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RESEARCH ARTICLE

SUSTAINABILITY ASSESSMENT OF POULTRY PRODUCTION USING ECONOMIC AND ENVIRONMENTAL INDICATORS: EVIDENCE FROM BARIND TRACT, BANGLADESH

Md. Mesbahul Alam¹, Saiful Islam¹, Most. Shabrina Afroz¹, Md. Palash Bin Faruque¹, Tanjinakhan¹, Md. Yeasir Arafat² and Md. Mostafizur Rahman¹

1. Data Mining and Environmental Research group, Department of Statistics and Data Science, University of Rajshahi, Rajshahi-6205, Bangladesh.
2. Department of Economics, Islamic University, Kushtia, Bangladesh.

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Abstract

Background: Poultry farming is simultaneously a driver of rural economic transformation and a source of environmental pressure, a tension that is especially acute in Bangladesh's Barind Tract, a drought-prone region where groundwater levels have fallen by up to 47 m over three decades. Existing research has examined the economic and environmental dimensions of poultry sustainability separately and has rarely focused on this specific agro-ecological zone.

Methods: A cross-sectional survey of 121 commercial and semi-commercial poultry farming households was conducted across the Rajshahi and Joypurhat districts of the Barind Tract using a two-stage, stratified sampling design. Data on socio-economic characteristics, production costs, environmental management practices, and operational constraints were analysed using descriptive statistics, the Relative Importance Index (RII), multiple linear and binary logistic regression, chi-square tests with Cramer's V, and the Friedman and Kruskal-Wallis tests. A composite Sustainability Index, combining Economic Challenge, Environmental Sustainability, and Challenge Severity sub-indices (Cronbach's $\alpha = 0.71-0.75$), was constructed and its determinants examined by multiple regression.

Results: Feed price was a near-universal economic concern (RII = 0.95). Education, farming experience, formal credit access, and flock size were significant positive predictors of total production cost ($R^2 = 0.306$, $p < 0.001$), while flock size was the dominant predictor of formal credit access (OR = 3.64, $p < 0.001$).

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Manure was overwhelmingly disposed of untreated — applied to cropland (45.5%) or used in ponds (35.5%) — and no sampled farm used a biogas digester, despite high farmer awareness of environmental impact (RII = 0.81).

Corresponding Author:-Md. Mostafizur Rahman

Address:-Data Mining and Environmental Research group, Department of Statistics and Data Science, University of Rajshahi, Rajshahi-6205, Bangladesh.

Disease outbreaks, day-old-chick cost, and heat stress were the most severe constraints ($RII = 0.71\text{--}0.80$; Friedman $\chi^2(7) = 295.47$, $p < 0.001$). District location was the strongest predictor of the composite Sustainability Score ($R^2 = 0.615$, $\beta = 0.137$, $p < 0.001$), exceeding the contribution of any individual farmer characteristic; training showed a significant negative association with sustainability ($\beta = -0.038$, $p = 0.009$).

Conclusions: Poultry sustainability in the Barind Tract is shaped more by spatially differentiated structural conditions than by individual farmer attributes. Credit and training systems currently reward scale rather than efficiency or environmental performance. Policy attention should combine farm-level biosecurity and heat-stress investment with structural, district-targeted support and the explicit integration of livestock water demand into regional groundwater governance.

Introduction:-

Sustainable development has become one of the defining priorities shaping economic, social, and environmental policy agendas worldwide, yet reconciling economic growth with environmental preservation remains a persistent challenge, particularly in agriculture and livestock production (Atkinson et al., 2007; Goodland & Daly, 1996; Holdgate, 1987). Within this broader tension, poultry farming occupies a distinctive position: it is one of the most resource-efficient sources of animal protein, requiring comparatively less land, water, and feed than other livestock species, and has been promoted globally as a pathway to improved nutrition, rural employment, and enterprise development (Rodić et al., 2011; Wossink & Wefering, 2003). Poultry has been identified as the fastest-growing agricultural sub-sector worldwide, particularly in developing countries, driven by population growth, rising incomes, and urbanization (Mottet & Tempio, 2017). Yet this growth carries a cost. The intensive, large-scale nature of modern poultry operations generates substantial volumes of manure and litter that, when poorly managed, contribute to nutrient leaching, greenhouse gas emissions, and degradation of local air and water quality (Steinfeld et al., 2006), while also elevating antimicrobial resistance and zoonotic disease risk as production scales up (Mottet & Tempio, 2017). This dual identity - poultry as an engine of rural economic transformation and a source of mounting environmental pressure - is the central tension motivating the present study.

Bangladesh illustrates this tension clearly. National poultry production has grown from roughly ninety-one million birds in 1990 to over 365 million by 2020–2021, transforming the sector from a backyard subsistence activity into a near-industrial commercial enterprise, and now the fastest-growing component of the country's livestock industry (M. M. Rahman et al., 2022). Poultry farming has become a critical source of self-employment, particularly for rural youth and women with limited access to formal education or other livelihood options (Dolberg, 2003; Moller et al., 2023), and functions for many households as an informal safety net during periods of economic hardship. A review of contract farming arrangements in the sector, in place since 1994, frames this growth as directly consistent with the Sustainable Development Goals, linking microeconomic farm decisions to macroeconomic development outcomes (Haq et al., 2021). Yet more than a decade ago, reviewers of the Bangladeshi poultry sector were already calling for research that examined multiple dimensions of sustainability together rather than production economics and disease management in isolation (S. M. Rahman et al., 2015)- a call that, as the literature below shows, remains only partially answered.

