

GENDERED BEHAVIORAL RESPONSES TO AGRI-ENVIRONMENTAL POLICIES: EFFECTS OF AIR POLLUTION AND WILDFIRE SMOKE ON PRODUCTIVITY AND WELFARE IN DEVELOPING COUNTRIES: A PANEL DATA ANALYSIS

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ABSTRACT

Agri-environmental policies (AEPs) are increasingly employed in developing countries to address environmental degradation, climate change, and agricultural sustainability. However, the effectiveness of these policies often depends on behavioral responses that vary across gender groups. This study investigates how air pollution and wildfire smoke influence productivity and welfare outcomes under agri-environmental policies, with a particular focus on gender differences. Using panel data from 1,200 rural households across India, Bangladesh, Kenya, and Ghana from 2015–2023, the study employs Fixed Effects (FE) and Random Effects (RE) models to estimate the impacts of environmental stressors on agricultural productivity and household welfare. The findings reveal that women experience significantly greater productivity losses and welfare reductions from pollution exposure compared to men. Female farmers demonstrate stronger support for environmental conservation measures and higher responsiveness to informational nudges. The results highlight the necessity of integrating gender-sensitive approaches into agri-environmental policy design. Policy recommendations include strengthening women's access to environmental information, financial resources, climate-resilient technologies, and decision-making institutions.

Keywords: Agri-environmental policies, panel data analysis, gender, air pollution, wildfire smoke, agricultural productivity, welfare, developing countries.

1. INTRODUCTION

Agriculture remains the backbone of many developing economies, providing livelihoods, food security, and employment for a substantial share of the population. However, agricultural productivity and rural welfare are increasingly threatened by environmental challenges such as air pollution and wildfire smoke, both of which

have intensified due to rapid industrialization, urbanization, deforestation, and climate change. According to the World Health Organization (WHO), air pollution is one of the leading environmental health risks globally, with developing countries experiencing disproportionately high exposure levels. Similarly, the frequency and severity of wildfires have

increased over the past decades, generating extensive smoke emissions that adversely affect human health, labor productivity, and agricultural activities.

Air pollution and wildfire smoke impose significant economic and social costs on agricultural communities. Exposure to particulate matter (PM_{2.5}), ozone, and other pollutants reduces labor productivity by causing respiratory and cardiovascular illnesses, increasing absenteeism, and lowering physical work capacity. In agricultural settings, pollution also affects crop yields through reduced photosynthesis and soil degradation. Wildfire smoke further exacerbates these impacts by disrupting farming operations, increasing health expenditures, and diminishing household welfare. These environmental stressors are particularly severe in developing countries where healthcare infrastructure, adaptive capacity, and environmental governance mechanisms remain relatively weak.

In response to growing environmental concerns, governments and international organizations have implemented various agri-environmental policies (AEPs) aimed at promoting sustainable agricultural practices, reducing environmental degradation, conserving natural resources, and enhancing climate resilience. Such policies include pollution control measures, forest conservation programs, climate-smart agriculture initiatives, ecosystem restoration projects, and incentive-based conservation schemes. The effectiveness of these policies, however, depends not only on their design but also on the behavioral responses of individuals and households affected by them.

Gender plays a crucial role in shaping environmental behavior, resource access, and policy participation. In many developing countries, women constitute a significant proportion of the agricultural workforce and are heavily involved in food production, resource management, and household welfare activities. Despite their contributions, women often face structural constraints such as limited land ownership, reduced access to credit and extension services, lower educational attainment, and restricted participation in decision-making

processes. These inequalities influence their ability to respond to environmental challenges and adopt agri-environmental practices.

Existing studies suggest that women often exhibit stronger environmental preferences, greater concern for community welfare, and higher willingness to participate in conservation activities than men. However, they are also more vulnerable to environmental shocks because of socioeconomic disadvantages and caregiving responsibilities. Consequently, air pollution and wildfire smoke may generate different productivity and welfare outcomes for men and women, leading to heterogeneous responses to environmental policies. Understanding these gendered behavioral responses is essential for designing equitable and effective agri-environmental interventions.

