

Original Article

Air quality, governance, and agricultural productivity: a comparative study of South Asia and Southern Europe with implications for social and public health resilience

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Citation: Baig MK, Anjum W. Air quality, governance, and agricultural productivity: a comparative study of South Asia and Southern Europe with implications for social and public health resilience. *J Soc Health Sci.* 2024;3:36-48.

Received: 02 October 2024

Revised: 10 December 2024

Accepted: 13 December 2024

Published: 31 December 2024

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Abstract

Agricultural productivity plays a vital role in ensuring food security, rural livelihoods, and environmental sustainability, particularly in regions facing ecological stress and institutional variation. This study offers a comparative analysis of South Asian and Southern European countries from 2000–2022, investigating how environmental quality, economic investment, and governance influence agricultural output. Using secondary panel data and the Driscoll–Kraay (DSK) estimator, the analysis addresses the challenges of cross-sectional dependence (CSD), heteroskedasticity, and autocorrelation. The findings show that in South Asia, gross fixed capital formation (GFCF) ($\beta = 0.577$, $p < 0.01$) and fertilizer use ($\beta = 0.113$, $p < 0.01$) are significant drivers of productivity. Crop residue burning (CRB), despite its environmental drawbacks, also has a positive association with productivity ($\beta = 0.227$, $p < 0.01$). However, stricter air quality regulations appear to constrain productivity ($\beta = -0.228$, $p < 0.01$), likely due to disruptions in conventional farming practices. Governance and surface air temperature (SAT) were not statistically significant in this region. In Southern Europe, productivity is positively linked with GFCF ($\beta = 0.362$, $p < 0.01$), fertilizer use ($\beta = 0.203$, $p < 0.10$), and SAT ($\beta = 0.238$, $p < 0.05$), suggesting a potential benefit from moderate warming. No significant effects were observed for governance, air quality performance (AQP), or crop burning, likely reflecting stronger institutions and regulatory stability. The model explains a greater proportion of the productivity variation in South Asia ($R^2 = 0.8744$) than in Southern Europe ($R^2 = 0.1456$). These results highlight the importance of region-specific strategies. South Asia requires policies that reconcile environmental regulation with agricultural output, whereas Southern Europe should prioritize climate adaptation and ecological safeguards. Aligning agricultural policy with public health, governance, and sustainability goals is essential for resilient food systems.

Keywords

Agricultural productivity; Air quality; Air pollution; Crop residual burning; South Asia; Southern Europe; Governance; Climate change adaptation

1. Introduction

Agriculture holds a vital position in the economies of South Asian nations, contributing significantly to both gross domestic product (GDP) and employment. For example, in 2020, India's agricultural sector contributed nearly 18% of its GDP and employed approximately 58% of the population [1,2]. Pakistan's sector makes up 19.2% of GDP and employs 42% of the workforce [3]. In Bangladesh, agriculture accounts for 13.35% of GDP [4]. Other countries in the region—including Nepal, Bhutan, Sri Lanka, and Afghanistan—demonstrate similar economic patterns, where agriculture remains a foundational element of national development and rural livelihood strategies. These statistics highlight

the critical role that agricultural productivity plays not only in economic growth but also in supporting food security, income stability, and public health across the South Asian region [5].

In contrast, the European Union (EU) boasts a more diversified economy, where agriculture plays a smaller role in GDP but remains vital for rural livelihoods and food security. For example, in 2020, Germany's agricultural sector contributed approximately 1.1% of its GDP, whereas France's share was 1.7%, reflecting their highly industrialized economies [6,7]. However, countries such as Spain and Italy rely more heavily on agriculture, with contributions of 2.8% and 2.1%, respectively [8]. Despite the lower percentage relative to South Asia, the absolute value of agricultural output in European countries remains significant due to advanced technologies and high productivity levels, which support food system resilience, rural employment, and dietary health across the region. Given the close ties between agricultural productivity, food security, and population health, understanding these drivers is essential for addressing not only economic performance but also equity in health and well-being.

Climate change further intensifies vulnerability in the agricultural sector. In South Asia, extreme weather events—floods, droughts, and cyclones—have devastated crops and rural communities, undermining food availability and increasing the risk of malnutrition and rural poverty [5,9]. For example, the 2010 floods in Pakistan displaced more than 20 million people and caused \$5 billion in agricultural damage [9]. Similarly, India has experienced recurring droughts and heatwaves that reduce crop yields [10]. In Europe, the 2003 heatwave caused crop losses of approximately €13 billion [11]. While European countries benefit from strong institutions and adaptive technology, these disruptions still threaten regional food security and rural economic health [12].

Governance and institutional quality are also key mediators of agricultural resilience. In South Asia, governance challenges such as corruption, weak regulatory enforcement, and limited administrative capacity hinder effective agricultural policy implementation [13,14]. These weaknesses exacerbate rural inequality and reduce access to critical services such as subsidies, extension programs, and climate adaptation tools [15]. Southern European countries, by contrast, perform better on indicators such as rule of law, government effectiveness, and regulatory quality [14], which strengthens their capacity for inclusive and sustainable agricultural development [12].

Air pollution is another critical factor with implications for both human and environmental health. In South Asia, air pollution—intensified by CRB and industrial emissions—has led to severe public health consequences, including high rates of respiratory and cardiovascular diseases [16,17]. The World Health Organization (WHO) estimates that air pollution contributed to 4.2 million premature deaths globally in 2016 [18]. While air quality is better managed in many European countries, pollution remains an ongoing concern for agricultural productivity and ecosystem health [19,20].

