparison with the historical data, as reflected in Table 10.

Table 10. ARIMA forecast.

Year	Predicted Yields (dt/ha)
2024	51.670
2025	51.874
2026	51.900
2027	51.903

The ARIMA model was chosen since the data had a trend, which needed differencing for stationarity. The autoregressive component accounts for the dependencies between current and past yield values, while the moving average component mitigates the impact of short-term disturbances and irregularities in the data. Combining these elements allows for an accurate representation of the dynamics within the time series data.

One of the important parameters that has been considered for the model was residual error, the randomness and stationarity of which were verified. The model fitted very well for historical data, according to the residual diagnostic analysis. According to the forecasts of yields until 2024–2028, stability can be expected with regard to its long-term trend, without significant variations.

Its capacity for catching the variability of historical data also makes it suitable for short-run yield forecasting. The ARIMA model assumes time pattern constancy and does not consider outside forces which might come into play, for example, climate change or agricultural policy changes, the presence of which have to be carefully considered when using the results of such a model.

In an ARIMA model, parameters describe autoregression and moving average. Both have been estimated on the basis of the historical data: an autoregression coefficient describing how values from a previous period affect a current outcome, while the moving average coefficient describes the effect of forecast errors of previous periods on a current forecast. Their optimal values were identified in a way to make the forecast error minimal when fitting the model.

The model required one differencing step (I) in the data to make it stationary. This means yield values were changed into differences between consecutive years, allowing the model to better grasp temporal patterns and eliminate the long-term trend that may disrupt forecasts.

Following the general upward trend of the last twenty years, the yield forecast is stabilizing at 51.9 dt/ha for the period 2024–2028. However, in cases of unexpected fluctuation in input data or other exogenous factors, the forecast precision may be reduced for this model.

A key conclusion from the model is that the time trend exerts a strong influence on yields. The differencing of data, captured by the “I” component of the model, represented changes in historical data quite well and led to better forecasts. The stabilization of the predicted values suggests that wheat yields in Poland might remain relatively high, provided environmental and technological conditions do not change dramatically.

Results obtained by the model allow us to make some important conclusions for agricultural policymakers as well as farmers about the stability of wheat production in Poland throughout the next years. The forecast can then be used for agricultural policy planning, including resource management and export strategy. In any case, to increase the robustness of the model in the future, an extension of it by further variables, including among others, soil condition data, financial support, and climatic factors, would be of great value. This would make the analysis more robust against changing external conditions and more informative.

In light of the results brought about by the analysis of the ARIMA model and available data on wheat yields in Poland, at least a few recommendations can be made for authorities in an attempt to preserve the stability of production and further development. The forecasted results show the stabilization of yields in the near future, which indicates the relative resilience of the agricultural sector to changes within the analyzed period. In this respect, stability could be enhanced by authorities through the support for modernization of the agricultural sector and management of risks associated with exogenous factors.

A key area of investment should be agricultural technologies that improve productivity and resilience in response to variable climatic conditions. Such an analysis places into focus the requirement for stable environmental conditions, including temperature and precipitation, supporting the research into drought-resistant and extreme-weather-tolerant wheat varieties. This may be further complemented by the expansion of irrigation systems in those regions that are relatively more vulnerable to water shortage.

In the meantime, authorities should closely follow changes in the global climate and their eventual consequences for wheat production in Poland. Predictive models, such as ARIMA, can help predict trends but cannot consider sudden climatic changes. Full-fledged agricultural risk management systems, including insurance against loss due to adverse weather conditions, should be developed.

More support in the form of grants for farm modernization and for buying advanced technologies may bring additional productivity growth to farmers. The authorities also need to pursue policies promoting agricultural exports, since stable yields create an opportunity for competitiveness in international markets. Further market trend analysis and keeping appropriate wheat prices will further encourage farmers to increase their crops' efficiency.

The onset of such conditions for stability, assumes continuity in adapting to climate conditions and further efficacy from the current practices that do not consider extreme weather conditions that could come aboard more frequently owing to the impacts of climate change, such as heat waves and droughts. It thus requires building adaptive capacity in agricultural systems through drought- and heat-resistant wheat varieties, improved soil management practices, and sustainable water-use strategies. Integrating these adaptation measures within future forecasting models would enable a far more robust and realistic assessment of the long-term sustainability of the sector.

The projection underlines the following: From a very economically relevant point of view, favorable conditions for farmers would continuously have to prevail in order to keep wheat production levels intact. Stable yields will hence provide opportunities to improve food security and competitiveness in international markets, provided that further investment in infrastructure, technological innovation, and market stability is pursued. Proactive policy intervention will, therefore, be highly relevant, as sudden changes in economic conditions, such as extreme shocks in input costs or in world wheat prices, cannot be considered by the ARIMA model. Definitely, efforts at resource use reduction with minimum environmental impact will contribute to the attainment of long-term agricultural resilience, with sustainability objectives being tuned towards these.

4.4. Grouping Provinces Using the K-Means Clustering Method from the Perspective of Wheat Yields per Hectare

K-means clustering was performed to group the provinces, which allowed the division of the observations into a previously determined number of groups with regard to the selected features. In this case, the following features were used for analysis: average wheat yield per hectare for the years 2004–2023 and standard deviation, reflecting the stability of production in individual provinces. The number of groups was intuitively chosen ($k = 3$) in order to capture the differences between high-yield, medium-yield, and low-yield provinces.

For that reason, the data have been standardized in advance to avoid the influence of differing measurement units and variable scales. The standardization of feature values transformed them into z-scores, defined as a difference between a value and mean, divided by standard deviation. In that way, both features equally influence the final result.

The k-means algorithm was run for 300 iterations with a convergence criterion of 10^{-4} . The algorithm assigned the provinces to one of the clusters by minimizing the sum of squared distances between data points and cluster centroids. The final clusters were

stable, meaning that repeated analysis produced consistent results, shown in Table 11. The spatial distribution of the clustering results on a map of Poland is in Figure 3.

Table 11. Cluster analysis results.

Province	2004–2023 Average	2004–2023 Standard Deviation	Cluster
Lower Silesia	49.1	5.8	0
Kuya–Pomerania	47.5	6.1	0
Lublin Province	43.5	7.8	2
Lubusz Province	44.7	9.1	2
Lodz Province	39.7	6.1	1
Lesser Poland	37.1	5.1	1
Masovia	36.5	3.8	1
Opole Province	58.3	8.0	0
Subcarpatia	36.0	4.4	1
Podlasie Province	32.2	4.6	1
Pomerania	50.4	5.9	0
Silesia	42.7	5.4	2
Holy Cross	33.3	4.4	1
Warmia–Masuria	45.3	6.8	2
Greater Poland	47.9	6.0	0
West Pomerania	49.4	6.4	0

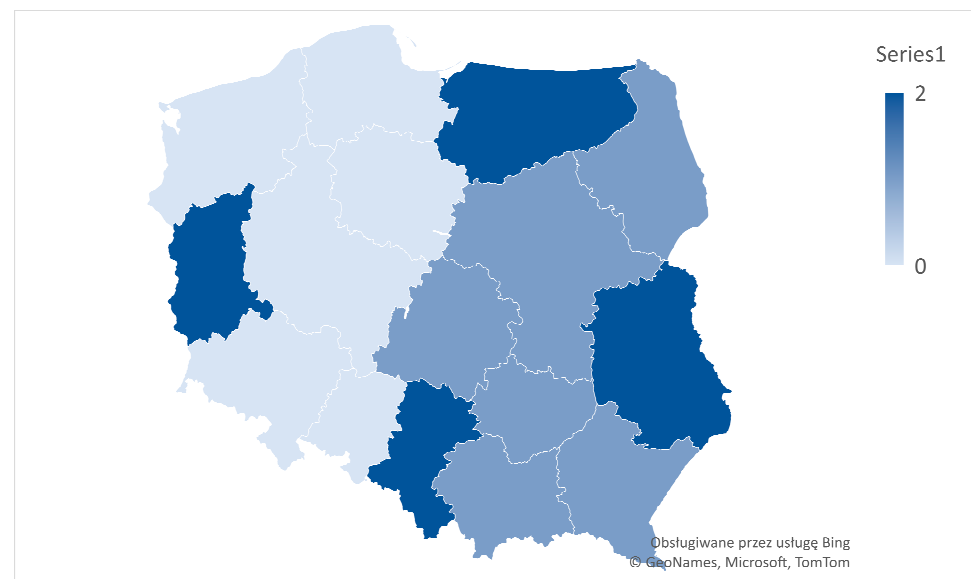


Figure 3. Spatial distribution of the clustering results.