On the economic side, a substantial body of work using gross margin analysis, benefit-cost ratios, and stochastic frontier methods has generally found poultry farming to be profitable, though with considerable variation across contexts: benefit-cost ratios have ranged from roughly 1.04 in Pakistan (Khan & Afzal, 2018) to 2.49 in Nigeria (Oladipo et al., 2020; Yusuf et al., 2016), and technical efficiency estimates in Bangladesh alone have ranged from 0.92 in early work (Sarker et al., 1999) to over 94% in more recent contract-farming studies (Saha et al., 2021). Feed cost, labor cost, mortality, and access to credit and veterinary services recur across this literature as the key determinants of profitability (Akpaeti et al., n.d.; Alam et al., 2025; Mulaudzi et al., 2022) while findings on socio-economic variables such as education and family size have been notably inconsistent - one study finds profitability inversely related to both education and family size (Alam et al., 2025), a counterintuitive result attributed to income dilution across larger households, which is itself a strong argument for testing these relationships in new contexts rather than assuming they generalize. On the environmental side, studies conducted elsewhere in Bangladesh (Mymensingh and Jhenaidah) have repeatedly found poultry farms to be economically profitable while simultaneously constituting a serious source of environmental concern, with untreated manure contributing to soil and air pollution and, in some cases, to the contamination of adjacent vegetable crops with *E. coli* and *Salmonella* (Ahmed et al., 2023; Begum et al., 2023; Hossen et al., 2015; Modak et al., 2019; M. M. Rahman et al., 2022). Adoption of improved waste management technologies such as biogas digesters and composting remains limited, constrained by farmer knowledge, investment capacity, and land requirements (M. M. Rahman et al., 2022). At the

international level, frameworks such as FAO's Global Livestock Environmental Assessment Model provide standardized emissions and water-use estimates across livestock species ((FAO), 2021; FAO, 2017), but such aggregate figures cannot capture the specific waste, water, and pollution dynamics of a water-stressed agro-ecological zone, underscoring the need for locally grounded, farm-level data.

That need is especially acute in the Barind Tract of northwestern Bangladesh, an agro-ecological zone marked by low rainfall, high dry-season temperatures, and heavy dependence on groundwater, where average water tables in the High Barind Tract have fallen from roughly 8 to 18 metres over the past three decades, with some localities declining to nearly 47 metres (Hasan et al., 2018; Mojid et al., 2021). A recent behavioral study of 385 Barind farm households found that greater farming experience was, counterintuitively, negatively associated with both climate perception and adaptive capacity - a form of cognitive lock-in in which strategies that worked historically no longer fit accelerating drought and groundwater decline (Mahedi et al., 2026). Against this backdrop of intensifying water scarcity, poultry production has nonetheless become an increasingly important livelihood strategy in the region (Hossain et al., 2021; M. B. Islam et al., 2010; M. S. Islam et al., 2019; Reza et al., 2020), while institutional weaknesses - limited coordination among extension services, credit providers, and local government - leave individual farmers largely on their own to manage disease outbreaks, waste disposal, and resource competition (Kamruzzaman et al., 2021; Nath et al., 2020).

The economic performance, socio-economic determinants, and environmental impact in poultry farming have each been studied extensively, but almost always in isolation from one another, and predominantly in regions outside the Barind Tract. No study identified combines gross margin analysis, regression-based analysis of socio-economic determinants, and a composite sustainability index spanning economic, environmental, and operational-challenge dimensions within this specific water-stressed, drought-prone setting. This gap matters because water scarcity and climatic stress in the Barind Tract create interlinked economic and environmental pressures that cannot be understood, or addressed by policy, through single-dimension analysis. The present study addresses this gap by providing an integrated economic-environmental assessment of poultry production in the Barind Tract, using primary household-level data from Rajshahi and Joypurhat districts. Specifically, the study (1) assesses the economic performance of poultry farms and the socio-economic factors influencing their productivity and profitability, (2) evaluates the environmental impacts of poultry farming and the factors associated with environmental management practices, and (3) examines the major economic, environmental, and institutional constraints faced by poultry farmers in the study area. In doing so, it contributes both region-specific empirical findings and a replicable analytical framework for assessing poultry sustainability in other water-constrained agro-ecological settings.

Materials and Methods:-

Study Area:-

This study was conducted in the Barind Tract of northwestern Bangladesh, an agro-ecological zone within Rajshahi Division characterized by elevated terrain, comparatively low and erratic rainfall, high dry-season temperatures, and heavy dependence on groundwater irrigation. Two districts, Rajshahi and Joypurhat, were purposively selected on the basis of their relatively high density of commercial and semi-commercial poultry farming activity, as recorded in Department of Livestock Services (DLS) statistics. These two districts collectively capture variation in farm type (broiler, layer, and Sonali), housing system, and groundwater-stress conditions across the wider Barind region, allowing the study to examine whether poultry farm performance and environmental practice differ systematically across zones of differing hydrological stress rather than treating the Barind Tract as a homogeneous unit.

Research Design and Sampling Procedure:-

The study used a cross-sectional, observational design. It describes current economic and environmental conditions and tests associations between farm characteristics and outcomes; it does not establish causality. A two-stage sampling procedure was used. In the first stage, the two study districts were purposively selected on the basis of poultry farming density. In the second stage, individual poultry farming households were selected at random from a sampling frame constructed from DLS farm registers and union-level lists, supplemented by field listing to capture unregistered farms. Stratification by farm type (broiler, layer, Sonali) and flock-size category was applied within each upazila to ensure adequate representation of the heterogeneous production systems characteristic of the Barind Tract. The target sample size was determined using Cochran's (1977) formula for proportions in a finite population, $n_0 = Z^2 p(1-p)/e^2$, with $Z = 1.96$ (95% confidence), $p = 0.5$ (conservative maximum-variance assumption), and $e = 0.05$. A finite-population correction was applied given the non-trivial sampling fraction, and the resulting sample

size was increased by approximately 10% to allow for anticipated non-response and data-quality attrition. The final achieved sample comprised 121 poultry farming households: 71 (58.7%) in Rajshahi and 50 (41.3%) in Joypurhat.