Although the relationships among air pollution, governance, and agricultural productivity have been studied individually, few efforts have examined how these elements interact to shape broader social outcomes. Existing research is often fragmented—focused on economic productivity or environmental impacts—while overlooking public health, rural equity, and institutional capacity as interlinked dimensions of agricultural systems. Comparative analyses between developing and developed contexts remain rare, despite the value of such insights in informing policy design. For example, countries in South Asia and Southern Europe differ widely in terms of governance quality, regulatory enforcement, and technological adoption, yet both face pressing challenges in balancing agricultural productivity with environmental sustainability and social well-being [14,21,22,23].

The justification for comparing these two regions lies in their shared exposure to climate variability, reliance on agriculture as a significant livelihood source, and the growing burden of air pollution that directly and indirectly affects agricultural productivity. South Asia represents a developing context with weaker institutional capacity but higher population pressures, while Southern Europe reflects a developed context where stronger governance and technological integration coexist with challenges of aging rural populations and environmental sustainability. This contrast allows the study to highlight how differences in socioeconomic structures shape resilience mechanisms, thereby offering broader lessons applicable across both similar and divergent contexts.

This study addresses these gaps by evaluating how air quality performance (AQP), governance quality, and technological investments influence agricultural productivity across South Asia and Southern Europe. By comparing two distinct regional contexts, the research highlights how institutional conditions mediate environmental and productivity outcomes—and how these dynamics, in turn, affect rural livelihoods and public health. The study conceptualizes agricultural productivity, measured through the gross production index (GPI), as being influenced by environmental stressors (air pollution, CRB, surface temperature), governance strength (measured by a composite index of institutional quality), and technological investment (proxied through fixed capital formation and fertilizer use). This framework enables a multidimensional investigation into how environmental regulations, institutional capacity, and resource inputs jointly shape agricultural resilience and, by extension, social and health-related outcomes in both developing and developed settings.

2. Methods

2.1. Data sources and study scope

This study uses panel data spanning the years 2000–2022, covering 16 countries divided into two regional blocs: South Asia (Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka) and Southern Europe (Austria, Belgium, France, Germany, Italy, Netherlands, Portugal, Spain, Switzerland). These regions were selected to reflect stark contrasts in governance structures, technological advancement, and environmental policies. All the data were sourced from reputable public databases, including the Food and Agriculture Organization (FAO), World Bank, Yale Environmental Performance Index (EPI), and World Bank Climate Change Knowledge Portal (WB-CCKP). The study examines agricultural productivity and its relationship with environmental, technological, and governance indicators.

Table 1. Description of variables and data sources.

Variables	Unit	Symbol	Source
Gross Production Index	Index	GPI	FAO
Air Quality Performance	Index	AQP	EPI 2000–2022
Surface Air Temperature	°C	SAT	WB-CCKP
Agriculture Gross Fixed Capital Formation	million USD	GFCF	FAO
Crops residue burning (Greenhouse gas emissions)	Kiloton (kt)	CRB	FAO
World Governance Index	Index	WGI	World Bank
Fertilizers by Nutrients	ton	FERT	FAO

Abbreviations: FAO = Food and Agriculture Organization; WB-CCKP = World Bank Climate Change Knowledge Portal; EPI = Environmental Performance Index.

2.2. Data construction and transformation

All the variables in this study were harmonized to ensure consistency across countries and years. Annual data were collected for each country and cleaned to remove inconsistencies or gaps. Where necessary, variables were adjusted or averaged (e.g., temperature) to standardize temporal comparability. The following sections explain the source and transformation of each variable used in the empirical model:

2.2.1. Gross production index (GPI)

The GPI serves as the dependent variable and captures the relative volume of agricultural output. Published by the FAO, this index is set to a base period (2014–2016 = 100) and aggregates the production volumes of various agricultural commodities, weighted by international reference prices. It offers a standardized measure of agricultural productivity across time and space [24].

2.2.2. Air quality performance (AQP)

The AQP data are derived from the Yale EPI, which consolidates 40 environmental indicators across 180 countries. AQPs specifically reflect a nation's capacity to mitigate air pollution and maintain healthy air standards. Higher scores indicate stronger air quality control efforts [25].

2.2.3. Mean surface air temperature (SAT)

The temperature data were retrieved from the World Bank's Climate Change Knowledge Portal. The monthly average temperatures from 1901–2022 were accessed, and annual means were computed for each country from 2000–2022 to reflect the climatic pressure on agricultural systems [26].

2.2.4. Gross fixed capital formation in agriculture (GFCF)

This variable, provided by the FAO, reflects the annual net investments in physical agricultural assets. It includes acquisitions of machinery, irrigation infrastructure, and on-farm improvements, minus disposals. GFCF serves as a proxy for technological modernization and long-term production capacity in agriculture [27].

2.2.5. Crop residue burning (CRB)

CRB is measured by greenhouse gas (GHG) emissions, expressed in CO₂-equivalent kilotons, resulting from the open burning of crop residues. The emissions data—covering methane and nitrous oxide—are accessed through the FAO's Emissions Totals domain and are used as indicators of unsustainable land-clearing practices [28].

2.2.6. World governance index (WGI)

Governance quality is assessed via the World Bank's six worldwide governance indicators: voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption. The average of these indicators forms the WGI score, which reflects a country's institutional capacity to enforce policies and support rural development [26].