The first feature to be considered in the analysis was the average wheat yield per hectare, ranging from 2004 to 2023. This feature gives a representation of the general potential of the production of the provinces regarding wheat production. The higher the average value, the more productive the farms in the region probably are due to favorable climatic conditions, more fertile soils, or better agricultural infrastructure (Figure 4).

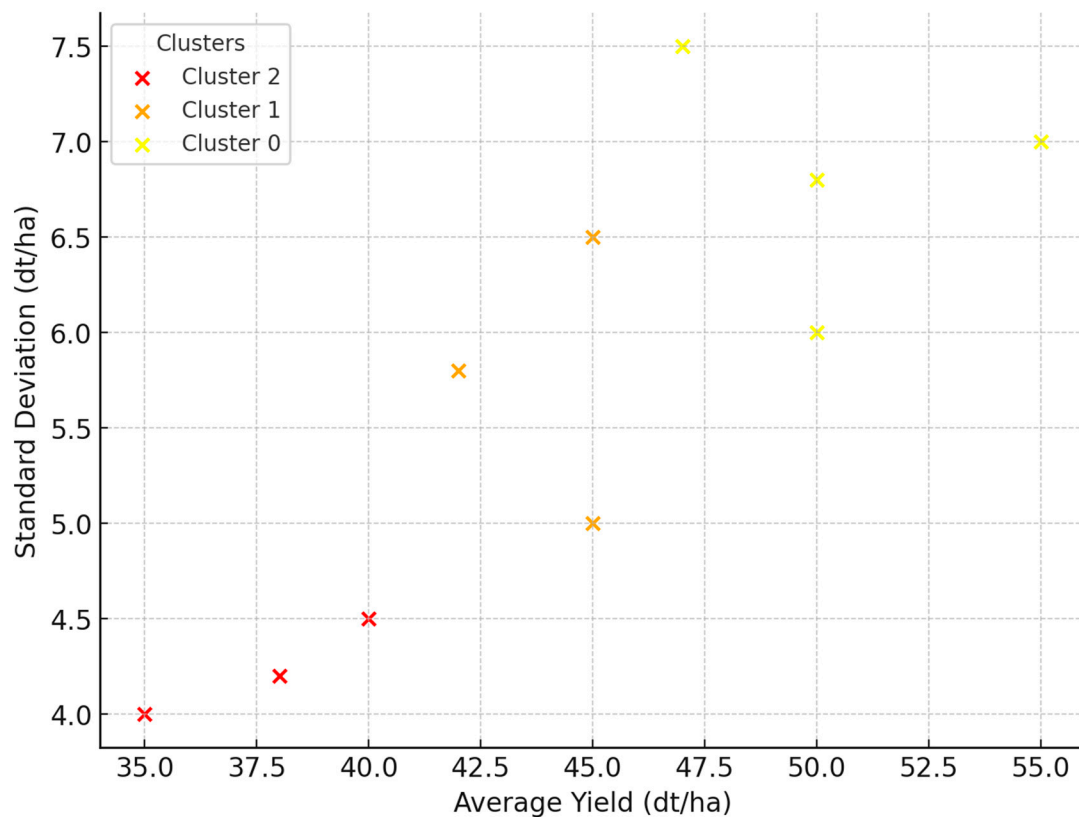


Figure 4. Classification of Polish provinces using k-means method.

The second feature was the standard deviation of yield, 2004–2023, as a measure of their variability over time. Low variability would suggest stability in production, again an important factor to consider in agricultural planning and investment. High variability may suggest that it is more sensitive to changing weather conditions or other risk factors, therefore making stable yield forecasting more difficult.

Since these two features taken together are supposed to form a correct judgment of both the general production potential of a region and its stability, these features were indispensable for classification. These two features taken together provide a comprehensive view of the conditions in several provinces.

Three were chosen to match the categorization of the high, medium, and low yields of each province. Intuitively, the three clusters represent leading, average, and lagging regions in terms of yields. Other numbers were tested for the number of clusters; however, the division into three clusters best showed the diversity of the data.

Iteratively, the cluster centroids had to be converged by minimizing the Euclidean distance between them. Each of the provinces was assigned to the cluster of the closest centroid, thus allowing the differentiation of three cohesive groups. Once all the cases had been assigned, the centroids of each cluster were recomputed as the centroid of the new cluster allocation, and the iteration process was repeated until convergence had been achieved.

- The result of the cluster analysis was to divide the set into three groups of voivodships: High Productivity Group: Provinces with high average yields along with low variability include the Opole Province and Pomerania. This is the region with very favorable production conditions and stable results of production.
- Medium Group: Warmia–Masuria and Kujawy–Pomerania are representatives of provinces that have medium results within the test on yields and stability. These regions have partial growth perspectives but require more substantial technological or infrastructural support.

- **Low Productivity Group:** The low yields and higher variability belong to the provinces of Podlasie and Holy Cross. Those regions may have more challenging climatic conditions and technological limitations.

This showed a significant difference between the clusters. The high-yield group consisted of those provinces with a high average and higher productive stability—that is, low deviation. The low-yield group presented as heterogeneous and variable, signaling possible points of intervention and support.

The regions that belong to the class of high-production regions, such as Opole and Pomerania, have to be treated as Polish agricultural leaders. Their further development should be encouraged. Experiences and practices used within these voivodeships could be inspiring and support other regions; their collaboration with less developed ones can lead to a balancing in agricultural development in general.

Medium productivity areas, such as Warmia–Masuria and Kujawy–Pomerania, may be developed but need special support. Investment in modern agricultural technologies, farmers’ training, and building transport and storage infrastructure can decisively increase their productivity. Yield stability will be at stake in the future and important for exploiting their full resources and potential.

In the case of the Podlasie and Holy Cross Regions, very low yields face high variability; a multi-tier program approach is required, which involves the simultaneous application of technical and financial support for farmers (concerning access to modern machinery and improved seed quality), climate change adaptations (increasing water retention ability and the introduction of irrigation systems), and, finally, agriculture insurance related to unpredictable conditions.

It means calling for the differentiation in agricultural policy at the national level into regionally viable strategies responsive to the needs and characteristics of each province and investments in research and development networks in support of innovative solutions matched with local conditions.

By addressing the regional disparities, Poland will be making its agriculture not only more efficient but also more competitive on the international market. By supporting the less productive regions’ development without deteriorating high performance in the best areas, ground can be formed for the sustainable development of the country’s agricultural sector.

These results are in the view of climate change and draw considerable attention to the high influence of environmental factors on agricultural productivity, especially in wheat cultivation. Climate change here comes off as a mega-stressor influencing wheat yields through increased temperatures, rainfall uncertainty, and increased frequency of extreme weather events such as droughts and heat waves [88–90]. These conditions threaten crop resilience and heighten regional disparities in productivity.

While the results also show that higher temperatures sometimes extend the growing seasons and, therefore, could improve yields, excessive heat stress during critical growth periods causes yield declines [91,92]. Additionally, while rainfall has generally been fairly good in many wheat-producing countries, localized drought or excess rain disrupts planting or harvesting cycles farther from agricultural stability [93,94].