Data Collection Instrument:-

Primary data were collected through face-to-face interviews using a structured questionnaire administered to the household member primarily responsible for managing the poultry enterprise. The instrument comprised seven sections: (A) introduction and informed consent; (B) socio-economic and farm profile; (C) economic performance and costs, including per-cycle production costs and access to credit and veterinary support; (D) environmental impacts and management, including manure and dead-bird disposal practices, water contamination and scarcity, and a five-point Likert battery on environmental perception; (E) information sources and future outlook; (F) an eight-item, five-point Likert battery on operational challenges and constraints; and (G) seasonality of disease. The questionnaire was pilot-tested prior to full-scale data collection, and enumerators recorded GPS coordinates for each farm.

Data Management and Missing Data Handling:-

Completed questionnaires were checked for completeness and logical consistency in the field before data entry. Missing data were handled according to their source: structural missingness from skip patterns was coded as 'not applicable'; item non-response on continuous variables with less than 5% missingness was addressed through stratum-specific (district $\times$ farm-type) median imputation; missingness between 5% and 15% was addressed using multiple imputation by chained equations (MICE), with regression models estimated separately on each imputed dataset and combined using Rubin's (1987) rules; and cases with more than 15% missingness, or missing values on a given analysis's dependent variable, were excluded from that specific analysis under listwise deletion. Continuous variables were screened for outliers using the interquartile-range rule, with genuine extreme values retained and tested using winsorization in sensitivity analyses.

Construction of composite indices:-

A central methodological contribution of this study is the construction of a composite Sustainability Index integrating economic, environmental, and operational constraint dimensions into a single farm-level measure. Three sub-indices were derived from dedicated Likert batteries: the Economic Challenge Index (ECI; five items, Part C), the Environmental Sustainability Index (ESI; five items, Part D), and the Challenge Severity Index (CSI; eight items, Part F). For each respondent, item scores within a battery were reverse-coded where necessary so that higher values consistently indicated a more challenging or less sustainable outcome, averaged to produce a raw sub-index score, and rescaled to a 0–1 range using min–max normalization. The composite Sustainability Score was defined as the arithmetic mean of the three sub-indices and, for interpretive purposes in the regression analyses, was expressed in positive-directional form (higher = more sustainable) by subtracting the composite challenge index from 1. Internal consistency of each sub-index was assessed using Cronbach's alpha, with $\alpha \geq 0.70$ taken as the threshold for acceptable reliability.

Statistical analysis:-

All data were analysed using IBM SPSS Statistics (Version 26) and R (Version 4.3.x). Descriptive statistics (means, standard deviations, frequencies) summarized sample characteristics, and the Relative Importance Index ($RII = \Sigma W / (A \times N)$, where W is the Likert score, A is the maximum possible score, and N is the number of respondents) was used to rank perceived severity across Likert-scale items. Independent-samples t -tests and one-way ANOVA (with Cohen's d and eta-squared effect sizes, respectively) compared continuous outcomes across categorical groupings, and Pearson correlations assessed bivariate associations among continuous variables. Chi-square tests with Cramer's V examined associations between categorical variables, specifically waste management practice (improved vs. unimproved) and farm/farmer characteristics. Because the Likert-scale constraint-severity data violate parametric interval-level assumptions, the Friedman test assessed whether constraints were perceived as differentially severe, with Bonferroni-corrected pairwise Wilcoxon signed-rank tests for post-hoc comparison, and the Kruskal–Wallis test examined differences in the Challenge Severity Index across poultry type and district. Multiple linear regression (ordinary least squares) was the primary technique used to examine the determinants of three continuous outcomes: log-transformed total production cost, the Environmental Sustainability Index, and the composite Sustainability Score. Binary logistic regression, with standardized predictors, was used to examine the determinants of formal credit access. All regression models were assessed for multicollinearity using the Variance Inflation Factor (VIF; threshold < 10), heteroskedasticity using the Breusch–Pagan Lagrange Multiplier test, and residual normality using the Shapiro–Wilk test. A significance threshold of $\alpha = 0.05$ was applied throughout, with *, **, and *** denoting significance at the 5%, 1%, and 0.1% levels, respectively.

Ethical approval and consent to participate:-

The study was approved by the Institutional Animal, Medical Ethics, Biosafety and Biosecurity Committee (IAMEBBC) for Experimentations on Animal, Human, Microbes and Living Natural Sources at the Institute of Biological Sciences, University of Rajshahi. The research was conducted in accordance with the ethical principles of the Declaration of Helsinki and following the Checklist for Reporting Results of Internet E-Surveys (CHERRIES) guidelines. Respondents were informed of the study's purpose at the outset, provided voluntary consent prior to participation, and were free to withdraw at any point; no monetary or non-monetary compensation was offered.

Results and Discussions:-**Sample characteristics:-**

Of the 121 sampled farms, 71 (58.7%) were located in Rajshahi and 50 (41.3%) in Joypurhat (Table 1). The sample was overwhelmingly male-operated (95.9%) and reasonably balanced across farm type: 39 broiler (32.2%), 38 layer (31.4%), and 44 Sonali farms (36.4%). Most respondents (76.9%) operated at the largest flock-size category (>2,000 birds), indicating a sample weighted toward larger commercial operations. Respondents averaged 39.2 years of age (SD = 11.65) and 11.6 years of farming experience (SD = 7.53), yet only 35.5% had received formal training and just 22.3% had accessed formal credit.

Table 1: Sample Profile of Surveyed Poultry Farming Households (N = 121).

Variable	Category	N	%
District	Joypurhat	50	41.3
	Rajshahi	71	58.7
Gender	Male	116	95.9
	Female	5	4.1
Education	No formal education	6	5
	Primary	13	10.7
	Secondary	32	26.4
	Higher secondary	43	35.5
	Graduate or above	27	22.3
Main occupation (poultry)	No	41	33.9
	Yes	80	66.1
Training received	No	78	64.5
	Yes	43	35.5
Farm ownership	Owned	114	94.2
	Rented/leased	6	5
	Shared	1	0.8
Poultry type	Broiler	39	32.2
	Layer	38	31.4
	Sonali	44	36.4
Formal credit access	No	94	77.7
	Yes	27	22.3
Housing system	Open	4	3.3
	Semi-controlled	105	86.8
	Controlled	12	9.9
Feeding system	Commercial	107	88.4
	Home-made	13	10.7
	Mixed	1	0.8
Flock size	>2,000 birds	93	76.9

Note: Continuous variables — age: mean 39.19 years (SD 11.65, range 20–75); farming experience: mean 11.56 years (SD 7.53, range 1–35); family size: mean 5.53 (SD 1.93). Full categorical breakdown is provided in Supplementary Table S1.

