



Original Research

Energy, FDI, and Agricultural Sustainability in Egypt: Environmental Governance as a Moderating Factor

Mohamed Elshahat Elzaabalawy*, Sanaa H. Sadek,
Nashwa Samir Shoaib and Samia E. A. Hatem

Agricultural Economics Research Institute, Agricultural Research Center, Giza, Egypt

* Corresponding author. Email: elzabalawim@yahoo.com; Tel.: +20 114 777 4001



ARTICLE HISTORY

Received: 09 July 2026

Revised: 30 August 2026

Accepted: 09 September 2026

Published: 15 September 2026

KEYWORDS

agricultural sustainability
climate-smart agriculture
Egypt
environmental governance
foreign direct investment
water scarcity

COPYRIGHT

© 2026 Author(s)

e-ISSN: 2583-942X

Exclusive Rights: Society for
AgroEnvironmental Sustainability,
Dehradun, India

LICENSE



This is an Open Access Article
published under a CC BY 4.0
International License

Abstract

Egypt's agricultural sector faces mounting pressure from rising energy consumption, foreign direct investment (FDI), and climate change, compounded by weak environmental governance and binding water constraints, yet no study has jointly quantified these channels or their distributional consequences. This study examines how agricultural energy consumption, FDI, and climate-related water scarcity jointly shape agricultural sustainability in Egypt and evaluates the extent to which environmental governance moderates these effects. We combine a Vector Error Correction Model for Egypt (1980–2024), a Fixed-Effects panel model for six North African countries (2000–2024), and an IMPACT-CGE simulation of 2020–2040 policy scenarios. Agricultural energy consumption raises CO₂ emissions (long-run elasticity = 0.141, $p < 0.01$); FDI increases the ecological footprint by 0.247%, an effect that reverses once female parliamentary representation exceeds 18.5% (interaction coefficient = -0.068 , $p < 0.01$), a threshold that most plausibly proxies broader institutional development rather than gender representation per se. A comprehensive rural-development scenario yields a realistic annual economic surplus of USD 2.8 billion by 2040 (benefit–cost ratio 4.5:1), but a structural water deficit of 15 billion m³ makes reducing rice area from 1.6 to 0.7 million feddans unavoidable, displacing over 200,000 farming families. These results indicate that agricultural sustainability in Egypt is technically achievable and economically attractive, but only if subsidy reform, land-tenure formalization, targeted credit, and livelihood-transition support are pursued jointly with water management and governance strengthening, offering a transferable framework for other water-stressed agricultural economies.

Citation: Elzaabalawy, M. E., Sadek, S. H., Shoaib, N. S., & Hatem, S. E. A. (2026). Energy, FDI, and Agricultural Sustainability in Egypt: Environmental Governance as a Moderating Factor. *AgroEnvironmental Sustainability*, 4(3), 391–398. <https://doi.org/10.59983/s20260403016>

Statement of Sustainability: This study advances SDG 2 (Zero Hunger) and SDG 13 (Climate Action) by identifying evidence-based pathways for reconciling agricultural productivity growth with binding water, energy, and institutional constraints in Egypt. By quantifying trade-offs among energy subsidies, FDI, and environmental governance, and by centering distributional impacts on smallholders and displaced rice farmers, the work also supports SDG 6 (Clean Water and Sanitation) and SDG 10 (Reduced Inequalities), offering a transferable model for other water-stressed developing agricultural economies.

1. Introduction

Agriculture is a cornerstone of Egypt's economy, contributing 13.2% of gross domestic product and employing 26.8% of the work-force, and it underpins national food security amid population growth of approximately 1.8% per year (CAPMAS, 2023). Yet the sector faces interconnected pressures from rising energy use, foreign direct investment (FDI), climate change, and structural weaknesses in Egypt's institutional and financial systems. Agricultural energy consumption grew at 3.35% per year between 1980 and 2024, from 7,342 to approximately 18,500 GWh, outpacing growth in real agricultural output (3.09%) as farming has become more mechanised and energy-intensive. This trend is reinforced by large price distortions: diesel fuel for agriculture is subsidized 35–40% below international prices and irrigation electricity is priced at EGP 0.40/kWh against an actual cost of EGP 1.20/kWh (World Bank, 2022), creating artificial incentives for energy-intensive production that a decoupling of growth from energy use, as envisioned by UNEP (2015), has not yet offset. Consistent with the ascending phase of the Environmental Kuznets Curve (Grossman & Krueger, 1995), Egypt's agricultural growth continues to be accompanied by rising, rather than falling, environmental pressure.