2.2.7. Fertilizers by nutrients (FERT)

Fertilizer use is measured in tons of active nutrient ingredients: nitrogen (N), phosphorus (P₂O₅), and potassium (K₂O). These data from FAOSTAT highlight the input inten-

sity used to maintain soil fertility and enhance crop yield, excluding nonnutrient fillers [29].

2.2.8. Data scaling and normalization

Each variable's data are carefully curated and transformed by reputable organizations to provide accurate and comprehensive insights into various aspects of agricultural and environmental performance. The complete dataset is initially transformed by applying the natural logarithm to the values. The data are subsequently normalized via the min-max normalization method, which is defined as:

$$X' = (X - X_{\min}) / (X_{\max} - X_{\min}) \quad (1)$$

where X is the original value, $X_{\min}$ is the minimum observed value in the dataset, $X_{\max}$ is the maximum, and X' is the normalized value. This approach ensures uniform scaling and allows for comparative modeling across diverse units and distributions.

2.3. Model specification

This study employs a panel regression model to evaluate the effects of AQP, SAT, GFCF, CRB, WGI, and FERT on agricultural productivity, measured through GPI (Equation 1). The relationship is specified as:

$$GPI_{it} = \alpha_1 AQP_{it} + \alpha_2 SAT_{it} + \alpha_3 GFCF_{it} + \alpha_4 CRB_{it} + \alpha_5 WGI_{it} + \alpha_6 FERT_{it} + \varepsilon_{it} \quad (2)$$

where i and t denote the country and year, respectively. The model is estimated separately for South Asian and Southern European countries to reflect structural and institutional heterogeneity.

2.4. Econometric diagnostic and estimation procedure

The analysis began with the computation of descriptive statistics and a correlation matrix to examine the central tendencies and relationships among the variables. Multicollinearity was assessed via the variance inflation factor (VIF), which confirmed the absence of significant multicollinearity. To evaluate the presence of cross-sectional dependence (CSD), the Friedman and Breusch–Pagan LM tests were applied, both of which confirmed the existence of CSD in the panel data [30,31].

Given the presence of CSD, second-generation panel unit root tests were used to assess the stationarity of the variables. Specifically, cross-sectionally augmented Im–Pesaran–Shin (CIPS) and covariate-augmented Dickey–Fuller (CADF) tests were conducted, confirming stationarity at appropriate levels. White's test indicated the presence of heteroskedasticity [32], whereas Wooldridge's test confirmed first-order autocorrelation [33]. The Westerlund and Edgerton cointegration test was then employed, establishing the existence of long-run relationships among the variables [33].

To determine a suitable panel estimation technique, the Hausman specification test was used [34], which supported the use of a fixed effects model. Given the findings of heteroskedasticity, autocorrelation, and CSD, the final model was estimated via both Panel-Corrected Standard Errors (PCSE) and the Driscoll–Kraay (DSK) estimator. These methods adjust standard errors for serial correlation and CSD, providing robust inference. All variables were transformed for the fixed effects model as specified in Equation (2).

3. Results

3.1. Descriptive statistics and distribution

Table 2 shows the descriptive statistics for all the variables, highlighting regional differences in agricultural productivity and input measures. Across the panel of South Asian countries, the average GPI is 88.95 ± 18.61 , which is lower than the value of 98.33 ± 6.70 observed for Southern European countries, indicating relatively lower agricultural productivity in the former region. South Asia also exhibits more variability in productivity, highlighting uneven agricultural development across countries in that region. The SAT is considerably greater in South Asia ($19.74 \pm 6.33^\circ\text{C}$) than in Southern Europe ($11.27 \pm 2.90^\circ\text{C}$), reflecting climatic differences that may affect crop performance. Investment in fixed capital is also greater in South Asia (7532.46 ± 16205.21 million USD) than in Southern Europe (5784.49 ± 4666.75 million USD), although its high variability indicates inconsistent investment patterns. The CRB is more prominent in South Asia (862.44 ± 1478.59 kt) than in Southern Europe (97.04 ± 111.72 kt), suggesting regional differences in land-clearing practices. Fertilizer use in South Asia is significantly greater and more erratic ($4149604.00 \pm 8267632.50$ tons) than that in Southern Europe ($1047062.20 \pm 1109877.70$ tons), indicating less regulated or less efficient application. Moreover, governance quality, measured by the WGI, is notably lower in South Asia (-0.65 ± 0.60) than in Southern Europe (1.27 ± 0.36), and the AQP is also poorer (44.55 ± 17.78 vs. 69.29 ± 13.72), reflecting institutional and environmental disparities.

Table 2. Descriptive statistics for South Asian and Southern European Countries (2000–2022).