Broiler farms were most prevalent in Rajshahi (n = 31) while Sonali farms dominated in Joypurhat (n = 25); layer farming ranked second in both districts (Figure 1).

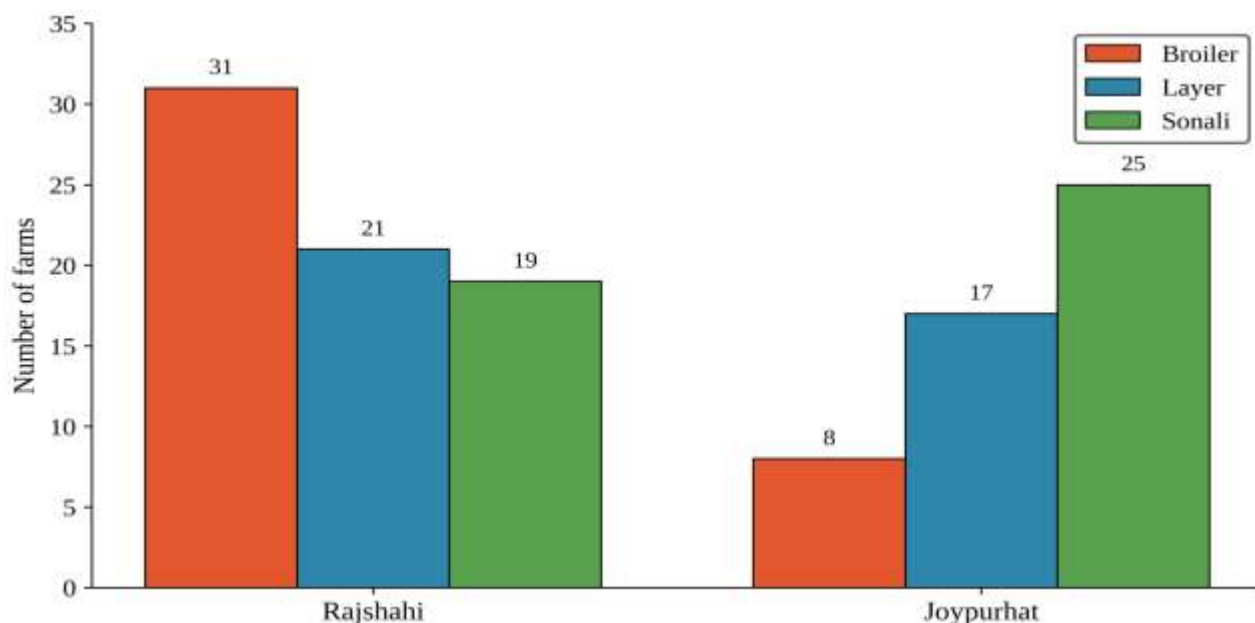


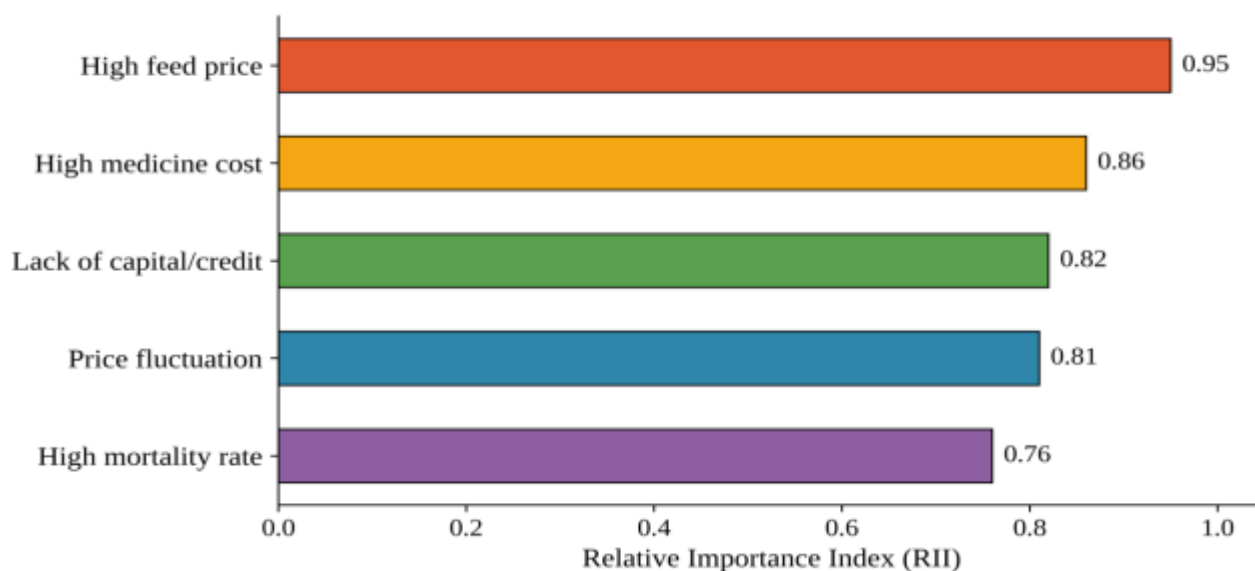
Figure 1: Sample Distribution by District and Poultry Type (N=121)

Reliability of composite indices:-

All three composite sub-indices exceeded the conventional 0.70 threshold for acceptable internal consistency: the Economic Challenge Index ($\alpha = 0.746$), the Environmental Sustainability Index ($\alpha = 0.750$), and the Challenge Severity Index ($\alpha = 0.709$), supporting the reliability of the measurement framework used throughout the analysis.