Although a growing body of literature has examined the impacts of environmental degradation on agriculture and welfare, limited research has integrated gender dimensions with air pollution, wildfire smoke exposure, and agri-environmental policy adoption within a longitudinal framework. Most existing studies rely on cross-sectional data, which often fail to capture dynamic behavioral changes and unobserved household-specific characteristics over time. Panel data analysis provides a more robust approach by tracking the same households across multiple periods, allowing researchers to account for temporal variations and individual heterogeneity while examining causal relationships.

This study seeks to investigate the gendered behavioral responses to agri-environmental policies under conditions of air pollution and wildfire smoke exposure in developing countries using panel data analysis. Specifically, the study examines how environmental stressors affect agricultural productivity and household welfare, whether these effects differ by gender, and how participation in agri-environmental policies influences adaptive behavior. By employing panel data techniques such as Fixed Effects and Random Effects models, the research aims to provide empirical evidence on the interaction

between environmental risks, policy interventions, and gender dynamics.

In this study are expected to contribute to the literature on environmental economics, agricultural development, and gender studies by highlighting the importance of incorporating gender-sensitive approaches into environmental policymaking. Furthermore, the study provides valuable insights for policymakers seeking to improve the effectiveness of agri-environmental policies while promoting social equity and sustainable rural development in developing countries.

Research Objectives

- 1.To examine the impact of air pollution and wildfire smoke on agricultural productivity in developing countries.
- 2.To assess the effects of environmental stressors on household welfare outcomes.
- 3.To analyze gender differences in behavioral responses to agri-environmental policies.
- 4.To evaluate the role of agri-environmental policy adoption in mitigating productivity and welfare losses.
- 5.To provide policy recommendations for gender-responsive environmental governance and sustainable agricultural development.

Research Questions

- 1.How do air pollution and wildfire smoke affect agricultural productivity and household welfare in developing countries?
- 2.Are there significant gender differences in responses to agri-environmental policies?
- 3.Does participation in agri-environmental programs reduce the adverse effects of environmental pollution?
- 4.What policy interventions can improve environmental outcomes while addressing gender inequalities in rural communities?

Hypotheses

H1: Air pollution negatively affects agricultural productivity and household welfare.

H2: Wildfire smoke exposure significantly reduces labor productivity and welfare outcomes.

H3: Female-headed households experience greater productivity and welfare losses from environmental stressors than male-headed households.

H4: Adoption of agri-environmental policies mitigates the negative impacts of air pollution and wildfire smoke.

H5: Gender significantly influences behavioral responses to agri-environmental policies in developing countries.

2. Literature Review

2.1 Theoretical Foundation

The relationship between environmental policies, human behavior, and welfare outcomes can be explained through Environmental Economics, Behavioral Economics, and Gender Development Theory. Environmental Economics suggests that environmental degradation imposes negative externalities that reduce social welfare and economic productivity (Pigou, 1920). Agri-environmental policies are designed to internalize these externalities by encouraging environmentally sustainable practices through incentives, regulations, and conservation programs.

Behavioral Economics emphasizes that individual responses to environmental policies are influenced by risk perceptions, information availability, social norms, and cognitive biases (Thaler & Sunstein, 2008). Gender Development Theory further argues that social and institutional inequalities shape access to resources, decision-making power, and adaptive capacities, leading to different responses among men and women when facing environmental challenges.

These theoretical perspectives provide the foundation for understanding how air pollution and wildfire smoke affect agricultural productivity and welfare, and how gender influences behavioral responses to agri-environmental policies.

2.2 Agri-Environmental Policies and Sustainable Agricultural Development

Agri-environmental policies (AEPs) have become an important policy instrument for promoting sustainable agricultural production while

addressing environmental degradation. These policies include conservation subsidies, climate-smart agricultural practices, ecosystem restoration programs, carbon sequestration initiatives, and pollution-control measures.

According to the Organisation for Economic Co-operation and Development (OECD, 2022), AEPs contribute significantly to biodiversity conservation, soil protection, water quality improvement, and greenhouse gas mitigation. Several studies have shown that participation in environmental programs increases farm sustainability and enhances resilience against climate-related risks.

Pannell et al. (2014) argued that the effectiveness of environmental policies depends largely on farmer participation and behavioral adaptation. Policies designed without considering social and economic characteristics often achieve lower adoption rates. Similarly, Knowler and Bradshaw (2007) found that socioeconomic factors such as education, income, and access to information significantly influence farmers' willingness to adopt conservation practices.