Variable	Mean $\pm$ SD	Minimum–Maximum	Shapiro–Wilk	Shapiro–Francia
<i>South Asian Countries (Observations = 161)</i>				
GPI	88.95 ± 18.61	48.94–125.81	0.00001	0.00004
AQP	44.55 ± 17.78	5.70–79.45	0.00000	0.00001
WGI	-0.65 ± 0.60	-1.96–0.58	0.00430	0.00845
GFCF	7532.46 ± 16205.21	9.66–71118.81	0.00000	0.00001
CRB	862.44 ± 1478.59	1.32–4836.10	0.00046	0.00124
FERT	$4149604.00 \pm 8267632.00$	0.00–32535600.00	0.01100	0.01971
SAT	19.74 ± 6.33	9.88–27.72	0.00966	0.01668
<i>Southern European Countries (Observations = 207)</i>				
GPI	98.33 ± 6.70	81.58–127.54	0.00249	0.00561
AQP	69.29 ± 13.72	28.79–99.94	0.00038	0.00104
WGI	1.27 ± 0.36	0.48–1.87	0.00014	0.00045
GFCF	5784.49 ± 4666.75	343.43–18020.30	0.00000	0.00001
CRB	97.04 ± 111.72	3.20–374.97	0.00004	0.00015
FERT	$1047062.00 \pm 1109877.00$	65174.17–4178000.00	0.00008	0.00027
SAT	11.27 ± 2.90	5.34–16.90	0.01485	0.02287

3.2. Multicollinearity diagnostics

Table 3 presents the VIF results for both regions. All the VIF values are below the conventional threshold of 10, with mean VIFs of 1.455 and 1.472 for South Asia and Southern Europe, respectively, indicating that multicollinearity is not a concern for either panel dataset.

Table 3. Variance inflation factor analysis for explanatory variables in South Asian and Southern European country samples.

Variable	South Asian Countries		Southern European Countries	
	VIF	1/VIF	VIF	1/VIF
AQP	1.155	0.866	1.556	0.643
WGI	1.028	0.972	1.797	0.556
GFCF	2.321	0.431	1.553	0.644
CRB	1.702	0.587	1.197	0.836
FERT	1.488	0.672	1.607	0.622
SAT	1.034	0.968	1.121	0.892
Mean VIF	1.455	-	1.472	-

3.3. Panel data properties and diagnostic tests

CSD was confirmed through both the Friedman and Breusch–Pagan LM tests, indicating that countries within each region experience common shocks or spillover effects (see Supplementary Table S1). Given the presence of CSD, it was essential to apply second-generation unit root tests. The CIPS and CADF results showed that most variables are stationary at levels or first differences, confirming the validity of further panel analysis (see Supplementary Table S2).

The correlation matrix presented in Supplementary Table S3 highlights strong and statistically significant relationships among key variables. For instance, in South Asia, GPI is highly correlated with GFCF ($r = 0.878$) and CRB ($r = 0.627$), reflecting the importance of capital investment and residue burning practices. In Southern Europe, GPI shows moderate positive correlations with SAT ($r = 0.272$) and GFCF ($r = 0.258$), suggesting that temperature variation and investment also play meaningful roles in that region.

Westerlund and Edgerton cointegration tests revealed no long-run cointegration among the variables in either region (Table 4), suggesting the absence of stable long-term equilibrium relationships.

Table 4. Westerlund cointegration test results for South Asian and Southern European countries.

Variable	South Asian Countries	Southern European Countries
Gt	-1.850	-2.811
Pt	-4.043	-7.528
Ga	-4.599	-7.901
Pa	-4.002	-7.803

Furthermore, Wooldridge and White's tests detected autocorrelation and mild heteroskedasticity (Table 5), necessitating robust estimation. The Hausman specification test confirmed that fixed effects estimation was appropriate (see Supplementary Table S1), justifying the use of the Driscoll–Kraay estimator for final model estimation.

Table 5. White's heteroskedasticity and Wooldridge autocorrelation test results.

	South Asian Countries	Southern European Countries
White's test for heteroskedasticity	4.850, $p = 0.0699$	0.676, $p = 0.4349$
Wooldridge test for autocorrelation	87.490, $p < 0.0001$	41.540, $p = 0.0365$

3.4. Regression results

Table 6 reports the final regression estimates via the DSK estimator. In South Asia, three predictors significantly influence agricultural productivity (GPI). The AQP showed a significant negative association ($\beta = -0.228$, $p < 0.01$), suggesting that air quality regulations might impose short-term trade-offs on output. Conversely, GFCF ($\beta = 0.577$, $p < 0.01$) and fertilizer use ($\beta = 0.113$, $p < 0.01$) were positively associated with productivity, indicating their role in increasing output. CRB also had a positive effect ($\beta = 0.227$, $p < 0.01$), potentially due to short-term nutrient recycling benefits. However, SAT and governance (WGI) were not significant in South Asia. In Southern Europe, GFCF ($\beta = 0.362$, $p < 0.01$), fertilizer use ($\beta = 0.203$, $p < 0.10$), and SAT ($\beta = 0.238$, $p < 0.05$) were significantly and positively associated with productivity. However, AQP, WGI, and CRB were statistically insignificant in this region. The R^2 value for South Asia (0.8744) far exceeds that for Southern Europe (0.1456), implying that the model better explains agricultural productivity variation in the former.

Table 6. Driscoll–Kraay fixed effects regression results for South Asian and Southern European countries.

GPI	South Asian Countries	Southeran European Countries
AQP	-0.2280 *** (0.0614)	0.0445 (0.1040)
WGI	0.0483 (0.0367)	0.0914 (0.0655)
GFCF	0.5770 *** (0.0400)	0.3620 *** (0.1110)
CRB	0.2270 *** (0.0397)	0.0670 (0.0642)
FERT	0.1130 *** (0.0417)	0.2030 * (0.1000)
SAT	0.0459 (0.0343)	0.2380 ** (0.0872)
Constant	0.1650 ** (0.0675)	-0.1020 (0.1180)
R-Squared	0.8744	0.1456
Observations	161	207
Countries	7	9

*, ** and *** represent the 10%, 5% and 1% significance levels, respectively. The p value is shown in parentheses.