A second channel runs through FDI. International evidence suggests that FDI can follow a “pollution haven” pattern, whereby multinational firms relocate polluting activities to jurisdictions with weaker environmental governance (Levinson & Taylor, 2008; Opoku & Boachie, 2020). Whether this effect is muted depends on institutional quality: lower corruption and greater transparency in government have been linked to fewer favoritism-driven environmental exemptions (Dollar et al., 2001) and to lower carbon emissions (Ergas & York, 2012; Mavisakalyan & Tarverdi, 2019). These studies typically proxy institutional quality with female parliamentary representation, currently 15–17% in Egypt. However, in Egypt’s administrative system environmental authority is concentrated in the executive branch, principally the Ministry of Environment and the Egyptian Environmental Affairs Agency (EEAA), rather than in parliament, and female parliamentarians are largely appointed rather than elected. This raises the possibility that any moderating effect detected through this proxy reflects broader institutional development rather than female political representation as such, a distinction with direct implications for which governance reforms are likely to be effective.

Climate change compounds these pressures. Temperatures in Egypt are projected to rise by 3.3 °C by 2040 and rainfall to decline by 2 mm per year (Tanarhte et al., 2024), intensifying heat and water stress and potentially reducing yields of strategic grains by approximately 14% (Siam & Nasser, 2024). Per-capita water availability has already fallen from 1,024 m³ in 1990 to 572 m³ in 2020, well below the internationally recognized water-scarcity threshold, and further supply reductions are anticipated as upstream consumption, including operation of the Grand Ethiopian Renaissance Dam (GERD), proceeds; hydro-economic modeling of the Eastern Nile shows that Egypt’s irrigation deficits and macroeconomic performance are highly sensitive to how GERD filling and operation are coordinated among riparian states (Basheer et al., 2021), with uncoordinated filling scenarios projected to cause substantial losses in Egyptian agricultural output and GDP (Kamara et al., 2022). These pressures interact with structural features of Egyptian agriculture: more than half of holdings are smaller than one feddan, 40% of agricultural land lacks formal registration and cannot be used as loan collateral, and most smallholders lack access to formal credit, constraints consistent with the broader finding that land-tenure formalization raises agricultural productivity and investment mainly by improving perceived tenure security rather than through a credit-access channel alone (Lawry et al., 2017). Climate-smart agriculture (CSA) technologies such as drip irrigation, heat-tolerant varieties, and conservation agriculture offer a potential route to reconciling productivity with resource constraints (Lipper et al., 2014), but their adoption in Egypt remains low and is constrained by exactly these capital, tenure, and risk-aversion barriers, so that adoption trajectories realistically fall well short of technically optimal rates (Perez et al., 2021).

Prior research has examined these energy, investment, climate, and governance dimensions largely in isolation, and existing assessments of Egypt’s agricultural investment options have tended to assume optimistic productivity and financing scenarios rather than testing them against the country’s binding water and fiscal constraints. This study addresses that gap by jointly estimating the causal linkages among agricultural energy consumption, emissions, and output; the moderating role of environmental governance in the FDI–environmental footprint relationship, including a critical assessment of the female-representation proxy in Egypt’s institutional context; the distributional consequences of alternative investment pathways across farm sizes; and the extent to which water scarcity constrains the feasible policy space. Accordingly, the objectives of this study are to measure the causal relationships between agricultural energy consumption, CO₂ emissions, and productivity in Egypt; to estimate the effect of FDI on the ecological footprint and how environmental governance moderates it; to simulate the productivity and distributional effects of alternative investment scenarios under water and climate constraints through 2040; and, on this basis, to identify a realistic, phased policy pathway toward agricultural sustainability that explicitly accounts for Egypt’s institutional and fiscal capacity. We hypothesize that agricultural energy consumption raises emissions through a subsidy-amplified channel, that FDI’s environmental effect is conditional on institutional rather than narrowly parliamentary governance quality, and that the economic gains from agricultural investment are unevenly distributed across farm sizes unless water scarcity and land-tenure constraints are addressed directly.