In developing countries, the effectiveness of AEPs is often constrained by institutional weaknesses, inadequate extension services, and unequal resource distribution. These challenges are particularly pronounced among female farmers, who generally have less access to agricultural support systems.

2.3 Air Pollution and Agricultural Productivity

Air pollution has emerged as a major environmental and public health concern globally. Pollutants such as particulate matter (PM_{2.5}), sulfur dioxide (SO₂), nitrogen oxides (NO_x), and ground-level ozone have been shown to adversely affect both human health and agricultural productivity.

Graff Zivin and Neidell (2018) demonstrated that air pollution reduces labor productivity by increasing fatigue, respiratory illnesses, and cognitive impairments. Their findings suggest that even moderate increases in pollution exposure can significantly decrease worker performance and economic output.

Agricultural productivity is particularly vulnerable to air pollution because crop growth depends heavily on atmospheric conditions. Burney and Ramanathan (2014) found that elevated pollution levels reduce photosynthesis, lower crop yields, and increase production costs. In South Asia and Sub-Saharan Africa, pollution-induced health problems among farm workers further reduce labor efficiency and agricultural output.

Recent evidence suggests that air pollution disproportionately affects rural populations due to limited healthcare access and lower adaptive capacity. These effects are especially severe for women, who often combine agricultural labor with household responsibilities, increasing their overall exposure to environmental stressors.

2.4 Wildfire Smoke and Rural Welfare

Climate change has increased the frequency and intensity of wildfires worldwide, generating substantial amounts of smoke and airborne particulate matter. Wildfire smoke contains pollutants that can travel long distances and affect populations far beyond the immediate fire zone.

Research indicates that wildfire smoke contributes to respiratory diseases, cardiovascular problems, and reduced labor productivity. According to the World Health Organization (WHO, 2023), prolonged exposure to wildfire smoke significantly increases healthcare costs and decreases overall quality of life.

Johnston et al. (2012) estimated that wildfire smoke exposure contributes to thousands of premature deaths annually and imposes significant economic losses through reduced workforce participation. In agricultural communities, wildfire smoke disrupts planting and harvesting activities, damages crops, and lowers household income.

The welfare impacts of wildfire smoke are particularly severe among vulnerable groups, including women, children, and elderly individuals. Female-headed households often face greater challenges in coping with environmental shocks due to lower income levels and limited access to adaptive resources.

2.5 Gender and Environmental Behavior

Gender has become an increasingly important dimension in environmental and development research. Studies consistently show that men and women differ in environmental attitudes, risk perceptions, and policy preferences.

Agarwal (2018) argues that women generally demonstrate stronger environmental concern due to their direct involvement in resource management, household welfare, and food security. Women's daily interactions with natural resources often make them more aware of environmental degradation and its consequences. Several studies have found that women exhibit higher willingness-to-pay (WTP) for environmental improvements and stronger support for conservation initiatives than men. Zelezny et al. (2000) reported that women consistently display more pro-environmental attitudes across different cultural contexts.

However, despite their environmental awareness, women frequently face barriers to participation in environmental decision-making. These barriers include limited access to land ownership, financial resources, extension services, and policy institutions. Consequently, women may be unable to translate their environmental preferences into effective action.

In agricultural communities, gender disparities influence the adoption of climate-smart practices, conservation technologies, and environmental policies. Female farmers often encounter higher transaction costs and information constraints, reducing their participation in environmental programs.

2.6 Gendered Impacts of Air Pollution and Wildfire Smoke

Recent literature highlights the unequal impacts of environmental degradation across gender groups. Women tend to experience greater health and welfare losses from pollution exposure because of biological, social, and economic vulnerabilities.

The Food and Agriculture Organization (FAO, 2022) reported that women in rural areas often have lower adaptive capacities due to restricted access to productive assets and financial resources.

As a result, environmental shocks such as air pollution and wildfire smoke can generate disproportionate effects on female productivity and welfare.

Studies in South Asia and Africa indicate that female agricultural workers are more likely to suffer productivity losses during periods of severe air pollution. Furthermore, caregiving responsibilities often increase women's exposure to environmental health risks, reducing their labor market participation and household income.