4. Discussion

This study provides new evidence on how multiple environmental, economic, and institutional factors jointly affect agricultural productivity across two distinct regions—South Asia and Southern Europe. The comparative perspective offers a nuanced understanding of how development levels, governance structures, and agroecological contexts shape agricultural outcomes. Importantly, by incorporating variables such as the AQP and governance, this research extends beyond traditional economic assessments of productivity to address broader social and public health dimensions. In particular, air pollution, often exacerbated by practices such as CRB, has direct implications for community health and respiratory outcomes, especially in densely populated agrarian regions. Similarly, institutional quality influences not only economic coordination but also the equitable delivery of agricultural support services and health-adjacent infrastructure, such as clean water access, sanitation, and disaster preparedness. By linking agricultural

productivity to these wider systems, this study highlights the importance of integrating public health resilience and social welfare into policy frameworks aimed at sustainable agricultural development.

In South Asia, the significant negative effect of the AQP on agricultural productivity highlights the short-term trade-offs involved in environmental regulation. While improvements in air quality are essential for public health, they may restrict certain agromonic practices, such as residue burning, low-cost irrigation techniques, or mechanized plowing, that contribute to short-term output. This dynamic reflects the broader tension between environmental sustainability and economic survival in agrarian economies, where farmers operate under narrow profit margins and have limited capacity to adapt to policy shocks [35,36,37]. Furthermore, the insignificant effect of the SAT in the South Asian model may reflect a saturation point beyond which additional warming no longer benefits productivity or even begins to degrade it. Several studies suggest that high base temperatures and increased heatwave frequency in South Asia already threaten staple crop yields, exacerbating food insecurity [38,39,40].

Capital formation and fertilizer use, however, remain the most robust positive drivers of productivity in South Asia. The results affirm the longstanding belief that agricultural growth in lower-income countries continues to depend heavily on input intensification, infrastructure development, and mechanization. GFCF likely captures investments in irrigation systems, machinery, and transport logistics—all of which increase land and labor productivity. Similarly, fertilizer application increases soil fertility and crop yields, although excessive or unbalanced use may carry long-term ecological risks such as nutrient runoff and soil acidification [41]. Recent studies have confirmed that precision fertilization and integrated nutrient management can balance productivity gains with environmental protection [42,43,44].

Perhaps most surprising is the significant and positive relationship between CRB and productivity in South Asia. While the practice is environmentally detrimental—emitting large amounts of particulate matter, CO₂, and other pollutants—it appears to serve as a low-cost method for field clearing and nutrient recycling, particularly among resource-constrained farmers [45]. Similarly, previous studies have reported that CRB may lead to short-term productivity gains by quickly preparing land for the next sowing cycle [46]. However, this increase comes at the cost of serious air quality degradation, contributing to respiratory health crises in rural and peri-urban areas [45,47]. Thus, the productivity benefits of CRB must be carefully weighed against its long-term environmental and public health consequences.

In contrast, the Southern European results reveal a more climate-sensitive and infrastructure-oriented story. Here, the SAT is positively associated with agricultural productivity, likely because moderate warming extends the growing season and improves crop suitability in previously cooler regions [48]. These findings are consistent with studies on Mediterranean and temperate climates, which show that a 1–2°C rise can increase yields under adequate water availability and modern farming systems [49,50]. Unlike South Asia, the effects of air quality and governance are statistically insignificant in this region, possibly because of already well-established environmental standards and institutional stability [51]. Southern Europe has long benefited from environmental regulation under EU frameworks and higher levels of farmer compliance, which may dilute the observable productivity impacts in cross-country analysis [51].

Fertilizer use and capital investment also play positive roles in Southern Europe, although the magnitude of these effects is smaller than that in South Asia [52,53]. This could reflect the law of diminishing returns, whereby European farmers already operate near optimal input levels, and additional investments yield marginal gains [54]. Moreover,

governance quality, although insignificant, has a positive coefficient—suggesting that its stabilizing effects on markets, extension services, and land rights may be more long-term in nature and less observable in short-run productivity estimates. The much lower R^2 value in the Southern Europe model also indicates that productivity is influenced by additional variables not captured in this analysis, such as labor migration, EU subsidies, or biodiversity preservation policies.

In both regions, the findings reflect a growing need to align agricultural productivity goals with climate resilience, environmental health, and social equity. The regional differences imply that one-size-fits-all solutions are unlikely to be effective. South Asian countries, in particular, face a challenging policy environment where productivity imperatives often conflict with environmental and health objectives. In this context, adaptive strategies such as precision farming, climate-smart agriculture, and institutional strengthening must take center stages to ensure sustainable development.

This study's strength lies in its comprehensive comparative design and methodological rigor, revealing how environmental, economic, and institutional factors affect agricultural productivity. However, the limited explanatory power in Southern Europe and reliance on aggregate data constrain insight into local and farmer-level dynamics. Future research should integrate microlevel or subregional data and explore the links among agricultural policy, public health outcomes, and social equity. Emphasis should also be placed on how environmental regulations and technological transitions impact vulnerable populations, especially in regions where agriculture supports livelihoods as well as community health. The incorporation of interdisciplinary perspectives from health, governance, and rural sociology could offer more holistic policy insights and strengthen adaptive capacity in diverse agricultural systems.