2. Material and Methods

2.1. Research Design and Data

This study employs a mixed-methods econometric design that integrates three complementary approaches: a Vector Error Correction Model (VECM) to examine long-run and short-run causal relationships between agricultural energy use, machinery, cultivated area, output, and CO₂ emissions in Egypt over 1980–2024; a panel Fixed-Effects model to assess how FDI and environmental governance jointly affect the ecological footprint across six North African countries (Algeria, Egypt, Libya, Mauritania, Morocco, and Tunisia) over 2000–2024; and an IMPACT-CGE simulation of three alternative policy scenarios for Egypt over 2020–2040, complemented by farm-size and agroecological distributional analysis. All data are secondary and drawn from national sources (CAPMAS; the Ministry of Agriculture (2023); the Ministry of Water Resources and Irrigation (2023); the Ministry of Finance (2023); the Central Bank of Egypt, 2023) and international sources (FAO FAOSTAT; World Bank (2025); World Development Indicators; the Global Footprint Network (2025); WorldClim 2.0 and associated general circulation models), as summarized in Table 1. Because the study relies exclusively on these secondary, national- and country-level data series for Egypt (approximately 26°N, 30°E) and the wider North African region rather than on primary field sampling, no site-specific geocoordinates apply; the analysis does not involve human participants, human data, or animal subjects, and no institutional or ethical approval was therefore required.



Table 1. Study variables, definitions, units, and data sources.

Variable	Definition	Unit	Source / Model
CO ₂ ag	CO ₂ emissions from agriculture	Million tonnes	Global Footprint Network; CAPMAS — VECM
AgOut	Agricultural real GDP	Billion EGP (2012 prices)	FAO; World Bank WDI — VECM
AgEn	Agricultural energy consumption	GWh	Ministry of Electricity — VECM
AgMach	Agricultural machinery stock	Thousand units	FAO; Ministry of Agriculture — VECM
AgArea	Cultivated area	Million feddans	Ministry of Agriculture — VECM
FDlin	Inward FDI in agriculture	USD million (IHS-transformed)	World Bank WDI — Panel FE
FemPar	Female parliamentary representation	% of seats (IHS-transformed)	World Bank WDI — Panel FE
EcoFP	Ecological footprint	Global hectares per capita	Global Footprint Network — Panel FE

Note: CO₂ag = agricultural CO₂ emissions; AgOut = agricultural output; AgEn = agricultural energy consumption; AgMach = agricultural machinery stock; AgArea = cultivated area; FDlin = inward foreign direct investment; FemPar = female parliamentary representation; EcoFP = ecological footprint. IHS = inverse hyperbolic sine transformation. Climate and precipitation projections (1970–2040) additionally draw on WorldClim 2.0 and associated general circulation models. Detailed scenario and technology-adoption assumptions for the IMPACT-CGE model are provided in Supplementary Table S1.

2.2. Vector Error Correction Model — Egypt, 1980–2024

Long-run cointegrating relationship:

$$\ln(\text{CO}_2\text{ag})_t = \gamma_0 + \gamma_1 \ln(\text{AgOut})_t + \gamma_2 \ln(\text{AgEn})_t + \gamma_3 \ln(\text{AgMach})_t + \gamma_4 \ln(\text{AgArea})_t + \epsilon_t$$

Short-run VECM equation:

$$\Delta \ln(\text{CO}_2\text{ag})_t = \alpha_0 + \alpha_1 \text{ECT}_{t-1} + \beta_1 \Delta \ln(\text{AgOut})_t + \beta_2 \Delta \ln(\text{AgEn})_t + \beta_3 \Delta \ln(\text{AgMach})_t + \beta_4 \Delta \ln(\text{AgArea})_t + \epsilon_t$$

where ECT_{t-1} is the lagged error-correction term. The system is estimated after confirming the order of integration of each series and testing for cointegration, and diagnostics include unit-root tests (ADF, PP), the Johansen cointegration test, Granger causality tests, and impulse-response functions (Supplementary Table S2).

2.3. Panel Fixed-Effects Model — North Africa, 2000–2024

For the six-country, 144-observation panel, the ecological footprint is modeled as:

$$\ln(\text{EcoFP})_{it} = \alpha + \beta_1 \text{IHS}(\text{FDlin})_{it} + \beta_2 \text{IHS}(\text{FemPar})_{it} + \beta_3 [\text{IHS}(\text{FDlin}) \times \text{IHS}(\text{FemPar})]_{it} + \beta_4 \ln(\text{RegQ})_{it} + \beta_5 \ln(\text{TradeOp})_{it} + \beta_6 \text{IHS}(\text{Infl})_{it} + \mu_i + \epsilon_{it}$$

where μ_i are country fixed effects and standard errors are Driscoll–Kraay robust to heteroskedasticity, autocorrelation, and cross-sectional dependence. The interaction term $\text{IHS}(\text{FDlin}) \times \text{IHS}(\text{FemPar})$ identifies the extent to which environmental governance moderates the effect of FDI on the ecological footprint, and the corresponding marginal effects are evaluated at representative levels of female parliamentary representation.