Economic performance and its determinants:-

Among the five economic challenge items, high feed price was rated the most severe, near-universal concern (mean = 4.77, RII = 0.95), followed by high medicine cost (RII = 0.86), lack of capital or credit (RII = 0.82), price



fluctuation (RII = 0.81), and high mortality rate (RII = 0.76) (Figure 2).

Figure 2: Relative Important Index of Perceived Economic Challenges

Bivariate analysis found no significant difference in log-transformed production cost by gender, training status, or main occupation ($p > 0.05$ in all cases), but significant differences by education level ($F(4,116) = 2.57$, $p = 0.041$), poultry type ($F(2,118) = 46.09$, $p < 0.001$), and district ($F(1,119) = 7.70$, $p = 0.006$). Production cost was positively correlated with farmer age ($r = 0.23$, $p = 0.011$), experience ($r = 0.29$, $p = 0.001$), and flock size ($r = 0.41$, $p < 0.001$). Full bivariate results are reported in Supplementary Table S2. A multiple linear regression of log-transformed total production cost (Table 2) explained a moderate share of variance ($R^2 = 0.306$, Adjusted $R^2 = 0.250$, $F(9,111) = 5.44$, $p < 0.001$). Education ($\beta = 0.232$, $p = 0.028$), farming experience ($\beta = 0.039$, $p = 0.018$), formal credit access ($\beta = 0.564$, $p = 0.045$), and flock size ($\beta = 0.0006$, $p = 0.006$) were significant positive predictors; training was not significant once other factors were controlled ($\beta = -0.187$, $p = 0.459$). All VIF values were below 1.7, indicating no problematic multicollinearity; diagnostic testing found mild heteroskedasticity (Breusch–Pagan LM = 20.10, $p = 0.017$) and non-normal residuals (Shapiro–Wilk $W = 0.956$, $p < 0.001$), attributable to a small number of very large commercial farms. Critically, this model explains the scale of expenditure rather than cost-efficiency: a positive coefficient indicates a larger or more input-intensive enterprise, not necessarily a less efficient one.

Table 2: Multiple Linear Regression: Determinants of ln(Total production cost)

Predictor	β	S.E.	t	p-value	VIF
(Intercept)	11.419	0.723	15.798	<0.001***	—
Education	0.232	0.104	2.228	0.028*	1.124
Experience	0.039	0.016	2.397	0.018*	1.258
Training	-0.187	0.252	-0.744	0.459	1.259
Family size	-0.017	0.071	-0.233	0.816	1.608
Family members in poultry	-0.159	0.088	-1.804	0.074	1.549
Farm ownership	0.083	0.4	0.208	0.835	1.083
Formal credit access	0.564	0.278	2.027	0.045*	1.162
Veterinary support access	0.156	0.383	0.406	0.685	1.136
Flock size (midpoint)	0.0006	0.0002	2.786	0.006**	1.221

Note: $R^2 = 0.306$, Adjusted $R^2 = 0.250$, $F(9,111) = 5.44$, $p < 0.001$. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Given the policy relevance of credit access, a binary logistic regression (Table 3) examined its determinants (27 farms with access vs. 94 without). Flock size was the dominant predictor ($\beta = 1.292$, OR = 3.640), substantially exceeding the contribution of education (OR = 1.288), training (OR = 1.227), and experience (OR = 1.161). Farm ownership showed a negative association (OR = 0.549), interpreted cautiously given limited variation in ownership status (94.2% owner-operated).

Table 3: Binary Logistic Regression: Determinants of Formal Credit Access

Predictor	Standardized β	Odds Ratio
Flock size (midpoint)	1.292	3.64
Education	0.253	1.288
Training	0.205	1.227
Experience	0.149	1.161
Family size	-0.014	0.986
Farm ownership	-0.600	0.549

Environmental impacts and their determinants:-

Manure and litter management practices were dominated by untreated, direct application: 45.5% of farms applied manure to their own cropland and 35.5% used it in ponds, while only 15.7% composted manure and no sampled farm used a biogas digester (Figure 3a). Dead-bird disposal was considerably safer, with 89.3% of farms burying dead birds. Farmers themselves expressed high awareness of environmental impact (mean = 4.04, RII = 0.81) and concern about water pollution from their own farm (RII = 0.77), yet self-reported water contamination and scarcity were both rare (87.6% and 90.9% reporting 'never', respectively) (Figure 3b).

