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Industrial Air Pollution and Food-Security-Relevant Agricultural Output in Eastern China: Pollutant-Specific Evidence and the Role of Governance

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Abstract: Industrial air pollution poses growing risks to agricultural development, yet evidence remains mixed on pollutant-specific effects and on whether governance capacity can effectively mitigate these damages. Using balanced provincial panel data from 11 eastern Chinese provinces over 2011–2021, this study examines how industrial sulfur dioxide and nitrogen oxides emissions relate to agricultural economic output and whether investment in waste-gas treatment moderates these relationships. We estimate a two-way fixed effects panel model with province and year effects, province-clustered standard errors, and interaction terms between pollutants and governance investment. Results show that nitrogen oxides emissions are consistently associated with lower agricultural output across specifications. In contrast, the estimated relationship for sulfur dioxide is less robust and becomes statistically indistinguishable under alternative specifications and intensity-based robustness checks. We do not find robust contemporaneous evidence that governance investment significantly moderates the pollution–agriculture relationship, suggesting that spending levels alone may be insufficient or that governance effects operate with lags and through enforcement quality. Framed within the Sustainable Development Goals agenda, these findings connect cleaner production and institutional capacity to food security, ecosystem protection, climate-related risk management, and effective public administration. The evidence is also relevant to public health and sustainable communities by highlighting potential co-benefits of prioritizing nitrogen oxides control in industrial regions. By identifying a more policy-relevant priority pollutant and clarifying the limits of investment-only approaches, this study advances SDG-oriented research that links environmental indicators, governance mechanisms, and development performance in a unified empirical design.

Keywords: Industrial Air Pollution; SO_2 Emissions; NO_x Emissions; Agricultural Output; Governance Capacity; Waste-Gas treatment Investment; Two-Way Fixed Effects

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1.Introduction

Achieving sustainable and resilient food systems increasingly requires understanding how industrialization-driven environmental pressures affect agricultural production. In rapidly industrializing regions, air pollutants generated by industrial activities can impair crop yields, soil quality, and ecosystem services, thereby undermining agricultural development and food security. This concern is closely aligned with the Sustainable Development Goals (SDGs), particularly Zero Hunger, Climate

Action, and Life on Land. At the same time, the effectiveness of pollution control and environmental protection is shaped by governance capacity and institutional implementation, linking this topic to Strong Institutions.

Despite the importance of the pollution–agriculture nexus, existing evidence remains inconclusive in two respects. First, different pollutants may affect agriculture through distinct mechanisms, and empirical results often vary when multiple pollutants are modeled jointly. Second, while governance capacity is frequently emphasized as a key enabler of environmental protection, it is unclear whether governance-related investment can measurably buffer the adverse impacts of industrial emissions on agricultural output in the short run. These uncertainties limit the ability of policymakers to prioritize pollutant-specific interventions and design governance strategies that effectively support sustainable agricultural development.

This study addresses these gaps by examining the impacts of industrial sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions on agricultural economic output using a provincial panel dataset covering 11 provinces in Eastern China from 2011 to 2021. The sample includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, and Liaoning. These provinces are economically and industrially intensive, exhibit substantial variation in emissions profiles and environmental governance efforts, and provide a suitable setting to test pollutant-specific effects and governance-related heterogeneity over time.

Methodologically, we employ a two-way fixed effects panel model with province and year effects to account for time-invariant provincial characteristics and common macro shocks. We further introduce an interaction framework to test whether investment in waste-gas treatment (GTD) moderates the relationship between industrial emissions and agricultural output. By distinguishing between SO_2 and NO_x and by evaluating the role of governance investment, this paper makes three contributions. First, it provides pollutant-specific estimates of how industrial emissions relate to agricultural output in an economically critical region. Second, it assesses whether governance investment acts as a buffering mechanism or whether its contemporaneous effect is limited. Third, it discusses how these findings inform SDG-oriented sustainability strategies that balance industrial development, emissions control, and food-system resilience.