2.4. IMPACT-CGE Policy Scenario Simulation, 2020–2040

The IMPACT computable general equilibrium framework (Robinson et al., 2015) links biophysical crop-yield responses to climate change with economy-wide market outcomes. Three policy scenarios are simulated through 2040: a business-as-usual scenario reflecting current budgets and climate change only; a technology-extension scenario assuming 20% climate-smart agriculture (CSA) adoption; and a phased rural-development scenario assuming comprehensive investment and 40% CSA adoption. Full financing, technology-target, and governorate-level assumptions for each scenario are documented in Supplementary Tables S1, S3, S4, S6, S9, and S10, and the associated implementation timeline in Supplementary Note S1. Outcomes are evaluated for aggregate productivity and economic surplus and disaggregated by farm size (subsistence, <1 feddan; small, 1–5 feddans; medium, 5–10 feddans; and commercial, >10 feddans) to capture distributional effects.

2.5. Statistics, Data Analysis, and Software

Long-run and short-run VECM parameters, panel fixed-effects coefficients, and CGE outcomes are reported with standard errors and significance levels of $p < 0.10$, $p < 0.05$, and $p < 0.01$. Model diagnostics for the VECM (unit-root, cointegration, and Granger-causality tests) are reported in the Results and in Supplementary Table S2, and panel estimates use Driscoll–Kraay standard errors robust to serial correlation and cross-sectional dependence. The VECM and panel fixed-effects models were estimated in EViews; the IMPACT-CGE policy simulation was implemented and solved in GAMS (General Algebraic Modeling System).

3. Results and Discussion



3.1. Energy Consumption, Agricultural Output, and CO₂ Emissions

Unit-root tests (ADF, PP) confirm that all VECM variables are integrated of order one, and the Johansen test identifies at least one cointegrating vector, supporting a long-run equilibrium relationship among agricultural output, energy use, machinery, cultivated area, and CO₂ emissions (Table 2). In the long run, a 10% increase in agricultural energy consumption is associated with a 1.41% increase in CO₂ emissions ($p < 0.01$), while a 10% increase in cultivated area raises emissions by 18.0%, the largest elasticity in the system, indicating that horizontal expansion of farmland is markedly more emission-intensive than intensification through machinery or output growth alone. The error-correction term (-0.318 , $p < 0.05$) implies that roughly three years are required for the system to return to equilibrium after a shock, and the short-run energy elasticity (0.087) is considerably smaller than its long-run counterpart, consistent with adjustment lags in farmer responses to energy-price and technology signals.

Table 2. VECM estimation results: long-run and short-run relationships, Egypt (1980–2024).

Variable	Long-run coeff.	Long-run SE	Short-run coeff. (Δ)	Short-run SE
Constant	−12.55	—	—	—
ln(AgOut)	0.768***	0.081	0.198*	0.085
ln(AgEn)	0.141***	0.026	0.087*	0.122
ln(AgMach)	0.885***	0.117	0.428**	0.203
ln(AgArea)	1.802***	0.368	0.621 (ns)	2.760
ECT($t-1$)	—	—	−0.318*	0.129

Note: Long-run equation: $R^2 = 0.973$, LR test = 285.4***. Short-run equation: Adj. $R^2 = 0.725$, $F = 18.47$ ***. Δ denotes first-difference terms; ECT($t-1$) is the lagged error-correction term. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; ns = not significant. Granger causality results underlying this table are reported in Supplementary Table S2.

Granger causality tests (Supplementary Table S2) show bidirectional causality between agricultural output and emissions, and unidirectional causality running from energy consumption, machinery, and cultivated area to emissions, indicating a self-reinforcing cycle in which agricultural growth and emissions drive one another rather than a simple one-way effect of production on pollution. This pattern is consistent with the ascending phase of the Environmental Kuznets Curve described by Grossman and Krueger (1995) and with prior VECM evidence for Egypt's agricultural sector (Abu El-Yazid & Abd El-Karim, 2026) and for China's grain-producing regions (Zhang et al., 2019), both of which find energy consumption to be a robust driver of agricultural emissions. A distinctive feature of the Egyptian case, however, is the extent to which these elasticities are inflated by energy-price distortions: diesel for agriculture is subsidized 35–40% below international prices and irrigation electricity is priced at roughly a third of its actual cost, and at cost-recovery prices the estimated energy elasticity would plausibly decline by 40–50%. This suggests that subsidy reform, rather than efficiency-enhancing technology alone, is central to reconciling the observed decoupling gap highlighted by UNEP (2015) between agricultural growth and its environmental footprint in Egypt.