The performance of wheat production is also strongly linked to climate variability, and regional disparities in performance reflect the fact that high-yielding regions enjoy certain steady environmental conditions and are relatively better endowed with modern technologies that offset climatic impacts. Poor soil, limited water availability, and relatively limited access to climate adaptation technologies represent a number of challenges facing low-yielding areas. The vulnerabilities of the region are, therefore, high, making them far

more susceptible to climate change impacts that heighten food insecurity and economic instability [95,96].

This study puts in a word on the urgent need for embedding climate adaptation measures into agricultural policies. These include strategies like the development of heat- and drought-resistant crop varieties, expansion of irrigation facilities, and precision agriculture for better resilience. In addition to this, sustainable agricultural practices such as crop rotation, organic farming, and soil conservation would reduce long-term effects on agro-ecosystems.

This means that climate change is considered a challenge facing sustainable food production. This paper highlights how the findings indicate the need for targeted intervention with a view to address vulnerability in climate-sensitive regions, while encouraging innovation and building resilience in the whole agricultural sector for both food security and agricultural sustainability, in an increasingly uncertain climatic future.

From the perspective of sustainable development, clustering analysis enables the indication that low-productive regions, like Podlasie and Subcarpathia, are usually faced with poor soil quality. Moreover, such a situation is not supported by gains in modern technologies and is highly exposed to adverse impacts of climatic variability. This leads to a higher variability of yields, symptoms of instability, and susceptibility to climate change and economic stressors. Such a situation will be improved by addressing the multifaceted nature of these challenges through improved soil management, expanded irrigation infrastructure, and financial incentives for modernizing agricultural practices. This would lead not only to increased productivity but also to greater environmental resilience in these lagging regions.

It brings out the socio-economic dimensions of sustainability; for instance, more developed regions mean more developed provinces, such as Lower Silesia and Greater Poland, translating into higher GDP per capita to invest in more agricultural technologies coupled with better infrastructure. Poor regions have only very limited opportunities to implement sustainable patterns of agriculture. Balancing the distribution of resources and differentiating regional policies are the main strategies for sustainability. In addition, paying particular attention to the needs of each cluster allows Poland to obtain a more durable and resilient agriculture that contributes to lessening regional disparities in ensuring food security over the long term.

Poland's wheat cultivation, while significant within the European agricultural sector, differs significantly from giants of wheat production such as China, Russia, and the United States in terms of size, climatic conditions, stage of technology advancement, and government subsidization. The world's largest producer of wheat is China, with the privilege of large-sized farmlands, well-established irrigation systems, and high-density agricultural practices that are able to bring forth copious harvests regardless of the climatic adversity in the region [58–60,97,98]. Chinese wheat farming relies heavily on subsidies and the excessive use of artificial fertilizers and irrigation, given the water deficit in northern wheat regions [60,61].

Russia, through its huge cultivable land, has become a major exporter of wheat by capitalizing on its large fertile Black Earth land [64,65]. Russia, despite having a large production scope, is faced with problems such as harsh winters, irregular precipitation, and logistic constraints due to its extremely large geographical area [66]. As compared to Poland, which benefits from the European Union's farm subsidies and stable trading relationships, the Russian wheat market is more geopolitically sensitive, for instance, to trade barriers and export controls that influence its market equilibrium [64,65].

The United States combines technological development with extensive commercial farming, and this enables it to maintain high productivity and harvests [99,100]. Areas

of the United States where wheat is cultivated, ranging from the Great Plains to the Pacific Northwest, experience differing climatic patterns, minimizing dependence on a single production area in the country [101]. The United States' agricultural sector is highly mechanized, employing precision agriculture, genetically modified crops, and sophisticated irrigation systems to improve production [84,85]. Compared to Poland, where wheat farming is more scattered and dependent on small farms, U.S. wheat farming is dominated by large agribusinesses with greater capital resources to invest in advanced technologies.

Poland's wheat harvests are dictated by moderate climatic conditions, with regional differences in soil quality and agricultural infrastructure [35–37]. The country benefits from EU subsidies, which allow for modernization, but its average farm size is smaller than in Russia or the U.S., limiting economies of scale. Poland has continued to be resilient in dealing with climatic fluctuation by embracing sustainable practices and enhancing technology, but its overall level of production is much lower than that of major producers. Additionally, even though Poland enjoys a strong export position within Europe [38,39], it is not as effective as Russia and the United States in global markets. Contrary to China, Poland is dominated by less intense farming but steadier climatic conditions with reduced reliance on man-made irrigation. As Poland's wheat sector modernizes and grows, it is based on a smaller foundation than the world's leading producers and is subject to a distinctive combination of environment, economic, and policy-driven conditions.

4.5. Fixed Effects Model (FEM)

The conducted Fixed Effects Model (FEM) analysis provides a comprehensive evaluation of factors influencing wheat yields across various Polish voivodeships in 2023, highlighting critical insights into regional agricultural productivity. The inclusion of province-specific fixed effects is instrumental in capturing unobserved heterogeneity, offering clarity about how local characteristics distinctly affect wheat yields beyond general climatic and economic factors.

Model (FEM) performed on the provided data:

- R-squared: 1.000, indicating the model explains nearly all variability in wheat yield;
- Intercept: -0.2933 ;
- Province fixed effects: Show variations in yields attributable specifically to each voivodeship (province), controlling for other factors. For example:
 - Opole Province: $+11.65$ (highest positive effect);
 - Lublin Province: $+10.24$;
 - Lubusz Province: -8.00 (strongest negative effect);
 - Silesia: -7.06 .

Climate and Economic Variables:

- Rainfall: $+0.0013$, indicating a minimal effect;
- Temperature during cultivation: $+3.44$, suggesting a significant positive impact;
- Average annual temperature: $+3.43$, also significant and positive;
- GDP per capita: $+0.0004$, minimal positive impact;
- Wheat price: $+2.57$, indicating that higher prices positively affect yields;
- Production cost: -0.32 , indicating a negative impact on yield, possibly due to less efficient production conditions in high-cost regions.

The FEM also produces an extremely high R-squared, indicating the model explains nearly all variability in the yields of the provinces under study. This finding indicates the independent variables selected, and along with the regional fixed effects, explains the determinants of Polish wheat productivity thoroughly. For example, the most significant positively signed fixed effect was found in Opole Province in the yields of the crop, which

may be an indicator of the favorable conditions of agriculture in the region, likely the outcome of quality soil, positive climatic patterns, or increased technological adoption. On the contrary, in the example of the provinces of Lubusz and Silesia negative fixed effects on a substantive level are seen, suggesting worse surrounding conditions, with economic limitations or fewer investments in the infrastructure and the adoption of the required technology.

From the variables analyzed, temperature in the wheat growing season was found to be the most influential variable positively correlated with yield levels. Such a result implies that higher average temperatures in critical growth periods of the region contribute to superior yields, presumably because better living conditions improve wheat ripening and productivity in the region. In the same way, mean annual temperature also showed a strong positive correlation with yields, affirming the significance of ideal thermal conditions for the entire year in maintaining crop health and yield.

Interestingly, precipitation only had a marginal positive influence; consequently, despite its prominence, the effect on the 2023 crop remained limited. This could be attributed to the sufficiency of rainfall in the respective zones during the stipulated period or the availability of efficient water regimes. Economic implications, in turn, presented intricate and significant findings. The market price of the crop displayed a positive association with the level of production, indicating that market prices positively influence the farmer to divert resources to productive uses, improve inputs or technology, and enhance productivity. But the production cost reflected an inverse relationship with the yields, indicating a negative relationship in the form that more inputs have more inefficiencies, which could be due to inherent problems or adverse climatic conditions during crop maturation, contributing to less productive yields.

The possible applications of these findings are extensive and significant. Policymakers are able to leverage findings on regional differences to adapt interventions effectively. For well-performing regions like Opole, policy attention could focus on maintaining productivity through ongoing technological improvement and optimal infrastructure maintenance. On the other hand, less productive regions like Lubusz and Silesia can be supported by specialized policies in the areas of infrastructure improvement, application of advanced farming practices, and financing mechanisms to cushion high costs of production.