These findings suggest that environmental policies may produce different outcomes for men and women, necessitating gender-sensitive policy design and implementation.

2.7 Panel Data Studies on Environmental Impacts

Panel data analysis has become an important methodological tool for examining environmental and socioeconomic relationships over time. Unlike cross-sectional studies, panel data allows researchers to control for unobserved heterogeneity and identify dynamic effects.

Baltagi (2021) notes that panel data models improve estimation efficiency by combining cross-sectional and time-series information. Fixed Effects (FE) and Random Effects (RE) models are commonly used to assess the impacts of environmental variables on economic outcomes. Several studies have applied panel data methods to examine pollution and productivity relationships. Chang et al. (2019) found that long-term exposure to air pollution significantly reduced labor productivity across multiple industries. Similarly, He et al. (2020) demonstrated that environmental degradation negatively affected rural welfare outcomes in developing countries.

Despite the growing use of panel data methods, few studies have examined gendered behavioral responses to agri-environmental policies within a panel framework. Most existing research focuses either on environmental impacts or gender issues separately.

2.8 Research Gap

The reviewed literature highlights significant advances in understanding agri-environmental policies, air pollution, wildfire smoke, and gender dynamics. However, several important gaps remain.

First, most studies examine air pollution, wildfire smoke, or environmental policy adoption independently rather than investigating their combined effects on productivity and welfare.

Second, existing research provides limited evidence regarding how gender influences behavioral responses to agri-environmental policies under environmental stress conditions.

Third, many studies rely on cross-sectional data, which cannot adequately capture behavioral changes and welfare dynamics over time.

Fourth, empirical evidence from developing countries remains relatively scarce despite their high vulnerability to environmental degradation.

To address these gaps, the present study employs panel data analysis to investigate the gendered behavioral responses to agri-environmental policies in the presence of air pollution and wildfire smoke. By examining productivity and welfare outcomes across multiple countries and years, the study contributes to the literature on environmental economics, gender studies, and sustainable agricultural development.

3. Research Methodology

3.1 Introduction

This study presents the research methodology adopted to investigate the gendered behavioral responses to agri-environmental policies under conditions of air pollution and wildfire smoke

exposure in developing countries. The study aims to examine how environmental stressors affect agricultural productivity and household welfare while exploring gender differences in policy adoption and adaptive behavior. To achieve these objectives, a quantitative research approach based on panel data analysis is employed. Panel data methods allow the examination of both cross-sectional and time-series variations, providing more robust estimates than conventional cross-sectional techniques.

3.2 Research Design

The study adopts a longitudinal research design using panel data collected from rural households across selected developing countries. A panel data approach is appropriate because it tracks the same households over multiple years, allowing the analysis of changes in productivity, welfare, pollution exposure, and policy participation over time.

The research investigates the relationship between: Air pollution exposure, Wildfire smoke exposure, Agri-environmental policy adoption, Agricultural productivity, Household welfare, Gender differences in behavioral responses. The study employs both descriptive and econometric analyses to identify causal relationships and dynamic effects.

3.3 Study Area and Sample Selection

The study focuses on developing countries that experience significant levels of air pollution, wildfire smoke exposure, and agricultural dependence.

Selected Countries

Region	Country
South Asia	India
South Asia	Bangladesh
Sub-Saharan Africa	Kenya
Sub-Saharan Africa	Ghana

These countries were selected because:

1. Agriculture contributes significantly to national income and employment.
2. Air pollution levels frequently exceed international safety standards.

3. Wildfire incidents and biomass burning are common.
4. Significant gender disparities exist in agricultural resource access.

3.4 Data Sources

The study utilizes both primary and secondary data sources.

Primary Data

Primary data are collected through household surveys conducted among farming households.

Survey Components

- Demographic characteristics
- Agricultural production information
- Exposure to pollution and smoke
- Environmental attitudes
- Policy participation

- Welfare indicators

Secondary Data

Secondary data are obtained from:

- World Bank Development Indicators
- World Health Organization (WHO)
- Food and Agriculture Organization (FAO)
- National Environmental Agencies
- Air Quality Monitoring Networks
- Climate and Wildfire Databases
-

3.5 Panel Data Structure

The study uses a balanced panel dataset.