3.2. FDI, Environmental Governance, and the Ecological Footprint

The panel fixed-effects model explains a meaningful share of within-country variation (within $R^2 = 0.235$, $F = 15.84$, $p < 0.01$) and shows that inward FDI significantly raises the ecological footprint (coefficient = 0.248, $p < 0.01$), consistent with a pollution-haven pattern in which environmentally intensive investment is drawn to jurisdictions with weaker enforcement (Table 3). Female parliamentary representation is independently associated with a higher footprint (0.162, $p < 0.01$), but its interaction with FDI is negative and highly significant (-0.069 , $p < 0.01$), indicating that the environmental cost of FDI is progressively offset as this governance proxy rises. Marginal-effects estimates (Table 4) show that FDI's effect on the footprint is positive and significant at low levels of female representation (7.7%), becomes statistically indistinguishable from zero near 18.5%, and turns negative, though imprecisely estimated, beyond that threshold.

Table 3. Panel fixed-effects results: FDI, female parliamentary representation, and ecological footprint, North Africa (2000–2024).

Variable	Coefficient	Std. error	t-stat	Sig.
IHS(FDI _{in})	0.2476	0.0584	4.24	***
IHS(FemPar)	0.1618	0.0327	4.95	***
IHS(FDI _{in}) $\times$ IHS(FemPar)	−0.0687	0.0128	−5.37	***
ln(RegQ)	−0.0482	0.0298	−1.62	ns
ln(TradeOp)	0.1498	0.0994	1.51	ns
IHS(lnfl)	−0.0364	0.0211	−1.73	*



Table 4. Marginal effect of FDI on the ecological footprint at selected levels of female parliamentary representation.

Female representation	Marginal effect	95% CI	Interpretation
7.7%	+0.0613*	[0.001, 0.122]	Positive (harmful)
13.0%	+0.0144	[-0.048, 0.077]	Neutral
18.5%	0.0000	—	Threshold
23.5%	-0.0234	[-0.150, 0.103]	Negative (beneficial)

Note: Within $R^2 = 0.235$, $F = 15.84^{***}$; $n = 144$ (6 countries $\times$ 24 years). Driscoll–Kraay robust standard errors. IHS = inverse hyperbolic sine transformation. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; ns = not significant.

This pattern extends the pollution haven hypothesis (Levinson & Taylor, 2008; Opoku & Boachie, 2020) by showing that its environmental costs are not fixed but can be reversed as institutional quality improves, in line with cross-national evidence linking female political representation to lower corruption (Dollar et al., 2001) and lower emissions (Ergas & York, 2012; Mavisakalyan & Tarverdi, 2019; Baraldi & Fosco, 2025). Three mechanisms plausibly underlie this moderating effect: reduced regulatory capture and corruption in permitting, greater environmental awareness among more diverse governing bodies, and increased transparency and accountability in enforcement. In Egypt’s specific institutional context, however, environmental authority sits primarily with the executive branch, principally the Ministry of Environment and the EEAA, rather than with parliament, and female parliamentarians are typically appointed rather than elected, so the 18.5% threshold most plausibly proxies broader institutional development rather than female political representation as such. This implies that governance reforms targeting administrative capacity and female technical leadership within EEAA and local environmental offices are likely to be more effective levers for Egypt than parliamentary gender quotas alone.

3.3. Policy Scenario Outcomes and Distributional Impacts

The IMPACT-CGE simulations show a clear ordering across scenarios (Table 5). Under business-as-usual, climate change alone reduces grain productivity by 9.96% and generates a negative annual economic surplus by 2040. The technology-extension scenario, with 20% CSA adoption, raises grain productivity by 7.07% and produces a positive annual surplus of USD 0.65 billion, with a benefit–cost ratio of 2.3:1. The comprehensive rural-development scenario, combining subsidy reform, land-tenure formalization, and 40% CSA adoption, raises grain productivity by 14.61% and generates the largest realistic annual surplus, USD 2.8 billion by 2040, with a benefit–cost ratio of 4.5:1. This figure is deliberately conservative relative to an earlier, more optimistic estimate of USD 7.89 billion, reflecting price effects and implementation constraints that are likely to attenuate gains in practice; treating the more conservative estimate as the central case is consistent with the broader literature’s caution that IMPACT-CGE assessments of Egypt’s agricultural investment options should be tested against realistic financing and adoption constraints (Perez et al., 2021) rather than assumed technology ceilings (Lipper et al., 2014).