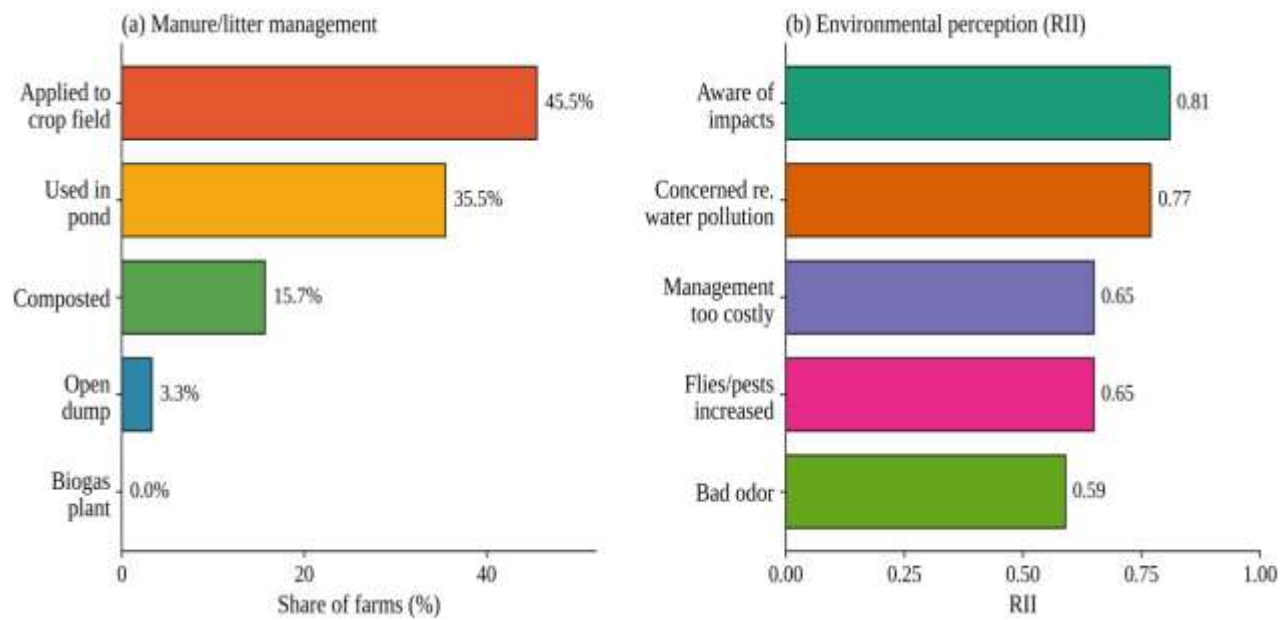


Figure 3: Manure Management Practice and Farmer Environmental Perception

No statistically significant association was found between improved manure management (compost or biogas; 19 farms, 15.7%) and poultry type ($\chi^2(2) = 1.63$, $p = 0.444$, Cramer's $V = 0.12$) or training status ($\chi^2(1) = 0.15$, $p = 0.696$, $V = 0.04$); a marginal association was found with education level ($\chi^2(4) = 8.46$, $p = 0.076$, $V = 0.26$), interpreted cautiously since 30% of cells had an expected count below 5. Full cross-tabulations are reported in Supplementary Table S3.

Table 4. Linear regression: Determinants of the Environmental Sustainability Index

Predictor	β	S.E.	t	p
(Intercept)	0.317	0.059	5.376	<0.001***
Training	0.044	0.021	2.05	0.043*
Farm ownership	0.029	0.036	0.81	0.42
Education	0.011	0.009	1.154	0.251
Flock size (midpoint)	<0.001	<0.001	0.022	0.983

Note: $R^2 = 0.053$, Adjusted $R^2 = 0.021$. ESI is scaled 0–1, where higher values indicate poorer environmental performance. * $p < 0.05$, *** $p < 0.001$.

A linear regression of the Environmental Sustainability Index (Table 4) explained only a small share of variance ($R^2 = 0.053$, Adjusted $R^2 = 0.021$). Training was the sole significant predictor, but in a counter-intuitive direction ($\beta = 0.044$, $p = 0.043$): trained farmers reported somewhat poorer environmental conditions or perceptions than untrained farmers. Given the model's low explanatory power and the cross-sectional design, this finding cannot distinguish a genuine adverse training effect from an awareness effect, in which trained farmers are more attuned to identifying problems on their own farms.

Operational constraints:-Disease outbreaks (Bird Flu, Newcastle Disease) emerged as the most severe operational constraint (RII = 0.80), followed by the high cost of day-old chicks (RII = 0.75) and heat stress due to high temperature (RII = 0.71); these formed a distinct top tier, clearly more severe than a second tier ranging from lack of access to credit (RII = 0.56) down to waste management difficulties, the least severe constraint (RII = 0.42) (Figure 4).

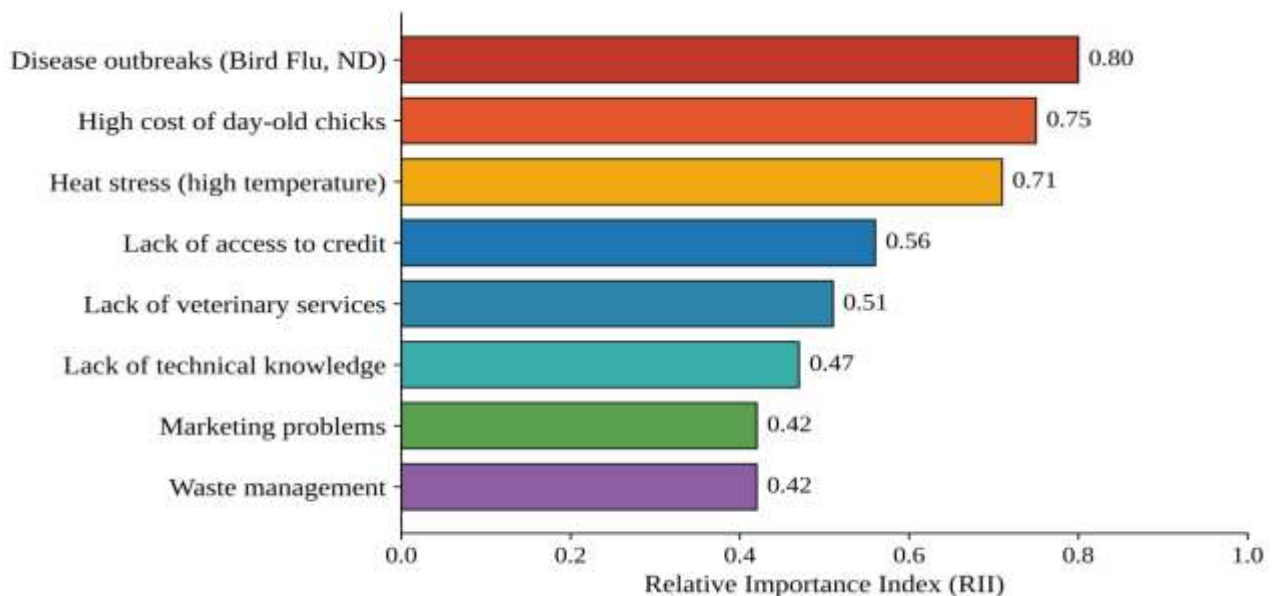


Figure 4: Ranked Severity of Operational Constraints

A Friedman test confirmed that constraints were not perceived as equally severe ($\chi^2(7) = 295.47$, $p < 0.001$). Bonferroni-corrected pairwise Wilcoxon signed-rank tests ($\alpha = 0.0083$) found that credit access was rated significantly less severe than each of the top three constraints, while no significant difference was found among disease outbreaks, chick cost, and heat stress themselves — indicating a clear top tier of closely clustered, severe production risks distinct from a less severe second tier. A Kruskal–Wallis test found significant differences in the Challenge Severity Index by poultry type ($H(2) = 8.94$, $p = 0.011$; broiler lowest at 0.41, Sonali highest at 0.51) and, more markedly, by district ($H(1) = 33.06$, $p < 0.001$; Rajshahi = 0.58 vs. Joypurhat = 0.40).