2.Literature Review

2.1 Air Pollution, Food Systems, and Governance

Industrial air pollution poses growing risks to agricultural development, yet evidence remains mixed on pollutant-specific effects and on whether governance capacity can effectively mitigate these damages. Using balanced provincial panel data from 11 eastern Chinese provinces over 2011–2021[1], this study examines how industrial sulfur dioxide and nitrogen oxides emissions relate to agricultural economic output and whether investment in waste-gas treatment moderates these relationships. We estimate a two-way fixed effects panel model with province and year effects, province-clustered standard errors, and interaction terms between pollutants and governance investment. Results show that nitrogen oxides emissions are consistently associated with lower agricultural output across specifications. In contrast, the estimated relationship for sulfur dioxide is less robust and becomes statistically indistinguishable under alternative specifications and intensity-based robustness checks[2]. We do not find robust contemporaneous evidence that governance investment significantly moderates the pollution–agriculture relationship, suggesting that spending levels alone may be insufficient or that governance effects operate with lags and through enforcement quality. Framed within the Sustainable Development Goals agenda, these findings speak directly to food security and sustainable agriculture, climate action, and the protection of terrestrial ecosystems, while also emphasizing the role of strong institutions in translating environmental investment into measurable outcomes. The evidence is further relevant to public health and sustainable communities by highlighting potential co-benefits of prioritizing nitrogen oxides control in industrial regions. By identifying a more policy-relevant priority pollutant and clarifying the limits of investment-only approaches, this study advances SDG-oriented research that links environmental indicators, governance mechanisms, and development performance in a unified empirical design.

2.2 Industrial Air Pollution and Agricultural Performance

A growing body of research documents that air pollutants can affect agricultural outcomes through multiple channels, including plant physiological stress, reduced photosynthesis, soil acidification, and changes in nutrient cycles[3]. However, empirical findings vary across contexts due to differences in crop structures, climate conditions, industrial composition, and measurement approaches. Moreover, studies that model pollutants separately may overstate or misattribute effects when pollutants are correlated or jointly determined by industrial activity and energy use. These considerations motivate a pollutant-specific and joint modeling strategy[4].

2.3 Governance Capacity and Pollution Mitigation

Environmental governance capacity—captured through regulatory institutions, fiscal resources, monitoring systems, and investment in pollution treatment—can theoretically mitigate pollution damage by reducing emissions intensity, improving compliance, and supporting technology upgrades[5]. Yet, governance effects may depend on implementation quality, enforcement credibility, and time lags between investment and observable environmental improvement[6]. As a result, empirical tests of governance buffering effects remain mixed and context-specific.

2.4 Pollutant Heterogeneity

$SO_2$and NO_x differ in sources, atmospheric chemistry, and environmental pathways. SO_2 is closely linked to coal combustion and can contribute to acid deposition, while NO_x plays a central role in ozone formation and nitrogen deposition, potentially exerting more persistent stress on crops and ecosystems[7]. Because these pollutants may co-move with industrial output yet influence agriculture differently, distinguishing their effects is crucial for both interpretation and policy prioritization.

Synthesizing the above, two gaps remain. First, the relative and joint impacts of SO_2 and NO_x on agricultural output are not consistently established in provincial panel settings that control for unobserved heterogeneity and time shocks. Second, it is unclear whether governance-related investment in waste-gas treatment meaningfully moderates the pollution–agriculture relationship contemporaneously. Accordingly, this study tests whether industrial emissions are associated with lower agricultural output and whether higher governance investment weakens these adverse associations, while allowing for pollutant-specific heterogeneity.

3.Data and Methodology

3.1 Data and variables

This study uses a provincial panel dataset for 11 provinces in Eastern China from 2011 to 2021. Agricultural economic output (AEG) is measured by the total agricultural output value. Industrial air pollution is captured by industrial SO_2 emissions and industrial NO_x emissions. Governance capacity is proxied by investment in waste-gas treatment (GTD), reflecting fiscal and administrative efforts to control industrial air pollution. Control variables include the proportion of agricultural fiscal expenditure (LAE), the urbanization rate, and the share of secondary industry in GDP (PSI), which account for agricultural support, demographic and structural change, and industrial structure.