Table 5. Scenario comparison: productivity, economic, and distributional outcomes, 2020–2040.

Indicator	BAU	TechDrive	RuralDev
Grain productivity change	-9.96%	+7.07%	+14.61%
Total production change	-11.53%	+6.66%	+7.61%
Annual economic surplus (USD billion)	-1.84	+0.65	+2.8
Total benefits, 2020–2040 (USD billion)	-40 to -50	35–40	85–95
Total costs, 2020–2040 (USD billion)	2–3	15–18	18–22
Net present value (USD billion)	-53 to -38	17–25	63–77
Benefit–cost ratio (mid-range)	Negative	2.3:1	4.5:1
CSA adoption rate by 2040	0%	20%	40%
Income gain — commercial farms (>10 fed.)	—	+35%	+42%
Income gain — medium farms (5–10 fed.)	—	+18%	+28%
Income gain — small farms (1–5 fed.)	—	+8%	+15%
Income gain — subsistence farms (<1 fed.)	—	+2%	+6%

Note: BAU = business-as-usual; TechDrive = technology-extension scenario (20% CSA adoption); RuralDev = phased comprehensive rural-development scenario. Net present value is total benefits minus total costs, taking the low-benefit/high-cost and high-benefit/low-cost combinations of each scenario’s reported ranges as lower and upper bounds. The benefit–cost ratio is the ratio of central (mid-range) total benefits to central total costs. Full scenario financing and technology-adoption assumptions are in Supplementary Tables S1, S3, S6, S9, and S10.

These aggregate gains, however, are not evenly shared (Table 6). By 2040 under rural development, commercial farms (>10 feddans) gain 42% in income while subsistence farms (<1 feddan) gain only 6%, and credit access, CSA adoption, and water-saving benefits all rise sharply with farm size. Large commercial farmers and the agro-processing sector are clear winners, while subsistence farmers, an estimated eight million landless agricultural laborers facing mechanization-induced job losses, and, in particular, Delta rice farmers bear disproportionate adjustment costs. Water scarcity is the binding constraint behind this last group’s exposure: by 2040, agricultural water demand of 65.5 billion m³ would exceed an available supply of roughly 50 billion m³, a structural deficit



of about 15 billion m³ that cannot be closed through efficiency gains alone and that makes reducing rice area from 1.6 to 0.7 million feddans a necessity rather than a policy choice, displacing an estimated 200,000 farming families and 500,000 associated laborers. This deficit is consistent with hydro-economic evidence that, absent coordinated management of the Nile system, filling and operating the GERD can impose substantial water and income losses on Egyptian agriculture (Kamara et al., 2022), whereas a coordinated operating strategy among Ethiopia, Sudan, and Egypt could materially reduce Egypt's irrigation deficits and support macroeconomic resilience (Basheer et al., 2021); the realized outcome therefore depends as much on transboundary cooperation as on domestic policy. Without explicit compensation, for example through livelihood-transition support and access to alternative high-value crops, political opposition is likely to block implementation of the very reforms that generate the aggregate surplus, underscoring that the distributional and water dimensions of the rural-development scenario are inseparable from its economic case.

Table 6. Distributional impact by farm size, 2040 (RuralDev scenario).

Impact dimension	Small (<1 fed.)	Medium (1–5 fed.)	Large (5–10 fed.)	Commercial (>10 fed.)
Income gain (2040)	+6%	+15%	+28%	+42%
Credit access	25%	55%	75%	90%
CSA adoption	15–20%	35–40%	50–55%	65–75%
Water savings benefit	Low	Medium	High	Very high
Subsidy phase-out impact	–10% income	–8% income	–5% income	–2% income
Farm abandonment risk (2040)	25%	8%	2%	<1%

Note: fed. = feddan ($\approx$ 0.42 hectares). CSA = climate-smart agriculture.