Sample Composition

Category	Number
Male-headed households	600
Female-headed households	600
Total households	1,200

Study Period

Variable	Period
Observation Years	2015–2023
Total Years	9

Total Observations

Total observations:

$$N \times T = 1,200 \times 9$$

$$= 10,800 \text{ observations}$$

The balanced panel structure allows consistent comparison across households and years.

3.6 Variable Specification

■ Dependent Variables

- **Agricultural Productivity (PROD):** Measured as a Agricultural Output per Hectare (tons/hectare)
- **Household Welfare (WEL):** Measured through a composite welfare index based on: Household income, Consumption expenditure, Health expenditure and Asset ownership.

Independent Variables

Variable	Symbol	Measurement
Air Pollution	POLL	PM2.5 concentration
Wildfire Smoke	SMOKE	Smoke exposure index
Gender	GENDER	Female=1, Male=0
Policy Adoption	POLICY	AEP participation score
Education	EDU	Years of schooling
Income	INC	Annual household income
Farm Size	FSIZE	Hectares cultivated

3.7 Measurement of Key Variables

■ Air Pollution Index

Air pollution is measured using annual average PM2.5 concentration levels.

Higher PM2.5 values indicate greater pollution exposure.

■ Wildfire Smoke Exposure

Wildfire smoke exposure is measured through:

- Number of smoke exposure days per year
- Average smoke intensity index

■ Agri-Environmental Policy Adoption Index

A composite index is developed based on participation in:

- Sustainable farming programs
- Tree plantation initiatives
- Conservation agriculture
- Pollution-control practices
- Climate adaptation programs
- Index values range from:

0 = No participation, 1 = Full participation

3.8 Econometric Model Specification

Model 1: Productivity Model

The first model estimates the impact of environmental factors on agricultural productivity.

$$PROD_{it} = \beta_0 + \beta_1 POLL_{it} + \beta_2 SMOKE_{it} + \beta_3 GENDER_{it} + \beta_4 POLICY_{it} + \beta_5 EDU_{it} + \beta_6 FSIZE_{it} + \mu_i + \epsilon_{it}$$

Where:

PROD = Agricultural productivity

POLL = Air pollution

SMOKE = Wildfire smoke exposure'

GENDER = Gender dummy variable

POLICY = Policy adoption index

EDU = Education level

FSIZE = Farm size

μ_i = Individual-specific effect

ϵ_{it} = Error term

Model 2: Welfare Model

The second model examines welfare impacts.

$$WEL_{it} = \beta_0 + \beta_1 POLL_{it} + \beta_2 SMOKE_{it} + \beta_3 GENDR_i + \beta_4 POLICY_{it} + \beta_5 INC_{it} + \beta_6 EDU_{it} + \mu_i + \epsilon_{it}$$

Where: WEL represents household welfare.

3.9 Gender Interaction Model

To assess gendered behavioral responses, interaction terms are introduced.

$$PROD_{it} = \beta_0 + \beta_1 POLL_{it} + \beta_2 SMOKE_{it} + \beta_3 (POLL \setminus GENDER)_{it} + \beta_4 (SMOKE \setminus GENDER)_{it} + \beta_5 POLICY_{it} + \mu_i + \epsilon_{it}$$

This model determines whether pollution impacts differ significantly between male and female farmers.

3.10 Estimation Techniques

➤ Pooled Ordinary Least Squares (OLS)

The analysis begins with pooled OLS estimation as a baseline model.

➤ Fixed Effects Model (FEM)

The Fixed Effects Model controls for unobserved household-specific characteristics that remain constant over time.

➤ Random Effects Model (REM)

The Random Effects Model assumes individual-specific effects are randomly distributed and uncorrelated with explanatory variables.

Decision Rule

Result	Preferred Model
$p\text{-value} < 0.05$	Fixed Effects
$p\text{-value} > 0.05$	Random Effects

The Fixed Effects Model is expected to be preferred because household characteristics are likely correlated with explanatory variables.

3.12 Diagnostic Tests

Several diagnostic tests are performed.

➤ Multicollinearity Test

Variance Inflation Factor (VIF) is used.

Decision Rule:

$VIF < 10$ indicates no multicollinearity.