Recognizing the immense impact of temperature factors helps to solidify the need to adjust to climate change in the development of crop strategies. In certain regions, poor thermal regimes may be enhanced by enhanced research efforts, alongside enhanced climate-resilient crop varieties and practices suitable for cooler climatic regimes. Water-use optimization strategies are also necessary, even though rainfall has minimal impact. The use of efficient water harvesting and irrigation practices can improve stability in production, considering the embedded variability of climatic trends.

For farmers and agricultural planners, the results on wheat price incentives and cost of production implications are priceless. Knowing that increased market prices can spur productivity offers a foundation for market-oriented policies and facilitates lobbying for beneficial pricing policies or market stabilization programs. At the same time, attempts to contain or minimize the cost of production through cooperative buying, subsidies, or enhanced resource efficiency measures could significantly improve profitability and yield performance.

5. Conclusions

The trends analyzed within wheat farming fields in Poland throughout the 20-year observation period have certain character phases (Q1). The wheat area during 2004–2013 remained relatively constant, fluctuating in the 2.1–2.3 million hectares range, with certain years' highs most likely explained by climatic factors and the dynamics of agricultural

policy. Throughout Poland, area differences in this regard should be noted; the Lublin, Lower Silesia, Kujawy–Pomerania, and Greater Poland areas were indicated for the continuous growing of high quantities because of their favorable soil and climate. In the next decade (2014–2023), in 2022, the wheat planted broke the record of 2.5 million hectares. This is due to more effective agriculture, the beneficial impacts of European Union support programs, and growing domestic and international demand. However, there is great diversity in the performance of regions, with some (e.g., Lublin) growing dynamically quickly and others (mainly Subcarpathian and Silesian) lagging relatively behind. Yield data also reveal some of those trends, with more variability at the beginning of the decade and average yields of about 4 tons per hectare, with such anomalies as the 2006 drought radically reducing production. The second decade, however, formed more stable market prices and higher volumes, which set the record high national average of 5.38 tons per hectare in approximately 2023. This upward trend shows that the yield of wheat on average per hectare has significantly risen, and this is proof that the production of Polish wheat is becoming more effective and is not susceptible to various external factors mainly due to technological advancements and the greater promotion of high-yielding wheat varieties.

Spatial variations in wheat yield and production at different territorial levels in Poland are readily identifiable, driven by differences in natural conditions, agricultural technology, and socio-economic factors (Q2). Voivodeships, such as Lower Silesia, Opole, Kujawy–Pomerania, and Wielkopolska, systematically achieve higher yields and larger cultivated areas due to their good environmental conditions, better farming practices, and higher investment in modern farming technologies. Conversely, areas such as Podlasie, Subcarpathia, and Lubusz are confronted with lower wheat production as a result of lower soil fertility, more severe climatic conditions, and less availability of high-quality inputs and farm technologies, which render their production systems more susceptible to climate variability. In addition to this, regional economic disparities also influence productivity, as wealthier regions, i.e., Greater Poland and Lower Silesia, have the benefit of more GDP per capita, which allows them to invest more in mechanization, irrigation, and improved seeds. Meanwhile, less economically privileged regions, i.e., Lublin and Subcarpathia, cannot modernize themselves due to insufficient funds, which hinders their use of progressive agricultural techniques. Policy interventions, namely agricultural subsidies and EU support programs, have played a pivotal role in improving overall efficiency as well as enhancing regional disparities, as more established agricultural areas were more effective in absorbing these funds, while lagging regions were left behind. Cluster analysis delineates three clusters: high-performance regions with yields that are both high and stable, medium-performing areas with relatively modest productivity, and low-yielding areas with high instability. These findings call for targeted investment, technological progress, and infrastructural enhancement to bridge regional disparities and enable a more even and sustainable agriculture in Poland over the long term.

The trends in Polish wheat production, as analyzed and forecasted by the ARIMA model, show continued stabilization in both cultivated area and yields, reflecting enhanced efficiency and resilience in the sector (Q3). The five-year forecast is that the yields of wheat will continue to be stable, demonstrating that the sector has successfully cushioned variability caused by climatic and economic stresses through enhanced agricultural practices, technologies, and policies. This stability underscores Polish agriculture's growing resilience to exogenous shocks, climate change, and market fluctuations while also emphasizing the need for further adaptive capacity development and strengthening. At the core of long-term productivity will be the adoption of high-tech agricultural technologies, including drought-tolerant wheat varieties, precision farming, and sustainable irrigation systems, alongside targeted soil management interventions and access to financial and technological

inputs in the lower-yielding areas. Additionally, the economic determinants of production costs and wheat prices are primary drivers of future trends, with higher wheat prices providing strong incentives for investment in more advanced farming methods. Production cost inefficiencies, however, remain an obstacle, and optimizing these would render the industry more profitable and stimulate additional innovation within the sector. The cluster analysis of yield performance across regions presents a range of action-oriented conclusions for policymakers, with high-performing regions like Lower Silesia and Opole serving as a best practice model, while medium- and low-performing regions require strategic intervention to break through their respective bottlenecks. These targeted approaches could help decrease regional disparities, leading to a more equitable and sustainable agricultural sector. Although stability is highlighted in the ARIMA model forecast, its failure to capture sudden climatic shifts or policy interventions necessitates constant monitoring and revision. Future analyses incorporating additional variables, such as soil characteristics and emerging climatic trends, will refine predictive precision and facilitate more informed decision-making among policymakers and agricultural stakeholders.

The ARIMA model prediction outcomes are indicative of the relative stabilization of Polish wheat yields over the next five years, with the implication that while the agricultural sector has been resilient, future productivity gains would be more a function of external interventions rather than natural yield growth. Such stability has significant practical significance for policymakers in that it demands long-term strategic planning rather than short-term reactive measures. In view of the projected stability in yields, policy interventions need to be aimed at bolstering efficiency by investing strategically in agricultural innovations, such as precision agriculture, drought-resistant crop varieties, and the optimization of fertilizers. Since climate variability is a given that cannot be controlled, policymakers should also give priority to developing adaptive capacities, such as increasing irrigation facilities in vulnerable regions and strengthening climate insurance schemes for farmers. The forecasted yield stability also provides the government with an opportunity to streamline its subsidy placement within the EU's Common Agricultural Policy framework, such that financial support is directed into those regions and types of agriculture that are most conducive to the sustenance and development of wheat production. Using ARIMA-driven predictions as a planning tool, policymakers are able to devise proactive, evidence-based agricultural policies that enhance resilience, promote sustainability, and maintain Poland's competitive position within the European wheat sector.

The clustering of regional wheat production data reveals disparities between high- and low-performing regions, guiding targeted intervention for enhanced productivity and stability (Q4). High-performing regions, like Opole, Lower Silesia, and Pomerania, can serve as best practice models, whereas medium-performing regions, like Kuyavia–Pomerania and Warmia–Masuria, must be invested in contemporary agricultural technologies and supported financially. Low-productivity regions, like Podlasie, Subcarpathia, and Holy Cross, face environmental and economic constraints, demanding sustainable agriculture, infrastructure for irrigation, and modernization subsidies. Resource allocation through policy support, climate change adaptation, and weather insurance can bridge such gaps effectively. While ARIMA forecasting shows stability, the inability to anticipate random climatic or economic shocks emphasizes the need for continuous data monitoring and adaptive solutions.