3.4. Integrated Assessment and Study Limitations

Taken together, the three analyses point to the same conclusion from different angles: Egypt's agricultural sustainability challenge is driven less by any single factor than by the interaction of price distortions in energy, weak but improvable environmental governance, and an increasingly binding water constraint. Addressing the energy–emissions cycle identified in the VECM results, reversing the pollution-haven pattern identified in the panel results, and realizing the distributional promise of the rural-development scenario all depend on the same underlying reforms: energy-subsidy reform, land-tenure formalization that unlocks credit for smallholders (Lawry et al., 2017), and governance strengthening concentrated in administrative rather than parliamentary institutions. These findings should nonetheless be read in light of several limitations. The panel model covers only six North African countries, limiting statistical power for the interaction term; female parliamentary representation, as discussed above, is an imperfect proxy for the institutional channels that matter most in Egypt; the IMPACT-CGE simulation relies on representative farms and may understate heterogeneity within each farm-size category; and the water-balance projections depend on uncertain future operation of the GERD, whose hydrological and macroeconomic consequences for Egypt vary considerably across filling and operating scenarios (Basheer et al., 2021; Kamara et al., 2022). Future research combining governorate-level data, household-level social accounting matrices, and political-economy modeling of reform coalitions would help to refine both the magnitude of these effects and the political feasibility of the reforms they imply.

4. Conclusion

This study shows that agricultural energy consumption, FDI, and climate-related water scarcity jointly constrain agricultural sustainability in Egypt, and that environmental governance, understood as administrative rather than purely parliamentary capacity, can meaningfully moderate the environmental costs of investment. Rising agricultural energy use is closely tied to CO₂ emissions through a subsidy-amplified channel, while the environmental costs of FDI decline as institutional quality improves. A comprehensive rural-development pathway is economically attractive in aggregate but delivers markedly uneven gains across farm sizes, and a structural water deficit makes reducing rice cultivation, and supporting the livelihoods this displaces, unavoidable rather than optional. We therefore recommend a phased strategy that sequences energy-subsidy reform, land-tenure formalization, targeted rural credit, climate-smart agriculture scaling, water-management investment, and livelihood-transition support for displaced rice farmers and landless laborers, coordinated through strengthened environmental administration; the corresponding governorate-level pilots, financing sources, risk mitigation measures, and implementation timeline are detailed in the Supplementary Materials. Egypt's experience offers a transferable model for other water-stressed developing agricultural economies confronting similar trade-offs between growth, environmental governance, and equity.

Author Contributions

Conceptualization, Elzaabalawy Mohamed Elshahat and Sanaa H. Sadek; Methodology, Elzaabalawy Mohamed Elshahat; Software, Elzaabalawy Mohamed Elshahat; Validation, Nashwa Samir Shoaib and Samia E. A. Hatem; Formal analysis, Elzaabalawy Mohamed Elshahat; Investigation, Sanaa H. Sadek and Nashwa Samir Shoaib; Resources, Sanaa H. Sadek; Data curation, Elzaabal-



awy Mohamed Elshahat and Nashwa Samir Shoaib; Writing – original draft preparation, Elzaabalawy Mohamed Elshahat; Writing – review and editing, Sanaa H. Sadek, Nashwa Samir Shoaib and Samia E. A. Hatem; Visualization, Elzaabalawy Mohamed Elshahat; Supervision, Samia E. A. Hatem; Project administration, Samia E. A. Hatem; Funding acquisition, not applicable. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

The authors acknowledge the institutional support of the Agricultural Economics Research Institute, Agricultural Research Center, Giza, Egypt.

Funding Information

This research received no specific external funding.

Declarations

Conflict of Interest: The authors declare no conflict of interest related to this work.

Data Availability/Supplementary Information: The online version of this article contains supplementary material.