To reduce skewness and interpret coefficients as elasticities, we log-transform AEG, SO_2, NO_x, GTD, and LAE. Urbanization rate and PSI are retained in percentage points. Table 1 summarizes the key variables used in the empirical analysis, including their definitions, measurement units, and data transformations. Agricultural economic output (AEG) and governance investment in waste-gas treatment (GTD) are measured in RMB (or 100 million RMB), while industrial air pollution is captured by SO_2 and NO_x emissions measured in tons (or 10,000 tons). To reduce skewness and allow coefficient interpretation in elasticity terms, AEG, SO_2, NO_x, and GTD are expressed in natural logarithms. The proportion of agricultural fiscal expenditure (LAE) is recorded as a percentage and is log-transformed when it is strictly positive. Urbanization rate and the share of secondary industry in GDP (PSI) are retained in percentage points (level form) to reflect structural and demographic conditions without additional scaling.

Table 1: Variables Description

Variable	Definition	Unit	Transformation
AEG	Total agricultural output value	RMB (or 100 million RMB)	ln(AEG)
SO_2	Industrial sulfur dioxide emissions	tons (or 10,000 tons)	$\ln(SO_2)$
NO_x	Industrial nitrogen oxides emissions	tons (or 10,000 tons)	$\ln(NO_x)$
GTD	Investment in waste-gas treatment	RMB (or 100 million RMB)	ln(GTD)
LAE	Proportion of agricultural fiscal expenditure	%	ln(LAE) (if in level >0)

Variable	Definition	Unit	Transformation
Urbanization	Urbanization rate	%	level
PSI	Share of secondary industry in GDP	%	level

Table 2 presents descriptive statistics for the main variables based on 121 province–year observations. The log-transformed measures of agricultural output (ln_aeg), industrial SO_2 emissions (ln_so2_emissions), industrial NO_x emissions (ln_nox_emissions), waste-gas treatment investment (ln_gtd), and agricultural fiscal expenditure share (ln_lae) show substantial cross-provincial and over-time variation, as reflected in their standard deviations and ranges. Urbanization_rate averages 69.645% (ranging from 45.589% to 89.583%), indicating marked differences in development levels across provinces. The industrial structure indicator (psi) has a mean of 38.902% with a wide spread (15.967% to 52.783%), suggesting notable heterogeneity in the relative importance of secondary industry. Overall, these summary statistics confirm sufficient variation in both pollution and governance-related variables to support the subsequent panel regression analysis.

Table 2: Descriptive Statistics

Variable	count	mean	std	min	max
ln_aeg	121	7.682	1.239	5.574	9.347
ln_so2_emissions	121	2.654	1.755	-1.966	5.208
ln_nox_emissions	121	3.735	1.019	1.343	5.194
ln_gtd	121	5.824	1.176	1.553	8.037
ln_lae	121	3.013	0.909	1.953	5.335
urbanization_rate	121	69.645	12.1	45.589	89.583
psi	121	38.902	10.487	15.967	52.783

3.2 Empirical Model

We estimate a two-way fixed-effects specification:

$$\ln AEG_{i,t} = \alpha + \beta_1 \ln(SO_2)_{it} + \beta_2 \ln(NO_x)_{it} + \gamma X_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t}$$

AEGi,t is the dependent variable and reflects the growth of the agricultural economy in region i in year t. Sulfur dioxide and nitrogen oxides are independent variables. Xi,t are control variables, including the proportion of agricultural fiscal expenditure (LAE), the proportion of urban population (PUP), and the proportion of secondary industry (PSI). Clustered standard errors at province level account for within-province serial correlation and heteroskedasticity[8].

Moderation by governance:

To test whether governance buffers damage, we estimate:

$$\ln AEG_{i,t} = \alpha + \beta_1 \ln(SO_2)_{it} + \theta(\ln(SO_2)_{it} \times \ln(NO_x)_{it}) + \gamma X_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t}$$

The interaction item mainly explores whether more investment in environmental governance will buffer the negative impact of industrial waste gas pollution on the agricultural system[9]. This approach contributes to ongoing discussions about adaptive food planning and spatial justice, especially in rapidly urbanizing contexts where environmental burdens are unequally distributed.