In the interest of increasing wheat yield in low-production areas, like Podlasie, Subcarpathia, and Holy Cross, part of a policy reaction has to be targeted towards improving fertility in the soils, increasing the availability of farm technology to farmers, and equipping them to adapt to climate change. The government must institute soil reclamation initiatives with incentives for farmers to adopt crop rotation, organic manures, and conser-

vation farming techniques in an attempt to improve the status of nutrients and the water holding capacity of the soils. Increasing precision farming through subsidizing economic support for GPS-based machinery, remote sensing, and smart irrigation systems would make the farmers there able to provide maximum input and maintain efficiency. These special fiscal incentives of low-interest loans and subsidies to purchase climate-resistant and high-yielding wheat would also assist small farmers to overcome cost hurdles and gain the benefit of higher productivity in terms of unfavorable conditions.

In order to deal with the effects of climate change on wheat production, investment in water management facilities at a regional level, in the framework of constructing effective irrigation systems and reservoirs to hold water in regions where dryness is dominant, is necessary. The government must enact local climate adaptation plans that expand and build capacity farms, familiarizing them with climate-resilient farming methods like zero-till agriculture and agroforestry, which retain soil water and avert soil erosion. Large-scale crop insurance programs with subsidized state premiums would allow farmers to insure against the risk of extreme weather events, rendering financial security and long-term investment in sustainable agriculture economically feasible. Also, redirecting the EU farm subsidy grant to the facilitation of climate change adaptation in the most vulnerable areas would supplement a fairer allocation of support with the poor-performing regions getting the support they deserve in order to produce more wheat while being environmentally conscious.

This is further limited in that some variables, which when added into the analysis, would work better to explain wheat productivity—for instance, those to do with soil quality, diseases, pest pressures, improved seed genetics, and socio-economic variables such as labor availability and farm ownership structures. Of course, this enriches the models and offers depth in the determination of wheat yields. Also, a limitation is the exclusion of biotic factors such as pests, diseases, and weed infestations, which can significantly impact wheat productivity and vary across regions and growing seasons. While soil quality was briefly mentioned, the study does not include detailed soil composition data, such as organic matter content, nutrient availability, and pH levels, which are critical determinants of wheat yield.

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References

1. Giongo, V.; Acosta, A.d.S.; Dossa, Á.A.; Santi, A.; Amaral, A.J.D.; Caierão, E.; Denardin, J.E.; Vieira, O.V.; de Figueirêdo, M.C.B.; Folegatti, M.I.d.S.; et al. How can the environmental impacts of wheat cultivation and wheat flour production be reduced? A life cycle assessment of Brazilian wheat. *J. Clean. Prod.* **2025**, *489*, 144650. [[CrossRef](#)]
2. Aljanabi, F.K.; Dedeoğlu, M. Machine learning algorithms and geographic information system techniques to predict land suitability maps for wheat cultivation in the Central Anatolia Region. *J. Ecol. Eng.* **2025**, *26*, 373–387. [[CrossRef](#)]
3. Rózewicz, M.; Grabiński, J.; Wyzińska, M. Growth Parameters, Yield and Grain Quality of Different Winter Wheat Cultivars Using Strip Tillage in Relation to the Intensity of Post-Harvest Soil Cultivation. *Agriculture* **2024**, *14*, 2345. [[CrossRef](#)]

4. Saquee, F.S.; Pakina, E.; Zargar, M.; Norman, P.E.; Vladimirovna, K.E.; Alexandrovna, T.V. Economic parameter estimates of spring wheat varieties grown under different cultivation technologies. *Biocatal. Agric. Biotechnol.* **2024**, *62*, 103454. [\[CrossRef\]](#)
5. Alemayehu, S.; Olago, D.; Opere, A.; Zeleke, T.T.; Dejene, S.W. Evaluating Wheat Cultivation Potential in Ethiopia Under the Current and Future Climate Change Scenarios. *Land* **2024**, *13*, 1915. [\[CrossRef\]](#)
6. El-Akhdar, I.; Shabana, M.M.A.; El-Khateeb, N.M.M.; Elhawat, N.; Alshaal, T. Sustainable Wheat Cultivation in Sandy Soils: Impact of Organic and Biofertilizer Use on Soil Health and Crop Yield. *Plants* **2024**, *13*, 3156. [\[CrossRef\]](#)
7. Alija, D.; Ołędzki, R.; Nikolovska Nedelkoska, D.; Wojciechowicz-Budzisz, A.; Xhabiri, G.; Pejcz, E.; Alija, E.; Harasym, J. The Addition of Pumpkin Flour Impacts the Functional and Bioactive Properties of Soft Wheat Composite Flour Blends. *Foods* **2025**, *14*, 243. [\[CrossRef\]](#)
8. Panyi, A.F.; Brorsen, B.W. Trends in the yield response to nitrogen of winter wheat in Oklahoma. *Agric. Environ. Lett.* **2024**, *9*, e20143. [\[CrossRef\]](#)
9. Nishio, Z.; Kurushima, M.; Suzuki, T.; Shimoda, S.; Hirota, T. Effects of Temperature, Precipitation, and Sunshine on Cold-Tolerant Wheat Yield Under Warming Trends: A 20-Year Study in Hokkaido, Japan. *Plants* **2024**, *13*, 3165. [\[CrossRef\]](#)
10. Boussakouran, A.; El Yamani, M.; Sakar, E.H.; Rharrabti, Y. Trend in yield and protein content relationship in a historical series of durum wheat varieties under rainfed and irrigated environments. *Crop Environ.* **2024**, *3*, 171–176. [\[CrossRef\]](#)
11. Wolniak, R.; Stecuła, K.; Aydın, B. Digital Transformation of Grocery In-Store Shopping-Scanners, Artificial Intelligence, Augmented Reality and Beyond: A Review. *Foods* **2024**, *13*, 2948. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Chandra, T.; Sahu, J.; Jaiswal, S.; Iquebal, M.A.; Kumar, D. Current research status and emerging trends in wheat: An integrated scientometric analysis based on ploidy uncovers hidden footprints in the scientific landscape. *Heliyon* **2024**, *10*, e36375. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Shah, S.A.A.; Wu, H.; Farid, M.F.; Tareen, W.-U.-H.; Badar, I.H. Climate Trends and Wheat Yield in Punjab, Pakistan: Assessing the Change and Impact. *Sustainability* **2024**, *16*, 4443. [\[CrossRef\]](#)
14. Ulukan, H. Wheat production trends and research priorities: A global perspective. In *Advances in Wheat Breeding: Towards Climate Resilience and Nutrient Security*; Springer: Singapore, 2024; pp. 1–22.
15. Blanco, A. Structure and Trends of Worldwide Research on Durum Wheat by Bibliographic Mapping. *Int. J. Plant Biol.* **2024**, *15*, 132–160. [\[CrossRef\]](#)
16. Alam, M.; Stephen Baenziger, P.; Frels, K. Emerging Trends in Wheat (*Triticum* spp.) Breeding: Implications for the Future. *Front. Biosci.* **2024**, *16*, 2. [\[CrossRef\]](#)
17. Utarova, N.; Kakimov, M.; Gajdzik, B.; Wolniak, R.; Nurtayeva, A.; Yeraliyeva, S.; Bembenek, M. Development of Gluten-Free Bread Production Technology with Enhanced Nutritional Value in the Context of Kazakhstan. *Foods* **2024**, *13*, 271. [\[CrossRef\]](#)
18. Moniruzzaman; Haque, S.; Haque, A.K.E.; Islam, A.H.M.S.; Salam, M.A. Farmer's perception, observed trend and adaptation measures to climate change: Evidence from wheat farmers in Bangladesh. *J. Agric. Food Res.* **2023**, *14*, 100873. [\[CrossRef\]](#)
19. Fradgley, N.S.; Bentley, A.R.; Gardner, K.A.; Swarbreck, S.M.; Kerton, M. Maintenance of UK bread baking quality: Trends in wheat quality traits over 50 years of breeding and potential for future application of genomic-assisted selection. *Plant Genome* **2023**, *16*, e20326. [\[CrossRef\]](#)
20. Khodarahmi, M.; Soughi, H.; Shahbazi, K.; Jafarby, J.; Khavarinejad, M.S. Trends in important agronomic traits, grain yield and its components in bread wheat cultivars released in northern warm and humid climate of Iran, 1968–2018. *Cereal Res. Commun.* **2023**, *51*, 1003–1101. [\[CrossRef\]](#)
21. Stecuła, K.; Wolniak, R.; Aydın, B. Technology Development in Online Grocery Shopping—From Shopping Services to Virtual Reality, Metaverse, and Smart Devices: A Review. *Foods* **2024**, *13*, 3959. [\[CrossRef\]](#)
22. Hussain, S.; Mustafa, G.; Haider Khan, I.; Liu, J.; Chen, C.; Hu, B.; Chen, M.; Ali, I.; Liu, Y. Global Trends and Future Directions in Agricultural Remote Sensing for Wheat Scab Detection: Insights from a Bibliometric Analysis. *Remote Sens.* **2023**, *15*, 3431. [\[CrossRef\]](#)
23. Nduku, L.; Munghemezulu, C.; Mashaba-Munghemezulu, Z.; Kalumba, A.M.; Chirima, G.J.; Masiza, W.; De Villiers, C. Global Research Trends for Unmanned Aerial Vehicle Remote Sensing Application in Wheat Crop Monitoring. *Geomatics* **2023**, *3*, 115–136. [\[CrossRef\]](#)
24. Sendhil, R.; Kumara, T.M.K.; Kandpal, A.; Kumari, B.; Mohapatra, S. Wheat Production, Trade, Consumption, and Stocks: Global Trends and Prospects. In *Wheat Science: Nutritional and Anti-Nutritional Properties, Processing, Storage, Bioactivity, and Product Development*; CRC Press: Boca Raton, FL, USA, 2023; pp. 33–55.
25. Prajapat, R.K.; Mathur, M.; Kumari, S.; Kumar, S.; Sharma, M.; Garg, N.K.; Sharma, D.; Meena, N.L. Trends and Approaches of Wheat Flour and End-Product Fortification Technologies. In *Wheat Science: Nutritional and Anti-Nutritional Properties, Processing, Storage, Bioactivity, and Product Development*; CRC Press: Boca Raton, FL, USA, 2023; pp. 373–395.
26. Abdalla, A.; Stellmacher, T.; Becker, M. Trends and Prospects of Change in Wheat Self-Sufficiency in Egypt. *Agriculture* **2023**, *13*, 7. [\[CrossRef\]](#)
27. Bahaudin, S.; Kumar, N.; Kumar, D.; Kumar, V.; Ritu. Trends in Area, Production and Productivity of Wheat Cultivation at Global Level. *Econ. Aff.* **2022**, *67*, 401–406.