References

- Abu El-Yazid, A., & Abd El-Karim, H. (2026). The causal relationship between energy consumption, economic growth, and CO2 emissions in Egypt's agricultural sector. *Egyptian Journal of Agricultural Economics*, 36(1), 1468–1498. <https://doi.org/10.21608/meae.2026.457995.1437>
- Baraldi, A. L., & Fosco, G. (2025). Clearing the air: Women in politics and air pollution. *Journal of Environmental Economics and Management*, 130, 103106. <https://doi.org/10.1016/j.jeem.2024.103106>
- Basheer, M., Nechifor, V., Calzadilla, A., Siddig, K., Etichia, M., Whittington, D., Hulme, D., & Harou, J. J. (2021). Collaborative management of the Grand Ethiopian Renaissance Dam increases economic benefits and resilience. *Nature Communications*, 12, 5622. <https://doi.org/10.1038/s41467-021-25877-w>
- CAPMAS (Central Agency for Public Mobilization and Statistics). (2023). Agricultural census 2020: Final report. Egyptian Ministry of Planning.
- Central Bank of Egypt. (2023). Monetary policy and financial stability report. CBE Publications.
- Dollar, D., Fisman, R., & Gatti, R. (2001). Are women really the 'fairer' sex? Corruption and women in government. *Journal of Economic Behavior & Organization*, 46(4), 423–429. [https://doi.org/10.1016/S0167-2681\(01\)00169-X](https://doi.org/10.1016/S0167-2681(01)00169-X)
- Ergas, C., & York, R. (2012). Women's status and carbon dioxide emissions: A quantitative cross-national analysis. *Social Science Research*, 41(4), 965–976. <https://doi.org/10.1016/j.ssresearch.2022.03.008>
- Global Footprint Network. (2025). National footprint and biocapacity accounts. <https://www.footprintnetwork.org/>
- Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *Quarterly Journal of Economics*, 110(2), 353–377. <https://doi.org/10.2307/2118443>
- Kamara, A., Ahmed, M., & Benavides, A. (2022). Environmental and economic impacts of the Grand Ethiopian Renaissance Dam in Africa. *Water*, 14(3), 312. <https://doi.org/10.3390/w14030312>
- Lawry, S., Samii, C., Hall, R., Leopold, A., Hornby, D., & Mtero, F. (2017). The impact of land property rights interventions on investment and agricultural productivity in developing countries: A systematic review. *Journal of Development Effectiveness*, 9(1), 61–81. <https://doi.org/10.1080/19439342.2016.1160947>
- Levinson, A., & Taylor, M. S. (2008). Unmasking the pollution haven effect. *International Economic Review*, 49(1), 223–254. <https://doi.org/10.1111/j.1468-2354.2008.00478.x>
- Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., et al. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, 4(12), 1068–1072. <https://doi.org/10.1038/nclimate2437>
- Mavisakalyan, A., & Tarverdi, Y. (2019). Gender and climate change: Do female parliamentarians make a difference? *European Journal of Political Economy*, 56, 151–164. <https://doi.org/10.1016/j.ejpoleco.2018.08.001>
- Ministry of Agriculture. (2023). Agricultural statistics and extension services report. Government of Egypt.
- Ministry of Finance. (2023). Budget statement: Agricultural subsidies analysis. Government of Egypt.
- Ministry of Water Resources. (2023). Annual water balance report 2023. Egyptian Ministry of Water Resources and Irrigation.
- Opoku, E. E. O., & Boachie, M. K. (2020). The environmental impact of industrialization and foreign direct investment. *Energy Policy*, 137, 111178. <https://doi.org/10.1016/j.enpol.2019.111178>
- Perez, N. D., Kassim, Y., Ringler, C., Thomas, T. S., ElDidi, H., & Breisinger, C. (2021). Climate-resilience policies and investments for Egypt's agriculture sector: Sustaining productivity and food security. International Food Policy Research Institute.
- Robinson, S., Mason-D'Croz, D., Sulser, T., Islam, S., Robertson, R., Zhu, T., et al. (2015). The international model for policy analysis of agricultural commodities and trade (IMPACT): Model description for version 3. International Food Policy Research Institute.
- Siam, G. M., & Nasser, A. Y. (2024). The impact of climate change on the productivity of strategic grain crops in Egypt. *Egyptian Journal of Agricultural Economics*, 34(4), 1468–1498.
- Tanahrte, M., De Vries, A. J., Zittis, G., & Chfadi, T. (2024). Severe droughts in North Africa: A review of drivers, impacts and management. *Earth-Science Reviews*, 250, 104701. <https://doi.org/10.1016/j.earscirev.2024.104701>
- United Nations Environment Programme. (2015). Decoupling: Natural resource use and environmental impacts from economic growth. UNEP.
- World Bank. (2022). Egypt economic update: Agricultural reform for sustainability. World Bank Group, Middle East and North Africa Region.



World Bank. (2025). World development indicators. <https://data.worldbank.org/>

Zhang, L., Pang, J., Chen, X., & Lua, Z. (2019). Carbon emissions, energy consumption and economic growth: Evidence from the agricultural sector of China's main grain-producing areas. *Science of the Total Environment*, 665, 1017–1025. <https://doi.org/10.1016/j.scitotenv.2019.02.313>

Publisher's note/Disclaimer: Regarding jurisdictional assertions in published maps and institutional affiliations, We maintains its neutral position. All publications' statements, opinions, and information are the sole responsibility of their respective author(s) and contributor(s), not We or the editor(s). We and/or the editor(s) expressly disclaim liability for any harm to persons or property caused by the use of any ideas, methodologies, or products described in the content.