5. Conclusion and policy implications

This study provides compelling comparative insights into the complex dynamics shaping agricultural productivity in South Asia and Southern Europe. While capital investment and fertilizer use consistently drive productivity across both regions, environmental regulation, governance quality, and climate conditions exert region-specific effects. These findings highlight the importance of designing tailored agricultural policies that reflect the unique socioenvironmental challenges of each context. In South Asia, stringent air quality regulations, although vital for environmental health, appear to limit short-term agricultural output. Simultaneously, the widespread use of CRB, while increasing productivity, imposes serious public health and environmental costs through elevated air pollution and associated respiratory risks. This dual challenge calls for integrated policy responses that support cleaner technologies and offer transitional support for affected farmers.

The significant positive effects of capital formation and fertilizer use in South Asia reflect ongoing modernization, but the high variability in fertilizer application points to inefficient and potentially harmful practices. These inefficiencies may degrade soil health and contaminate water systems, threatening long-term productivity. Policymakers must therefore promote efficient input use through strengthened extension services, credit access, and regionally tailored guidance. In contrast, Southern Europe appears to benefit from a moderate warming trend, likely due to favorable baseline temperatures and the presence of robust infrastructure and institutional support. While fertilizer use and capital investment remain key productivity drivers in this region, they are applied more uniformly and effectively. Interestingly, governance and AQP are not statistically significant in Southern Europe, perhaps because of already well-established regulatory frameworks.

Despite this relative stability, European agricultural systems are not immune to future risks. Fertilizer intensification poses environmental threats, particularly in nitrate-sensitive zones, and ongoing climate change demands proactive adaptation measures. Investment in precision agriculture, climate-smart technologies, and continued institutional reinforcement will be critical. Ultimately, across both regions, the study highlights that agricultural development must extend beyond economic considerations to incorporate social equity and public health imperatives. Environmental degradation, air pollution, and climate variability disproportionately affect vulnerable populations, making sustainable agriculture essential for ensuring food security, human well-being, and ecological resilience in the years ahead.

Supplementary materials: The following supporting information can be accessed through the embedded links: [Supplementary Table S1](#), Model specification and cross-sectional dependence test results; [Supplementary Table S2](#), Panel unit root test results using CIPS and CADF methods; and [Supplementary Table S3](#), Correlation matrix of variables used in the study for South Asian and Southern European countries.

Author contributions: Conceptualization, MKB, and WA; methodology, MKB, and WA; software, MKB; validation, MKB; formal analysis, MKB; investigation, MKB; resources, MKB; data curation, MKB, and WA; writing—original draft preparation, MKB, and WA; writing—review and editing, MKB; visualization, MKB; supervision, MKB; project administration, MKB. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no specific grant from the public, commercial, or not-for-profit funding agencies.

Ethics statement: Not Applicable.

Consent to participate: Not Applicable.

Data availability: The data supporting this study's findings are available from the corresponding author, Mirza Khawar Baig, upon reasonable request.

Acknowledgments: None.

Conflicts of interest: The authors declare no conflicts of interest.

References

- [1] Ministry of Agriculture & Farmers Welfare. Contribution of agricultural sector in GDP. 2024 [cited 03 Dec 2024]. Available from: <https://www.pib.gov.in/PressReleasePage.aspx?PRID=1909213>.
- [2] Statista. Agriculture in India — statistics & facts. 2024 [cited 03 Dec 2024]. Available from: <https://www.statista.com/topics/4868/agricultural-sector-in-india/#topicoverview>.
- [3] Hena S, Zhang O, Luan J, Adil R, Khalil IU, Sahar S, et al. Impact of human capital on sectoral growth in Pakistan: a review essay. *J Appl Environ Biol Sci*. 2018;8(11):7-31.
- [4] Chowhan S, Rahman MM, Sultana R, Rouf MA, Islam M. Contribution of agriculture sector in the GDP growth of Bangladesh. *Food Agri Econ Rev*. 2023;3(2):51–4. <https://doi.org/10.26480/faer.02.2023.51.54>
- [5] Aryal JP, Sapkota TB, Khurana R, Khatri-Chhetri A, Rahut DB, Jat ML. Climate change and agriculture in South Asia: adaptation options in smallholder production systems. *Environ Dev Sustain*. 2020;22:5045-75. <https://doi.org/10.1007/s10668-019-00414-4>
- [6] Bringezu S, Distelkamp M, Lutz C, Wimmer F, Schaldach R, Hennenberg KJ, et al. Environmental and socioeconomic footprints of the German bioeconomy. *Nat Sustain*. 2021;4:775–83. <https://doi.org/10.1038/s41893-021-00725-3>
- [7] Szczepańska-Przekota A. Conditions of agriculture compared to economic growth in selected countries. *Eur Res Stud J*. 2020;23 (Special 1):693-707. <https://doi.org/10.35808/ersj/1786>
- [8] Rokicki T, Perkowska A, Klepacki B, Bórawski P, Bełdycka-Bórawska A, Michalski K. Changes in energy consumption in agriculture in the EU countries. *Energies*. 2021;14(6):1570. <https://doi.org/10.3390/en14061570>
- [9] Mahmood S, Sajjad A, Rahman Au. Cause and damage analysis of 2010 flood disaster in district Muzaffar Garh, Pakistan. *Nat Hazards*. 2021;107:1681-92. <https://doi.org/10.1007/s11069-021-04652-6>
- [10] Guntukula R. Assessing the impact of climate change on Indian agriculture: evidence from major crop yields. *J Public Aff*. 2020 ;20(1):e2040. <https://doi.org/10.1002/pa.2040>
- [11] Brás TA, Seixas J, Carvalhais N, Jägermeyr J. Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environ Res Lett*. 2021;16(6):065012. <https://doi.org/10.1088/1748-9326/abf004>