The integrated Sustainability Index:-

The composite Sustainability Score ranged from 0.18 to 0.62 across the 121 sampled farms (mean = 0.44, SD = 0.10, median = 0.43; skewness = -0.12). The three sub-indices were only moderately intercorrelated ($r = 0.38$ –0.42), confirming that they capture related but distinct dimensions of farm-level sustainability rather than a single redundant construct. A multiple regression of the Sustainability Score (Table 5) explained a substantial share of variance ($R^2 = 0.615$, Adjusted $R^2 = 0.595$), with no evidence of heteroskedasticity (Breusch–Pagan LM = 8.93, $p = 0.178$) or non-normal residuals (Shapiro–Wilk $W = 0.989$, $p = 0.401$).

Table 5: Multiple Linear Regression: Determinants of the Composite Sustainability Score

Predictor	β	S.E.	t	p	VIF
(Intercept)	0.383	0.04	9.543	<0.001***	—
District (Joypurhat = 1)	0.137	0.015	8.988	<0.001***	1.544
Training	-0.038	0.014	-2.651	0.009**	1.288
Formal credit access	-0.030	0.016	-1.851	0.067	1.284
Farm ownership	-0.001	0.023	-0.035	0.972	1.102

Education	-0.001	0.006	-0.121	0.904	1.09
Experience	0.0001	0.0009	0.141	0.888	1.227

Note: $R^2 = 0.615$, Adjusted $R^2 = 0.595$. ** $p < 0.01$, *** $p < 0.001$.

District location (Joypurhat = 1) was by far the strongest and most robust predictor ($\beta = 0.137$, $p < 0.001$): net of education, training, experience, ownership, and credit access, farms in Joypurhat scored, on average, 0.137 points higher on the 0–1 scale than otherwise comparable farms in Rajshahi — consistent with the marked separation in the two districts' score distributions (median ≈ 0.50 in Joypurhat vs. ≈ 0.35 in Rajshahi; Figure 5). Training again showed a significant negative association ($\beta = -0.038$, $p = 0.009$). Education, experience, farm ownership, and formal credit access ($p = 0.067$) were not significant predictors once district and training were accounted for. All VIF values were below 1.6.

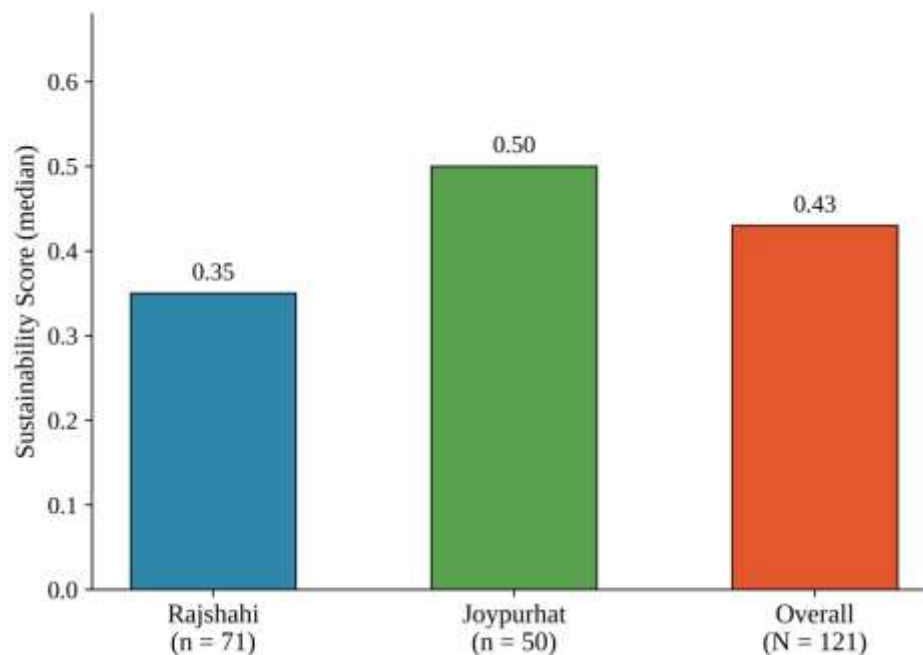


Figure 5: Median Composite Sustainability Score by District (Overall mean = 0.44, SD = 0.10)

Discussions:-

This study set out to test whether the economic and environmental dimensions of poultry sustainability, typically studied separately, move together or independently at the farm level in a water-stressed agro-ecological zone, and to identify whether farmer characteristics or structural, location-specific conditions are the more decisive lever for improving sustainability. Three findings stand out. First, the economic results indicate that human-capital and institutional variables conventionally associated with improved farm performance, education, experience, and formal credit access, were more strongly associated with the scale at which farms operate than with their efficiency. Farmers with more education, more experience, or credit access ran larger, costlier enterprises rather than necessarily more cost-efficient ones, and flock size was overwhelmingly the strongest predictor of who obtains formal credit ($OR = 3.64$), far outweighing human-capital variables. This is consistent with, but sharpens, prior Bangladeshi evidence that education and household characteristics shape poultry profitability in complex and sometimes counter-intuitive ways (Alam et al., 2025), and echoes the broader concern that sector growth may concentrate benefits among already larger operators (Mottet and Tempio, 2017). If formal credit continues to be allocated primarily on existing scale, these risks reinforcing rather than narrowing the divide between larger commercial operations and smaller producers, including the rural youth and women identified as key beneficiaries of poultry-led livelihood diversification in Bangladesh (Das et al., 2008; M. S. Rahman et al., 2017).