28. Shorinola, O.; Simmonds, J.; Wingen, L.U.; Uauy, C. Trend, population structure, and trait mapping from 15 years of national varietal trials of UK winter wheat. *G3 Genes | Genomes | Genetics* **2023**, *12*, jkab415. [[CrossRef](#)]
29. Erenstein, O.; Jaleta, M.; Abdul Mottaleb, K.; Donovan, J.; Braun, H.-J. Global Trends in Wheat Production, Consumption and Trade. In *Wheat Improvement: Food Security in a Changing Climate*; Springer: Cham, Switzerland, 2022; pp. 47–66.
30. Sendhil, R.; Kumari, B.; Khandoker, S.; Jalali, S.; Acharya, K.K.; Gopalareddy, K.; Singh, G.P.; Joshi, A.K. Wheat in Asia: Trends, Challenges and Research Priorities. In *New Horizons in Wheat and Barley Research: Global Trends, Breeding and Quality Enhancement*; Springer: Singapore, 2022; pp. 33–61.
31. Mittal, S. Wheat and Barley Production Trends and Research Priorities: A Global Perspective. In *New Horizons in Wheat and Barley Research: Global Trends, Breeding and Quality Enhancement*; Springer: Singapore, 2022; pp. 3–18.
32. Kashyap, P.L.; Gupta, V.; Gupta, O.P.; Jasrotia, P.; Singh, G.P. *New Horizons in Wheat and Barley Research: Global Trends, Breeding and Quality Enhancement*; Springer: Singapore, 2022; pp. 1–842.
33. Oleksiak, T.; Spyroglou, I.; Pacoń, D.; Matysik, P.; Pernisová, M.; Rybka, K. Effect of drought on wheat production in Poland between 1961 and 2019. *Crop Sci.* **2022**, *62*, 728–743. [[CrossRef](#)]
34. Pishgar-Komleh, S.H.; Zylowski, T.; Rozakis, S.; Kozyra, J. Efficiency under different methods for incorporating undesirable outputs in an LCA + DEA framework: A case study of winter wheat production in Poland. *J. Environ. Manag.* **2020**, *260*, 110138. [[CrossRef](#)]
35. Holka, M.; Jankowiak, J.; Bieńkowski, J.F.; Dąbrowicz, R. Life cycle assessment (LCA) of winter wheat in an intensive crop production system in Wielkopolska region (Poland). *Appl. Ecol. Environ. Res.* **2016**, *14*, 535–545. [[CrossRef](#)]
36. Skowera, B.; Baranowska, A.; Węgrzyn, A.; Bartoszek, K.; Wojkowski, J.; Ivanišová, E. The Meteorological Conditions of Precipitation Deficits in the Cultivation of Winter Wheat in Central and Eastern Poland. *J. Ecol. Eng.* **2023**, *24*, 50–62. [[CrossRef](#)]
37. Syp, A.; Jarosz, Z.; Faber, A.; Borzecka-Walker, M.; Pudelko, R. Greenhouse gas emissions from winter wheat cultivation for bioethanol production in Poland. *J. Food Agric. Environ.* **2012**, *10*, 1169–1172.
38. Bernat, E.; Chojnacka, S.; Wesołowska-Trojanowska, M.; Gawęda, D.; Kwiecińska-Poppe, E.; Haliniarz, M. Effect of Crop Protection Intensity and Nitrogen Fertilisation on the Quality Parameters of Spelt Wheat Grain cv. 'Rokosz' Grown in South-Eastern Poland. *Agriculture* **2024**, *14*, 1815. [[CrossRef](#)]
39. Lachutta, K.; Jankowski, K.J. Quality of Winter Wheat Flour from Different Sowing and Nitrogen Management Strategies: A Case Study in Northeastern Poland. *Appl. Sci.* **2024**, *14*, 5167. [[CrossRef](#)]
40. Kozłowski, M.; Otremba, K.; Pajak, M.; Pietrzykowski, M. Changes in Physical and Water Retention Properties of Technosols by Agricultural Reclamation with Wheat–Rapeseed Rotation in a Post-Mining Area of Central Poland. *Sustainability* **2023**, *15*, 7131. [[CrossRef](#)]
41. Zieliński, M.; Jadczyzyn, J.; Sobierajewska, J. Predispositions and challenges of agriculture from areas particularly facing natural or other specific constraints in Poland in the context of providing environmental public goods under EU policy. *Agric. Econ.* **2023**, *69*, 309–320. [[CrossRef](#)]
42. Wiśniewski, L.; Biczowski, M.; Rudnicki, R. Natural potential versus rationality of allocation of Common Agriculture Policy funds dedicated for supporting organic farming development—Assessment of spatial suitability: The case of Poland. *Ecol. Indic.* **2021**, *130*, 108039. [[CrossRef](#)]
43. Michalak, D. Adapting to climate change and effective water management in Polish agriculture—At the level of government institutions and farms. *Ecohydrol. Hydrobiol.* **2020**, *20*, 134–141. [[CrossRef](#)]
44. Ti, J.; Yang, Y.; Pu, L.; Wen, X.; Yin, X.; Chen, F. Ecological compensation for winter wheat fallow and impact assessment of winter fallow on water sustainability and food security on the North China Plain. *J. Clean. Prod.* **2021**, *328*, 129431. [[CrossRef](#)]
45. Russo, A.; Sardeshpande, M.; Rupprecht, C.D.D. Urban rewilding for sustainability and food security. *Land Use Policy* **2025**, *149*, 107410. [[CrossRef](#)]
46. Chang, H.-H. Development of food sharing online networks for sustainability: Consumer perspectives on food security and sharing. *Asia Pac. J. Mark. Logist.* **2024**, *36*, 3446–3465. [[CrossRef](#)]
47. Sarangi, P.K.; Pal, P.; Singh, A.K.; Sahoo, U.K.; Prus, P. Food Waste to Food Security: Transition from Bioresources to Sustainability. *Resources* **2024**, *13*, 164. [[CrossRef](#)]
48. Cadavid, L.; Arulnathan, V.; Pelletier, N. Food Security and Food Sovereignty: A Review of Commonly Used Indicators and Consideration of Environmental Sustainability Aspects. *Sustainability* **2024**, *16*, 11034. [[CrossRef](#)]
49. Aliyu, U.S.; Cavusoglu, B.; Hassanie, S.; Abba, S.I.; Sammen, S.S.; Kisi, O. Food, energy, and water security sustainability; an asymmetric approach for achieving sustainable development goals. *Discov. Sustain.* **2024**, *5*, 417. [[CrossRef](#)]
50. Song, G.; Cai, Z. How to improve the sustainability of food security? A new perspective on competition in the spatial utilization of cultivated land between food crops and cash crops. *Stoch. Environ. Res. Risk Assess.* **2024**, *38*, 4809–4824. [[CrossRef](#)]
51. Sharma, H.; Kumar, A.; Singh, R.; Malik, A.; Juyal, R. Enhancing food security and sustainability: Harnessing nano-omics-based technologies for quality monitoring. In *Sustainable Agriculture: Nanotechnology, Biotechnology, Management and Food Security*; De Gruyter: Berlin, German, 2024; pp. 191–212.