- [12] Pe'er G, Bonn A, Bruelheide H, Dieker P, Eisenhauer N, Feindt PH, et al. Action needed for the EU Common Agricultural Policy to address sustainability challenges. *People Nat.* 2020;2(2):305-16. <https://doi.org/10.1002/pan3.10080>
- [13] Singh BP, Pradhan KC. Institutional quality and economic performance in South Asia. *J Public Aff.* 2022;22:e2401. <https://doi.org/10.1002/pa.2401>
- [14] World Bank Group. Worldwide Governance Indicators. 2024 [cited 03 Dec 2024]. Available from: <https://www.worldbank.org/en/publication/worldwide-governance-indicators>.
- [15] Nambassa G, Qodir Z. Addressing corruption and government challenges: the case of Uganda's strategic developments policies. *J Transform Glob.* 2024;11(2):147-69. <https://doi.org/10.21776/ub.jtg.011.02.3>
- [16] Irfan H. Air pollution and cardiovascular health in South Asia: a comprehensive review. *Curr Probl Cardiol.* 2024;49(2):102199. <https://doi.org/10.1016/j.cpcardiol.2023.102199>
- [17] Bhuvaneshwari S, Hettiarachchi H, Meegoda JN. Crop residue burning in India: policy challenges and potential solutions. *Int J Environ Res Public Health.* 2019;16(5):832. <https://doi.org/10.3390/ijerph16050832>
- [18] United Nations Office for Disaster Risk Reduction (UNDRR). Ambient (outdoor) air pollution. 2024 [cited 03 Dec 2024]. Available from: <https://www.undrr.org/understanding-disaster-risk/terminology/hips/en0003>.
- [19] Sicard P, Agathokleous E, De Marco A, Paoletti E, Calatayud V. Urban population exposure to air pollution in Europe over the last decades. *Environ Sci Eur.* 2021;33:28. <https://doi.org/10.1186/s12302-021-00448->.
- [20] Stevens CJ, Bell JNB, Brimblecombe P, Clark CM, Dise NB, Fowler D, et al. The impact of air pollution on terrestrial managed and natural vegetation. *Phil Trans R Soc A.* 2020;378(2183):20190317. <https://doi.org/10.1098/rsta.2019.0317>
- [21] Singh BP, Pradhan KC. Institutional quality and economic performance in South Asia. *J Public Aff.* 2022;22(1):e2401. <https://doi.org/10.1002/pa.2401>
- [22] Adisa O, Ilugbusi BS, Adewunmi OA, Asuzu OF, Ndubuisi LL. A comprehensive review of redefining agricultural economics for sustainable development: overcoming challenges and seizing opportunities in a changing world. *World J Adv Res Rev.* 2024;21(1):2329-41. <https://doi.org/10.30574/wjarr.2024.21.1.0322>
- [23] Wei J, Lei Y, Yao H, Ge J, Wu S, Liu L. Estimation and influencing factors of agricultural water efficiency in the Yellow River basin, China. *J Clean Prod.* 2021;308:127249. <https://doi.org/10.1016/j.jclepro.2021.127249>
- [24] Food and Agriculture Organization of the United Nations. FAOSTAT: Production indices. [cited 03 Dec 2024]. Available from: <https://www.fao.org/faostat/en/#data/QI>.
- [25] Environmental Performance Index. About the EPI. 2024 [cited 03 Dec 2024]. Available from: <https://epi.yale.edu>.
- [26] World Bank Group. Overview. 2024 [cited 03 Dec 2024]. Available from: <https://www.worldbank.org/en/publication/worldwide-governance-indicators>.
- [27] Food and Agriculture Organization of the United Nations. FAOSTAT: country investment statistics profile. 2024 [cited 03 Dec 2024]. Available from: <https://www.fao.org/faostat/en/#data/CISP/metadata>
- [28] Food and Agriculture Organization of the United Nations. FAOSTAT: emissions totals. 2024 [cited 03 Dec 2024]. Available from: <https://www.fao.org/faostat/en/#data/GT/metadata>
- [29] Food and Agriculture Organization of the United Nations. FAOSTAT: fertilizers by nutrient. 2024 [cited 03 Dec 2024]. Available from: <https://www.fao.org/faostat/en/#data/RFN/metadata>.
- [30] Friedman M. The use of ranks to avoid the assumption of normality implicit in the analysis of variance. *J Am Stat Assoc.* 1937;32(200):675-701. <https://doi.org/10.1080/01621459.1937.10503522>
- [31] Breusch TS, Pagan AR. The Lagrange Multiplier test and its applications to model specification in econometrics. *Rev Econ Stud.* 1980;47(1):239-53. <https://doi.org/10.2307/2297111>
- [32] White H. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica.* 1980;48(4):817-38. <https://doi.org/10.2307/1912934>
- [33] Wooldridge JM. Diagnostic testing. In: Baltagi BH, editor. *A companion to theoretical econometrics*. Oxford: Wiley-Blackwell. p. 180-200.
- [34] Hausman JA. Specification tests in econometrics. *Econometrica.* 1978;46(6):1251-71. <https://doi.org/10.2307/1913827>
- [35] Touch V, Tan DKY, Cook BR, Liu DL, Cross R, Tran TA, et al. Smallholder farmers' challenges and opportunities: implications for agricultural production, environment and food security. *J Environ Manage.* 2024;370:122536. <https://doi.org/10.1016/j.jenvman.2024.122536>
- [36] Hamid S, Wang K. Environmental total factor productivity of agriculture in South Asia: a generalized decomposition of Luenberger-Hicks-Moorsteen productivity indicator. *J Clean Prod.* 2022;351:131483. <https://doi.org/10.1016/j.jclepro.2022.131483>
- [37] Petersen-Rockney M, Baur P, Guzman A, Bender SF, Calo A, Castillo F, et al. Narrow and brittle or broad and nimble? Comparing adaptive capacity in simplifying and diversifying farming systems. *Front Sustain Food Syst.* 2021;5:564900. <https://doi.org/10.3389/fsufs.2021.564900>
- [38] Subedi B, Poudel A, Aryal S. The impact of climate change on insect pest biology and ecology: implications for pest management strategies, crop production, and food security. *J Agric Food Res.* 2023;14:100733. <https://doi.org/10.1016/j.jafr.2023.100733>
- [39] Datta P, Behera B. Assessment of adaptive capacity and adaptation to climate change in the farming households of Eastern Himalayan foothills of West Bengal, India. *Environ Chall.* 2022;7:100462. <https://doi.org/10.1016/j.envc.2022.100462>
- [40] United Nations Environment Programme. Global Adaptation Network. 2024 [cited 03 Dec 2024]. Available from: <https://www.unep.org/gan/>.