➤ Heteroskedasticity Test

Breusch-Pagan Test is conducted.

➤ Autocorrelation Test

Wooldridge Test for serial correlation in panel data.

➤ Cross-Sectional Dependence Test

Pesaran CD Test is applied.

Robust standard errors are used when necessary.

3.11 Hausman Specification Test

To determine the appropriate panel model, the Hausman Test is conducted.

4. Results and Discussion

4.1 Introduction

In this study represents the empirical findings of the study on gendered behavioral responses to agri-environmental policies under conditions of air pollution and wildfire smoke exposure in developing countries. The analysis is based on a balanced panel dataset comprising 1,200 agricultural households observed over the period 2015–2023, resulting in 10,800 observations.

4.2 Descriptive Statistics

Descriptive statistics provide an overview of the distribution and variation of variables included in the analysis.

Table 4.1 Descriptive Statistics of Study Variables

Variable	Mean	Std. Dev.	Minimum	Maximum
Agricultural Productivity (tons/hectare)	3.84	1.15	1.21	7.82
Welfare Index	62.47	12.38	28.50	91.30
PM2.5 Concentration ($\mu\text{g}/\text{m}^3$)	43.21	11.45	12.70	89.60
Smoke Exposure Index	5.84	2.17	0.90	12.40
Policy Adoption Score	0.58	0.24	0.00	1.00
Education (Years)	8.73	4.11	0	18
Farm Size (Hectares)	2.36	1.52	0.30	9.80
Household Income (USD)	2,145	986	430	6,450

The average agricultural productivity is 3.84 tons per hectare, indicating moderate productivity levels among sampled households. The mean PM2.5 concentration of $43.21 \mu\text{g}/\text{m}^3$ exceeds

WHO guidelines, confirming substantial pollution exposure. The average policy adoption score of 0.58 suggests moderate participation in agri-environmental programs.

4.3 Gender Comparison Analysis

Table 4.2 Mean Comparison between Male- and Female-Headed Households

Variable	Male-Headed	Female-Headed	Difference
Productivity	4.12	3.56	-0.56
Welfare Index	67.34	57.60	-9.74
Policy Adoption	0.54	0.63	+0.09
Smoke Exposure	5.41	6.27	+0.86
PM2.5 Exposure	41.90	44.53	+2.63

Female-headed households exhibit lower productivity and welfare levels than male-headed households. However, women show higher adoption rates of agri-environmental policies.

Higher pollution and smoke exposure among women suggests greater vulnerability to environmental stressors.

4.4 Correlation Analysis

Table 4.3 Correlation Matrix

Variable	PROD	WEL	POLL	SMOKE	POLICY
PROD	1.000				
WEL	0.691	1.000			
POLL	-0.472	-0.531	1.000		
SMOKE	-0.418	-0.463	0.587	1.000	
POLICY	0.384	0.412	-0.176	-0.152	1.000

Productivity and welfare are positively correlated. Air pollution and smoke exposure are negatively associated with productivity and welfare. Policy

adoption demonstrates a positive relationship with both outcome variables.

4.5 Multicollinearity Test

Table 4.4 Variance Inflation Factor (VIF)

Variable	VIF
PM2.5	2.84
Smoke Exposure	2.67
Policy Adoption	1.95
Education	1.72
Farm Size	1.84
Income	2.11

Mean VIF = 2.19

All VIF values are below the threshold of 10, indicating no multicollinearity problem among explanatory variables.



4.6 Hausman Test

Table 4.5 Hausman Specification Test

Test Statistic	Value
Chi-square	27.84
p-value	0.000

Since the p-value is less than 0.05, the null hypothesis is rejected. Therefore, the Fixed Effects Model is preferred over the Random Effects Model.

4.7 Fixed Effects Regression Results: Productivity Model

Table 4.6 Fixed Effects Estimates for Agricultural Productivity

Variable	Coefficient	Std. Error	t-value	Significance
PM2.5	-0.184	0.034	-5.42	***
Smoke Exposure	-0.127	0.026	-4.88	***
Gender (Female)	-0.096	0.035	-2.71	**
Policy Adoption	0.214	0.034	6.31	***
Education	0.087	0.030	2.94	**
Farm Size	0.148	0.028	5.29	***

Variable	Coefficient	Std. Error	t-value	Significance
Constant	3.962	0.421	9.41	***

$R^2 = 0.71$, F-statistic = 95.63, Prob > F = 0.000

Significance Levels:

*** $p < 0.01$

** $p < 0.05$

$p < 0.10$

Air pollution significantly reduces agricultural productivity. A one-unit increase in PM2.5 concentration decreases productivity by 18.4%.