52. Mata, F.; Barros, D.; Pereira-Pinto, R.; Pires, P. EU Citizens' Perception of Risks Posed to the Sustainability of EU Food Security. *Sustainability* **2024**, *16*, 9840. [\[CrossRef\]](#)
53. Zhang, H.; Zhou, X. Research on Leveraging Technology for Environmental Sustainability and Food Security. In *Proceedings of the 2024 4th International Conference on Artificial Intelligence, Big Data and Algorithms, Zhengzhou, China, 5–7 July 2024*; ACM International Conference Proceeding Series; Association for Computing Machinery (ACM): New York, NY, USA, 2024; pp. 125–128.
54. Gulyaeva, E.; Shaydayuk, E.; Shreyder, E.; Kushnirenko, I.; Shamanin, V. Genetic Diversity of Promising Spring Wheat Accessions from Russia and Kazakhstan for Rust Resistance. *Plants* **2024**, *13*, 2469. [\[CrossRef\]](#)
55. Abys, C.; Skakun, S.; Becker-Reshef, I. Two decades of winter wheat expansion and intensification in Russia. *Remote Sens. Appl. Soc. Environ.* **2024**, *33*, 101097. [\[CrossRef\]](#)
56. Joshi, A.; Pradhan, B.; Chakraborty, S.; Behera, M.D. Winter wheat yield prediction in the conterminous United States using solar-induced chlorophyll fluorescence data and XGBoost and random forest algorithm. *Ecol. Inform.* **2023**, *77*, 102194. [\[CrossRef\]](#)
57. Liu, S.; Xu, L.; Wu, Y.; Simsek, S.; Rose, D.J. End-Use Quality of Historical and Modern Winter Wheats Adapted to the Great Plains of the United States. *Foods* **2022**, *11*, 2975. [\[CrossRef\]](#)
58. Liu, D.; Tian, B.; Zhang, M.; Jiang, L.; Li, C.; Qin, X.; Ma, J. Meta-analysis of the effects of different tillage methods on wheat yields under various conditions in China. *Soil Tillage Res.* **2025**, *248*, 106449. [\[CrossRef\]](#)
59. Wang, D.; Li, Y.; Zhang, B.; Jiang, T.; Wu, S.; Wu, W.; Li, Y.; He, J.; Liu, D.; Dong, Q.; et al. Explore the evolution of winter wheat production and its response to climate change under varying precipitation years in the Loess Plateau of China. *Agric. Water Manag.* **2025**, *309*, 109335. [\[CrossRef\]](#)
60. Yan, Z.; Xu, Y.; Chu, J.; Guillaume, T.; Bragazza, L.; Li, H.; Shen, Y.; Yang, Y.; Zeng, Z.; Zang, H. Long-term diversified cropping promotes wheat yield and sustainability across contrasting climates: Evidence from China and Switzerland. *Field Crops Res.* **2025**, *322*, 109764. [\[CrossRef\]](#)
61. Zhang, L.; Cao, Y.; Qian, W.; Tian, J.; Huang, S.; Qiu, X.; Liu, B.; Tang, L.; Xiao, L.; Cao, W.; et al. Spatiotemporal optimization of irrigation practices for winter wheat in China: Rationale, implications, and solutions. *Agric. Water Manag.* **2025**, *308*, 109297. [\[CrossRef\]](#)
62. Jiang, T.; He, L.; Feng, H.; He, J.; Yu, Q. Understanding the impacts of extreme temperature and humidity compounds on winter wheat traits in China. *Agric. For. Meteorol.* **2025**, *362*, 110354. [\[CrossRef\]](#)
63. Rebouh, N.Y.; Mohamed, E.S.; Polityko, P.M.; Dokukin, P.A.; Kucher, D.E.; Latati, M.; Okeke, S.E.; Ali, M.A. Towards improving the precision agriculture management of the wheat crop using remote sensing: A case study in Central Non-Black Earth region of Russia. *Egypt. J. Remote Sens. Space Sci.* **2023**, *26*, 505–517. [\[CrossRef\]](#)
64. Aliu, F.; Kučera, J.; Hašková, S. Agricultural Commodities in the Context of the Russia-Ukraine War: Evidence from Corn, Wheat, Barley, and Sunflower Oil. *Forecasting* **2023**, *5*, 351–373. [\[CrossRef\]](#)
65. Gulyaeva, E.; Gannibal, P.; Shaydayuk, E. Long-Term Studies of Wheat Leaf Rust in the North-Western Region of Russia. *Agriculture* **2023**, *13*, 255. [\[CrossRef\]](#)
66. Georgieva, V.; Guerov, G.; Blagoeva, N. Impact of economic and environmental factors on agricultural product pricing in the EU. *Agric. Resour. Econ.* **2024**, *10*, 47–73. [\[CrossRef\]](#)
67. Mandych, O.V.; Staverska, T.O.; Kemza, R.G.; Makohon, V.V. Assessment of trends in the functioning of the grain industry of the EU countries using ARDL modeling. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1415*, 012045. [\[CrossRef\]](#)
68. Aljohani, E.S.; Chidmi, B. Analyzing technical efficiency in cereal production across selected European Union countries. *Sustainability* **2024**, *16*, 546. [\[CrossRef\]](#)
69. Polish Statistic Database. Available online: <https://bdl.stat.gov.pl/bdl/start> (accessed on 16 January 2025).
70. Warunki Klimatyczne w Polsce. Available online: https://hikersbay.com/climate-conditions/poland/warunki-klimatyczne-w-polsce.html?lang=pl&utm_source=chatgpt.com (accessed on 16 January 2025).
71. Wieści Rolnicze, Ceny Zboż. Available online: https://wiescirolnicze.pl/ceny-rolnicze/zboza/?utm_source=chatgpt.com (accessed on 16 January 2025).
72. Ile Rolnik Zarobi Lub Straci na Zbożach i Rzepaku? Available online: https://www.tygodnik-rolniczy.pl/pieniadze/oplalnosc-w-rolnictwie/ile-rolnik-zarobi-lub-straci-na-zbozach-i-rzepaku-znamy-wyliczenia-ekspertow-2453174?utm_source=chatgpt.com (accessed on 16 January 2025).
73. Siamba, S.; Otieno, A.; Koech, J. Application of ARIMA, and hybrid ARIMA Models in predicting and forecasting tuberculosis incidences among children in Homa Bay and Turkana Counties, Kenya. *PLoS Digit. Health* **2023**, *2*, e0000084. [\[CrossRef\]](#)
74. Liu, W.; Ganbaatar, B.; Wang, Z. Sales innovation and synergy strategy of Chinese pharmaceutical enterprises in the context of digital transformation: A perspective from the affordance theory. *J. Infrastruct. Policy Dev.* **2024**, *8*, 8352. [\[CrossRef\]](#)
75. Hamby, D.M. A review of techniques for parameter sensitivity analysis of environmental models. *Environ. Monit. Assess.* **1994**, *32*, 135–154. [\[CrossRef\]](#) [\[PubMed\]](#)
76. Saltelli, A.; Ratto, M.; Andres, T.; Campolongo, F.; Cariboni, J.; Gatelli, D.; Saisana, M.; Tarantola, S. *Global Sensitivity Analysis: The Primer*; John Wiley & Sons: London, UK, 2008.