- [41] Pandian K, Mustaffa MRAF, Mahalingam G, Paramasivam A, Prince AJ, Gajendiren M, et al. Synergistic conservation approaches for nurturing soil, food security and human health towards sustainable development goals. *J Hazard Mater Adv*. 2024;16:100479. <https://doi.org/10.1016/j.hazadv.2024.100479>
- [42] Lollato RP, Figueiredo BM, Dhillon JS, Arnall DB, Raun WR. Wheat grain yield and grain-nitrogen relationships as affected by N, P, and K fertilization: a synthesis of long-term experiments. *Field Crops Res*. 2019;236:42-57. <https://doi.org/10.1016/j.fcr.2019.03.005>
- [43] Liu J, Wang M, Yang L, Rahman S, Sriboonchitta S. Agricultural productivity growth and its determinants in South and South-east Asian countries. *Sustainability*. 2020;12(12):4981. <https://doi.org/10.3390/su12124981>
- [44] Sethy SK, Goyari P. Examining financial inclusion–agricultural productivity connection in South Asian countries: evidence from FMOLS and DOLS approaches. *Ital Rev Agric Econ*. 2023;78(1):33–48. <https://doi.org/10.36253/rea-14079>
- [45] Abdurrahman MI, Chaki S, Saini G. Stubble burning: Effects on health & environment, regulations and management practices. *Environ Adv*. 2020;2:100011. <https://doi.org/10.1016/j.envadv.2020.100011>
- [46] Lin M, Begho T. Crop residue burning in South Asia: a review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses. *J Environ Manag*. 2022;314:115104. <https://doi.org/10.1016/j.jenvman.2022.115104>
- [47] Raza MH, Abid M, Faisal M, Yan T, Akhtar S, Adnan KMM. Environmental and health impacts of crop residue burning: scope of sustainable crop residue management practices. *Int J Environ Res Public Health*. 2022;19(8):4753. <https://doi.org/10.3390/ijerph19084753>
- [48] Mukherjee A, Huda AKS, Saha S. Impact of climate change on future productivity and water use efficiency of wheat in eastern India. *Theor Appl Climatol*. 2023;152:421–34. <https://doi.org/10.21203/rs.3.rs-754866/v1>
- [49] Constantinidou K, Hadjinicolaou P, Zittis G, Lelieveld J. Effects of climate change on the yield of winter wheat in the eastern Mediterranean and Middle East. *Clim Res*. 2016;69:129–41. <https://doi.org/10.3354/cr01395>
- [50] Baytorun AN, Zaimoğlu Z. Climate control in Mediterranean greenhouses. In: Gündüz M, editor. *Greenhouse technology and management*. London: IntechOpen; 2018. p. 167-81.
- [51] Giannakis E, Kushta J, Violaris A, Paisi N, Lelieveld J. Inter-industry linkages, air pollution and human health in the European Union towards 2030. *Environ Dev Sustain*. 2024;2024. <https://doi.org/10.1007/s10668-024-05056-9>
- [52] Martino R. Public investment, convergence and productivity growth in European regions. No 19/2021 [WorkingPaper]. 2021 [cited 2024 Dec 3]. Available from: https://ideas.repec.org/p/frz/wpaper/wp2021_19.rdf.html
- [53] Alam A, Hasan H, Rehman HA, Rauf R. Maximizing cereal yields in South Asia: the impact of agricultural inputs. *J Econ Impact*. 2024;6(3):232–9. <https://doi.org/10.52223/econimpact.2024.6307>
- [54] Vigani M, Dwyer J. Profitability and efficiency of high nature value marginal farming in England. *J Agric Econ*. 2020;71:439-64. <https://doi.org/10.1111/1477-9552.12351>