Similarly, wildfire smoke exposure negatively affects farm output. Policy adoption significantly improves productivity, indicating the effectiveness of agri-environmental interventions. Female-headed households experience significantly lower productivity, suggesting gender-based constraints in adaptation and resource access.

4.8 Fixed Effects Regression Results: Welfare Model

Table 4.7 Fixed Effects Estimates for Welfare

Variable	Coefficient	Std. Error	t-value	Significance
PM2.5	-0.241	0.039	-6.15	***
Smoke Exposure	-0.198	0.037	-5.37	***
Female Household	-0.152	0.039	-3.92	***
Policy Adoption	0.275	0.037	7.44	***
Income	0.319	0.039	8.17	***
Education	0.106	0.032	3.31	***
Constant	48.721	3.214	15.16	***

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$R^2 = 0.76$, F-statistic = 118.42, Prob > F = 0.000

Pollution and smoke exposure significantly reduce household welfare. Female-headed households experience greater welfare losses, reflecting higher vulnerability to environmental shocks. Participation in agri-environmental

programs significantly improves welfare outcomes.

4.9 Gender Interaction Effects

To investigate whether environmental impacts differ across gender groups, interaction terms were introduced.

Table 4.8 Gender Interaction Model

Variable	Coefficient	t-value
PM2.5	-0.151	-4.72***
Smoke Exposure	-0.109	-3.84***
Female × PM2.5	-0.087	-2.95**
Female × Smoke	-0.074	-2.63**
Policy Adoption	0.201	5.88***

$R^2 = 0.74$

The interaction terms are negative and statistically significant. This indicates that women

suffer larger productivity losses from air pollution and wildfire smoke than men. These findings

support the hypothesis that environmental stressors disproportionately affect female

agricultural workers.

4.10 Agri-Environmental Policy Adoption by Gender

Table 4.9 Adoption of Agri-Environmental Practices

Practice	Male (%)	Female (%)
Sustainable Farming	65	57
Tree Plantation	61	78
Climate Adaptation	59	72
Water Conservation	55	68
Pollution Monitoring	54	50

Female farmers participate more actively in conservation-related activities such as tree plantation and climate adaptation measures. Male farmers show higher participation in technology-intensive interventions.

4.11 Willingness-to-Pay for Environmental Protection

Table 4.10 Mean Annual Willingness-to-Pay (USD)

Gender	Mean WTP
Male	26.4
Female	34.8

t-statistic = 4.87

p-value = 0.000

Women demonstrate significantly higher willingness-to-pay for environmental improvements, indicating stronger environmental preferences and greater concern for long-term household welfare.

4.12 Discussion of Findings

The empirical findings indicate that air pollution and wildfire smoke significantly reduce agricultural productivity and household welfare in developing countries. These results are consistent with previous studies that highlight the adverse effects of environmental degradation on economic performance and public health.

The negative coefficient of PM2.5 concentration confirms that pollution reduces labor efficiency and crop productivity. Similarly, wildfire smoke exposure significantly lowers agricultural output due to increased health risks and reduced working hours.

Gender differences emerge as a critical factor in explaining environmental vulnerability. Female-

headed households experience significantly larger productivity and welfare losses than male-headed households. This finding supports Gender Development Theory, which argues that unequal access to resources and adaptive capacities increases women's vulnerability to environmental shocks.

The positive impact of agri-environmental policy adoption demonstrates the effectiveness of conservation programs in mitigating environmental damages. Furthermore, women exhibit stronger environmental preferences and greater participation in conservation-oriented practices, suggesting that gender-sensitive policy interventions can improve both environmental and social outcomes.

Almost results support the study's hypotheses and emphasize the importance of integrating gender considerations into agri-environmental policymaking. Policies that enhance women's access to information, credit, land rights, and climate-resilient technologies are likely to produce greater productivity gains and welfare improvements.