3.3 Evaluation Metrics and Validation

Firstly, by examining pairwise correlations(Table 3), we determined that there was a reasonable linear relationship between the core variables, and the OLS VIF test showed that all VIFs were below 10. There was no significant multicollinearity between the regression variables, and Hausman's comparison suggested that this study should use bidirectional fixed effects. Accordingly, all regressions include province and year fixed effects, and standard errors are clustered at the province level to address within-province serial correlation and heteroskedasticity.

Table 3: Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) ln_aeg	1.000						
(2) ln_so2_emissions	0.647*	1.000					
	(0.000)						
(3) ln_nox_emissions	0.726*	0.907*	1.000				
	(0.000)	(0.000)					
(4) ln_gtd	0.327*	0.611*	0.487*	1.000			
	(0.000)	(0.000)	(0.000)				
(5) ln_lae	-0.855*	-0.639*	-0.545*	-0.404*	1.000		
	(0.000)	(0.000)	(0.000)	(0.000)			
(6) urbanization_r~e	-0.733*	-0.501*	-0.433*	-0.440*	0.830*	1.000	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)		
(7) psi	0.644*	0.813*	0.790*	0.486*	-0.651*	-0.418*	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

In the baseline fixed-effects model with both pollutants entered simultaneously, ln(NOX) carries a negative and statistically significant coefficient, indicating that higher NOx emissions are associated with lower agricultural economic output after controlling for covariates and fixed effects. By contrast, the coefficient on ln(SO_2) is small and not robustly negative once NOx is included. Among controls, the coefficient on ln(agricultural expenditure) is negative and significant, while urbanization and industrial share are small and generally not significant in the baseline[10].

To test moderation, I add ln(GTD) (exhaust-gas treatment investment) and the interaction ln(SO_2)×ln(GTD). The interaction term is statistically indistinguishable from zero in this sample, and marginal-effect calculations show no material change in the SO_2 effect across observed governance levels. Two robustness checks confirm the main pattern. First, replacing raw emissions with population-standardized intensities (per 10,000 people) leaves the NOx coefficient negative and significant, while SO_2 remains small and not significant. Second, using income-standardized intensities (per 10,000 GDP per capita) delivers the same conclusion[11]. Across specifications, the sign and significance of NOx are stable, whereas SO_2 effects are weak and sensitive to definition. Overall, the evidence highlights NOx as the primary pollutant driving agricultural economic losses in the panel, with no strong statistical support for a governance-based buffering of SO_2 within the observed range[12].

4.Empirical Analysis and Results

4.1 Baseline Fixed-Effects Results

Table 4 reports the two-way fixed-effects estimates with province and year dummies and standard errors clustered by province (N = 121). Both pollutants enter the model together, alongside controls for agricultural expenditure, urbanization, and the secondary-industry share[13]. Coefficients are elasticities because the variables are in logs.

Table 4: FE Baseline Regression

Variable	Coef.	Std.Err.	t	P>|t|
Constant	6.5147	0.6575	9.9088	0
ln(SO_2)	0.1214	0.0605	2.0056	0.0449
ln(NOX)	-0.231	0.082	-2.8167	0.0049
ln(Ag. Expenditure)	-0.3074	0.0564	-5.4467	0
Urbanization rate	0.0091	0.0092	0.9913	0.3215
Secondary industry share	0.0097	0.01	0.9644	0.3348
Observations	121			
R-squared	0.9979			
FE (Prov/Year)	Yes / Yes			
SE (clustered by prov.)	Yes			

*Note: Parenthetical z-statistics(*** $p<0.01$, ** $p<0.05$, * $p<0.1$)

The headline result is the negative and statistically significant effect of NOx on the agricultural economy. The coefficient on ln(NOX) is −0.231 (SE = 0.082, p = 0.0049), implying that, holding other factors constant, a 1% rise in NOx emissions is associated with about a 0.23% reduction in provincial agricultural output. This supports the view that nitrogen oxides impose a persistent drag on agricultural performance within provinces over time.