77. Zhang, K.; Chu, Z.; Xing, J.; Zhang, H.; Cheng, Q. Urban Traffic Flow Congestion Prediction Based on a Data-Driven Model. *Mathematics* **2023**, *11*, 4075. [CrossRef]
78. Saxena, A.; Prasad, M.; Gupta, A.; Bharill, N.; Patel, O.; Tiwari, A.; Er, M.J.; Ding, W.; Lin, C.-T. A review of clustering techniques and developments. *Neurocomputing* **2017**, *267*, 664–681. [CrossRef]
79. Xu, D.; Tian, Y. A comprehensive survey of clustering algorithms. *Ann. Data Sci.* **2015**, *2*, 165–193. [CrossRef]
80. Hyndman, R.J.; Athanasopoulos, G. *Forecasting: Principles and Practice*; OTexts: Melbourne, Australia, 2018; Available online: <https://robjhyndman.com/uwafiles/fpp-notes.pdf> (accessed on 15 January 2025).
81. Shumway, R.H.; Stoffer, D.S. *Time Series Analysis and Its Applications: With R Examples*; Springer: Cham, Switzerland, 2017.
82. Jain, A.K. Data clustering: 50 years beyond K-means. *Pattern Recognit. Lett.* **2010**, *31*, 651–666. [CrossRef]
83. Gong, X.; Li, B.; Yang, Y.; Xiang, X.; Zhou, X. Construction and Application of Optimized Model for Mine Water Inflow Prediction Based on Neural Network and ARIMA Model. *Sci. Rep.* **2025**, *15*, 2009. [CrossRef]
84. Jia, J.-s.; Zhao, J.-z.; Deng, H.-b.; Duan, J. Ecological footprint simulation and prediction by ARIMA model—A case study in Henan Province of China. *Ecol. Indic.* **2010**, *10*, 538–544. [CrossRef]
85. Muda, I.; Sidauruk, S.H.; Siregar, H.S.; Nurzaimah. The Effect of Corporate Social Responsibility on Company's Value with Common Effects Model (CEM), Fixed Effects Model (FEM) and Random Effects Model (REM) Approaches (Empirical Evidence in Indonesia Stock Exchange). *Qual. Access Success* **2018**, *19*, 79–90.
86. Luvhengo, U.; Shoko, R.R.; Lekunze, J.N. Using the Fixed Effect Model (FEM) to Determine the Effects of the South African National Health Insurance (NHI) Policy on Public Health Expenditure. *Asia Life Sci.* **2018**, *27*, 277–290.
87. Available online: https://commons.wikimedia.org/wiki/File:POLSKA_mapa_woj_z_powiatami.png (accessed on 17 February 2025).
88. Asare-Nuamah, P.; Botchway, E.; Nuamah, N.J.; Anane-Aboagye, M. The influence of climate change perception, experience and emotions on youths' participation in agriculture and agribusiness. *Clim. Dev.* **2025**. [CrossRef]
89. Sharofiddinov, H.; Islam, M.; Kotani, K. Adaptation indicator to climate change and farm sizes in agriculture: A reflection of farming culture and history. *Ecol. Indic.* **2025**, *170*, 112976. [CrossRef]
90. Szwed, M.; Karg, G.; Pińskwar, I.; Radziejewski, M.; Graczyk, D.; Kędziora, A.; Kundzewicz, Z.W. Climate change and its effect on agriculture, water resources and human health sectors in Poland. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 1725–1737. [CrossRef]
91. Ziętara, W.; Pietrzak, M.; Malak-Rawlikowska, A. Polish Dairy Farm Transformations and Competitiveness 20 Years after Poland's Accession to the European Union. *Animals* **2024**, *14*, 2013. [CrossRef]
92. Dadrasi, A.; Chaichi, M.; Nehbandani, A.; Salmani, F.; Nemati, A. Addressing food insecurity: An exploration of wheat production expansion. *PLoS ONE* **2023**, *18*, e0290684. [CrossRef]
93. Czuba, K.; Bastrzyk, A.; Rogowska, A.; Janiak, K.; Pacyna, K.; Kosińska, N.; Kita, M.; Chrobot, P.; Podstawczyk, D. Towards the circular economy—A pilot-scale membrane technology for the recovery of water and nutrients from secondary effluent. *Sci. Total Environ.* **2021**, *791*, 148266. [CrossRef] [PubMed]
94. Kolecka, N. Greening trends and their relationship with agricultural land abandonment across Poland. *Remote Sens. Environment.* **2021**, *257*, 112340. [CrossRef]
95. Gradziuk, P.; Gradziuk, B.; Trociewicz, A.; Jendrzewski, B. Potential of straw for energy purposes in Poland—Forecasts based on trend and causal models. *Energies* **2020**, *13*, 5054. [CrossRef]
96. Munsif, F.; Arif, M.; Khan, A.; Akhtar, K.; Ali, K.; Vincevica-Gaile, Z.; Rasul, F.; Iqbal, A.; Fahad, S.; Burlakovs, J.; et al. Dual-purpose wheat technology: A tool for ensuring food security and livestock sustainability in cereal-based cropping pattern. *Arch. Agron. Soil. Sci.* **2021**, *67*, 1889–1900. [CrossRef]
97. Khan, G.-E.-L.; Irshad, G.; Ijaz, R.; Javaid, S.; Tahir, N.; Mehmood, S. Emboldening food security for global sustainability yoking artificial intelligence. *Discov. Food* **2025**, *5*, 2. [CrossRef]
98. Sahoo, S.; Singha, C.; Govind, A.; Moghimi, A. Review of climate-resilient agriculture for ensuring food security: Sustainability opportunities and challenges of India. *Environ. Sustain. Indic.* **2024**, *25*, 100544. [CrossRef]
99. Morey, C.; Kubota, J.; Anand, S.; Feng, X. Whole grains and ancient wheats: Knowledge, attitudes, consumption behavior and sensory liking of breads among participants in the United States. *Food Humanit.* **2025**, *4*, 100524. [CrossRef]
100. McBreen, J.; Babar, M.A.; Jarquin, D.; Santantonio, N.; Van Sanford, D.A. Enhancing prediction accuracy of grain yield in wheat lines adapted to the southeastern United States through multivariate and multi-environment genomic prediction models incorporating spectral and thermal information. *Plant Genome* **2025**, *18*, e20532. [CrossRef] [PubMed]
101. West, M.H.; Smith, W.B.; Mullenix, M.K.; Rabinowitz, A.N.; Dillard, S.L. Evaluation of dual-purpose wheat varieties in the Southeast United States. *Appl. Anim. Sci.* **2024**, *40*, 446–455. [CrossRef]

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