5. Conclusion and Policy Recommendations

5.1 Conclusion

This study examined the gendered behavioral responses to agri-environmental policies under the influence of air pollution and wildfire smoke in developing countries using panel data analysis. By analyzing a balanced panel dataset of agricultural households from selected developing countries over the period 2015–2023, the study explored how environmental stressors affect agricultural productivity and household welfare while assessing the role of gender in shaping policy adoption and adaptive behavior.

The empirical results reveal that air pollution and wildfire smoke significantly reduce agricultural productivity and household welfare. The fixed effects regression analysis demonstrated that increased exposure to PM_{2.5} concentrations and wildfire smoke leads to lower agricultural output, reduced labor efficiency, and declining welfare outcomes. These findings confirm that environmental degradation poses a serious threat to sustainable agricultural development and rural livelihoods in developing countries.

A major contribution of the study is the identification of significant gender differences in environmental impacts and behavioral responses. The results indicate that female-headed households experience greater productivity losses and welfare reductions compared to male-headed households. The interaction effects between gender and environmental stressors reveal that women are disproportionately affected by air pollution and wildfire smoke due to limited access to productive resources, lower adaptive capacity, and greater household responsibilities.

Despite facing greater vulnerability, women exhibited stronger environmental awareness and higher participation in conservation-oriented agri-environmental practices. Female farmers demonstrated greater willingness to adopt tree plantation programs, climate adaptation measures, and sustainable resource management practices. Moreover, women showed a significantly higher willingness-to-pay for environmental protection initiatives, reflecting stronger environmental preferences and long-term welfare considerations.

The findings further indicate that participation in agri-environmental policies significantly improves productivity and welfare outcomes. Households adopting environmental conservation measures experienced lower productivity losses and better welfare performance, highlighting the effectiveness of policy interventions in mitigating environmental risks. However, unequal access to information, credit facilities, land ownership, and agricultural extension services continues to limit the full participation of women in environmental programs.

Finally the study concludes that environmental degradation, particularly air pollution and wildfire smoke, has substantial negative consequences for agricultural productivity and household welfare in developing countries. At the same time, gender plays a crucial role in determining vulnerability, adaptation capacity, and policy effectiveness. Therefore, the integration of gender-sensitive approaches into agri-environmental policymaking is essential for achieving sustainable agricultural development, environmental protection, and social equity.

5.2 Policy Recommendations

Based on the empirical findings of this study, several policy measures are recommended to address the adverse effects of air pollution and wildfire smoke on agricultural productivity and household welfare while promoting gender equity in developing countries.

First, governments should integrate gender perspectives into agri-environmental policies by recognizing the distinct needs, vulnerabilities, and adaptive capacities of men and women. Gender-responsive policy frameworks can enhance women's participation in environmental programs, improve policy effectiveness, and reduce gender-based inequalities.

Second, strengthening women's access to productive resources is essential. Female farmers should be provided with greater access to land ownership, agricultural credit, climate-resilient technologies, irrigation facilities, and extension services. Such measures will enhance their adaptive capacity, increase agricultural productivity, and improve household welfare.

Third, policymakers should expand environmental information and early warning systems through mobile-based pollution alerts, community radio programs, village awareness campaigns, and wildfire warning mechanisms. Improved access to environmental information will help vulnerable households take timely protective measures and reduce exposure to environmental risks.

Fourth, governments should promote climate-smart and sustainable agricultural practices, including conservation agriculture, agroforestry, sustainable land management, and integrated crop management systems. Special incentives should be designed to encourage women's participation in these programs, thereby increasing resilience to environmental stressors and supporting long-term sustainability.

Fifth, stronger pollution mitigation policies are necessary to reduce environmental degradation. Measures such as regulating industrial emissions, reducing agricultural residue burning, improving forest management, investing in clean energy technologies, and implementing community-based wildfire prevention programs can significantly lower pollution exposure and improve public health outcomes.

Furthermore, women's participation in environmental governance should be enhanced through representation in environmental committees, farmer organizations, and climate adaptation planning processes. Inclusive governance structures can ensure that women's interests are reflected in policy decisions and contribute to more effective environmental management.

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