The results also showed that under the control of nitrogen oxide levels and governance measures, if the concentration of sulfur dioxide increased by 1%, agricultural yield would increase by 0.12%. The sign is unexpected if one views SO_2 in isolation, but it is consistent with a conditional relationship: provinces and years with more combustion-intensive economic activity may simultaneously generate more SO_2 and more agricultural income (e.g., through energy access or agro-processing), while NOx captures the more damaging channel. Put differently, once the shared variation with NOx is partialled out by the joint specification and the fixed effects, the partial association of SO_2 with agriculture can turn positive. This pattern motivates the intensity and lag checks reported later[14].

Turning to the controls, ln(Ag. Expenditure) is negative and precisely estimated (−0.307, SE = 0.0564, $p < 0.001$). A reasonable interpretation is policy targeting or timing: higher agricultural spending tends to flow to provinces and years with weaker agricultural performance, or the benefits materialize with lags not captured in the contemporaneous specification. The urbanization rate (0.0091, SE = 0.0092, p = 0.322) and the secondary-industry share (0.0097, SE = 0.010, p = 0.335) are small and statistically indistinguishable from zero. Within-province movements in these shares are gradual and heavily absorbed by fixed effects and year shocks; their incremental explanatory power beyond pollution and expenditure is therefore limited in this setting.

Model fit is high (R-squared = 0.9979), which is common in fixed-effects panels with comprehensive province and year dummies: most level differences are removed by design, and identification comes from within-province changes over time. Inference relies on province-clustered standard errors, making the reported t and p values robust to serial correlation and heteroskedasticity within provinces.

In sum, the baseline establishes a clear adverse role of NOx for agricultural output and a conditional, positive association of SO_2 once NOx and fixed effects are controlled. This differential pattern is precisely why the subsequent sections examine (i) intensity-scaled specifications and (ii) dynamic responses with lags—to check whether the NOx penalty persists and whether the SO_2 sign is sensitive to alternative definitions and timing.

4.2 Governance Buffering Test

Table 5 introduces the governance channel by adding ln(GTD)—exhaust-gas treatment investment—and the interaction $\ln(SO_2) \times \ln(GTD)$ to the fixed-effects baseline. Province and year fixed effects are retained and standard errors are clustered by province (N = 121). Coefficients can be read as elasticities[15].

Table 4: Moderation

Variable	Coef.	Std.Err.	t	P>|t|
Constant	6.4915	0.6377	10.179	0
$\ln(SO_2)$	0.1213	0.0552	2.1975	0.028
ln(GTD)	0.0133	0.0157	0.8517	0.3944
$\ln(SO_2) \times \ln(GTD)$	-0.0012	0.0072	-0.1706	0.8646
ln(NOX)	-0.2339	0.0985	-2.3741	0.0176
ln(Ag. Expenditure)	-0.3161	0.0538	-5.8721	0
Urbanization rate	0.0087	0.0083	1.0523	0.2927
Secondary industry share	0.0122	0.009	1.362	0.1732
Observations	121			
R-squared	0.998			

Two findings are immediate. First, the NOx effect remains negative and statistically significant. The coefficient on ln(NOX) is −0.2339 (SE = 0.0985, p = 0.0176), implying that a 1% increase in NOx emissions is associated with roughly a 0.23% decline in agricultural economic output, ceteris paribus. This confirms the baseline result and underscores NOx as the pollutant most consistently linked to losses in agricultural performance within provinces over time.

Second, there is no evidence that governance investment moderates the SO_2 relationship in this sample. The interaction term $\ln(SO_2) \times \ln(GTD)$ is −0.0012 (SE = 0.0072, p = 0.8646), extremely small in magnitude and far from statistical significance. Substantively, the marginal effect of SO_2 on agricultural output is given by

$$\frac{\vartheta \ln AEG}{\vartheta \ln SO_2} = \beta SO_2 + \theta \ln GTD$$

With βSO_2 =0.1213 and $\theta \approx 0$, the slope is essentially flat over the observed range of governance investment. In other words, higher GTD is not associated with a systematic weakening (or strengthening) of the SO_2–agriculture link in the contemporaneous specification.

Looking at main effects, $\ln(SO_2)$ remains positive and significant when entered jointly with NOx and governance (0.1213, SE = 0.0552, p = 0.028). This conditional positive association mirrors the baseline joint-pollutant model: after partialling out NOx and the fixed effects, SO_2 appears to track provinces and years with stronger economic activity, which may coincide with better agricultural outcomes through energy access, processing capacity, or related inputs.

The coefficient of ln (GTD) itself is very small (0.0133, SE=0.0157, p=0.3944), indicating that under fixed effects and control measures in place, investment in exhaust gas treatment has no significant impact on agricultural output. This may be related to the instability of environmental investment and endogenous factors in various problematic provinces, leading to a lag in the effectiveness of waste gas treatment investment, so it is impossible to see benefits in the same year or even in the short term.

Control variables behave similarly to the baseline[16]. ln(Ag. Expenditure) is negative and precise (−0.3161, SE = 0.0538, $p < 0.001$), consistent with countercyclical budgeting or delayed payoffs. At the same time, the insignificant SO_2–GTD interaction highlights the need to probe timing (lagged governance effects), measurement (composition and quality of treatment investment), and heterogeneity (e.g., industrial–agricultural overlap zones) before drawing firm conclusions about the effectiveness of governance in altering the SO_2 pathway.

4.3 Robustness to Intensity Definitions

Tables 6–7 re-estimate the model after converting emissions into intensity measures and taking ln(1+x) to stabilize skewness. Table 6 standardizes by population (per 10,000 people); Table 7 standardizes by income (per 10,000 GDP per capita). Province and year fixed effects and province–clustered standard errors are retained (N = 121).

Table 6: Robustness Test with Intensity Pop

Variable	**Coef.**	**Std.Err.**	**t**	**P>|t|**
Constant	6.7055	0.5406	12.4028	0
$\ln(SO_2$ per 10k pop + 1)	0.0897	0.0678	1.3236	0.1856
ln(NOX per 10k pop + 1)	-0.249	0.0854	-2.9162	0.0035
ln(Ag. Expenditure)	-0.3604	0.0545	-6.6168	0
Urbanization rate	0.0145	0.0091	1.5922	0.1114
Secondary industry share	0.0067	0.0106	0.6323	0.5272
Observations	121			
R-squared	0.9979			
FE (Prov/Year)	Yes / Yes			
SE (clustered by prov.)	Yes			

Table 7: Robustness Test with Intensity LnC

Variable	Coef.	Std.Err.	t	P>|t|
Constant	6.2216	0.4053	15.3491	0
ln(SO_2 per 10k GDPpc + 1)	0.0147	0.0957	0.1535	0.878
ln(NOX per 10k GDPpc + 1)	-0.2338	0.1003	-2.3301	0.0198
ln(Ag. Expenditure)	-0.4135	0.0508	-8.1441	0
Urbanization rate	0.0206	0.0063	3.2696	0.0011
Secondary industry share	0.0044	0.0083	0.5316	0.595
Observations	121			
R-squared	0.9979			
FE (Prov/Year)	Yes / Yes			
SE (clustered by prov.)	Yes			

The core pattern is unchanged: NOx remains a statistically significant drag on the agricultural economy across both intensity specifications. In the population–standardized model, the coefficient on ln(NOX per 10k pop + 1) is −0.249 (SE = 0.0854, p = 0.0035). In the income–standardized model, ln(NOX per 10k GDPpc + 1) is −0.2338 (SE = 0.1003, p = 0.0198). Under the same control conditions, for every 1% increase in nitrogen oxide concentration, the agricultural yield of a province will decrease by 0.23-0.25%.

In Table 6, ln(SO_2 per 10k pop + 1) is 0.0897 (SE = 0.0678, p = 0.186). In Table 7, ln(SO_2 per 10k GDPpc + 1) shrinks to 0.0147 (SE = 0.0957, p = 0.878). Ln (Ag. Endurance) maintained negative values and accuracy in both robustness checks (-0.3604 in Table 6; -0.4135 in Table 7; both p<0.001), indicating that funds may have flowed to underperforming years or there may be lagged effects that the model cannot capture. When standardized by population, the urbanization rate is positive but not significant (0.0145, p=0.111), while it is positive and significant when standardized by income (0.0206, SE=0.0063, p=0.0011). It is possible that as per capita income increases and services improve, agricultural performance also improves. However, compared to nitrogen oxide emissions, this impact can only be seen as complementary and cannot be considered competitive.

5.Discussion

5.1 Results Interpretation: Ecological Disruption and the Role of Governance

This study highlights meaningful heterogeneity across industrial air pollutants in their empirical association with agricultural output. The consistently negative relationship between NO_x emissions and agricultural output aligns with pathways involving ozone formation and nitrogen deposition that can impose persistent stress on crops and ecosystems. By comparison, the SO_2 association appears more sensitive to model specification and scaling, which may reflect that SO_2 emissions are more tightly correlated with industrial energy structure and concurrent economic activity, making its partial association with agricultural output less stable in joint models.

The moderation analysis suggests that governance investment in waste-gas treatment (GTD) does not generate a robust contemporaneous buffering effect in this setting[19]. This finding does not imply that governance is irrelevant; rather, it points to the importance of implementation quality, enforcement credibility, and potential time lags between investment and environmental improvement[18]. Future work may benefit from incorporating lag structures, regulatory enforcement indicators, or monitoring coverage measures to capture governance effectiveness beyond expenditure levels[20].

5.2 Implications and Policy Recommendations

Based on the exploration of government intervention factors, this study proposes several policy recommendations to improve regional environmental planning and promote sustainable development of the agricultural system.

The results speak directly to SDG-oriented sustainability strategies. For SDG 2 (Zero Hunger), the stable negative association between NO_x emissions and agricultural output suggests that industrial air pollution can pose a nontrivial threat to food-system stability and agricultural productivity[21]. For SDG 13 (Climate Action) and SDG 15 (Life on Land), the pollutant-specific findings underscore the need to prioritize emission sources and mechanisms that generate more persistent ecological stress[22]. For SDG 16 (Strong Institutions), the limited contemporaneous moderation effect of GTD highlights that institutional strength should be evaluated not only by spending levels but also by enforcement, accountability, and effective implementation.

Policymakers should prioritize NO_x reduction strategies in regions where NO_x emissions are persistently associated with lower agricultural output, including targeted controls on high-emitting industrial sources and energy-use adjustments. Governance investment should be paired with implementation mechanisms—such as monitoring capacity, inspection frequency, compliance incentives, and enforcement credibility—to ensure that spending translates into measurable environmental improvements[23]. Interventions should be regionally differentiated: provinces with heavier industrial structures and higher emission intensity may require stricter standards and more rigorous enforcement, while provinces with more agriculture-dependent economies may benefit from integrated land–air management strategies that protect agricultural resilience[24].

6.Conclusion

Using provincial panel data from 11 eastern Chinese provinces over 2011–2021, this study examines pollutant-specific effects of industrial air pollution on agricultural output and assesses whether governance investment in waste-gas treatment moderates these effects. The evidence indicates that NO_x emissions are consistently associated with lower agricultural output, while the SO_2association is less robust and becomes statistically indistinguishable under alternative specifications and intensity-based checks. We do not find robust contemporaneous moderation effects of GTD, suggesting that governance spending alone may not immediately buffer pollution damages without effective enforcement and implementation quality.

These findings provide SDG-relevant insights for sustainable development: they highlight pollution-related risks to agricultural production, support prioritization of effective emissions management strategies, and emphasize the role of strong institutions and accountable implementation in translating governance inputs into outcomes. Future research could incorporate lag structures and enforcement-based governance indicators to better capture dynamic policy effects.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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