Second, the study documents a gap between environmental awareness and environmental practice. Farmers reported high awareness of environmental impact ($RII = 0.81$) and concern about water pollution ($RII = 0.77$). Yet manure

management remained almost entirely untreated, and no farm adopted biogas, despite national literature promoting it as a technology that both cuts pollution and generates income (M. M. Rahman et al., 2022). The environmental regression explained only a small share of variance in practice ($R^2 = 0.053$); on its own, this low fit is also consistent with unmeasured factors driving adoption, so it cannot by itself establish that structural barriers rather than awareness are the binding constraint. Read alongside the absence of any significant association between improved practice and either training or poultry type, however, the pattern is more consistent with structural barriers, such as cost, land requirements, and technical complexity, constraining adoption even among farmers who recognize the underlying problem, than with an awareness deficit; this interpretation aligns with waste-management adoption barriers documented elsewhere in the region (Arefin et al., 2024; Hossen et al., 2015). The counter-intuitive negative association between training and both the Environmental Sustainability Index and the composite Sustainability Score warrants particular attention: because the cross-sectional design cannot establish causal direction, this pattern may reflect a genuine gap in current training content, a self-selection effect in which farmers facing more challenging operations seek out training, or an awareness effect in which trained farmers are simply more attuned to identifying and reporting problems on their own farms.

Third, and most significantly for the integrated framework motivating this study, district location was the dominant determinant of overall sustainability: its own coefficient ($\beta = 0.137$, $p < 0.001$) exceeded the explanatory contribution of every individual farmer or farm characteristic examined, and the full composite model achieved substantially higher explanatory power ($R^2 = 0.615$) than any single-dimension model alone - indicating that location's effect is not merely large in isolation but central to what makes the integrated model outperform its parts. The self-reported rarity of direct water contamination or scarcity (87.6% and 90.9% "never," respectively) should not be read as evidence that poultry production is decoupled from the Barind Tract's water resource constraints; rather, it is consistent with a cumulative pressure dynamic in which many individually low-impact farms collectively contribute to the aggregate groundwater depletion well documented at the regional level (Hasan et al., 2018; Hossain et al., 2021; Mojid et al., 2021). The magnitude of the district effect, net of every measured farmer characteristic, indicates that spatially differentiated structural conditions, plausibly including differential access to extension services, market infrastructure, or locally embedded institutional support, are at least as important as individual farmer attributes in shaping sustainability outcomes in this setting. This finding extends the existing literature by demonstrating empirically that location-specific structural factors, rather than farmer characteristics alone, may be the more decisive lever for improving poultry sustainability in an agro-ecologically constrained region. These findings confirm that the economic and environmental dimensions of poultry sustainability are related but only moderately so (inter-sub-index $r = 0.38-0.42$), supporting the value of an integrated, multidimensional measurement approach over single-dimension analyses that would not have detected the dominant district effect.

Conclusions and Policy Implications:-

This study provides an integrated, farm-level assessment of the economic and environmental sustainability of poultry production in Bangladesh's Barind Tract, drawing on primary survey data from 121 households. Three conclusions follow from the results. First, credit access and, to a lesser extent, training currently function as instruments of production scale rather than efficiency or environmental improvement: flock size was the strongest predictor of formal credit access ($OR = 3.64$), far outweighing education, experience, or other human-capital variables. Second, environmental management remains dominated by untreated manure disposal and zero biogas adoption despite high farmer awareness of environmental risk ($RII = 0.81$), and the constraints farmers themselves rank as most severe (disease outbreaks, day-old-chick cost, and heat stress) are predominantly biological and market-based production risks rather than the institutional-access constraints most often targeted by development interventions, pointing to a mismatch between farmer-perceived priorities and conventional policy design. Third, and most consequentially, district location was the dominant predictor of overall sustainability ($\beta = 0.137$, $p < 0.001$), exceeding the contribution of any individual farmer characteristic, indicating that structural and locational factors deserve at least as much policy attention as farmer-level capacity building.

These conclusions carry direct implications for policy and practice:-

- **Farm level:** Prioritize biosecurity, vaccination scheduling, and heat-stress mitigation (ventilation, shading, water cooling), given that 86.8% of sampled farms operate semi-controlled rather than fully controlled housing and that disease and heat stress rank among farmers' most severe constraints. Reframe improved waste management as an income-diversification opportunity (organic fertilizer, household biogas) rather than a compliance measure, to close the gap between environmental awareness and adoption.

- **Institutions and policymakers:** Decouple credit eligibility from flock size alone, through group-based lending, graduated credit ladders, or training-linked credit access, to allow smaller and newer producers, including the rural youth and women identified as key beneficiaries of poultry-led livelihood diversification in Bangladesh, to access formal credit on a more equitable basis. Review and restructure training curricula to explicitly incorporate waste management, biosecurity, and heat-stress adaptation content, with outcomes tracked through monitoring and evaluation. Target structural and infrastructural support - extension services, market access, input supply chains - toward comparatively lower-performing districts such as Rajshahi, rather than relying solely on farmer-targeted interventions. Subsidize composting and biogas adoption through demonstration farms and technical support bundled with capital assistance.
- **Water governance:** Although individual farms rarely reported direct water contamination or scarcity, this should not be read as evidence that poultry production is decoupled from the Barind Tract's water resource constraints; many individually low-impact farms may nonetheless contribute cumulatively to the aggregate groundwater depletion well documented at the regional level. Water governance authorities should explicitly incorporate livestock and poultry water demand (drinking, cleaning, and husbandry requirements) into regional groundwater allocation planning, rather than treating groundwater policy as a crop-irrigation issue alone.

Limitations:-

Several limitations should be considered when interpreting these findings. (a) The cross-sectional design identifies statistical association, not causation, a limitation particularly relevant to the counter-intuitive training findings: it cannot be determined whether training caused poorer environmental outcomes, whether farmers facing more challenging operations were more likely to seek training, or whether trained farmers are simply more attentive to identifying problems on their own farms. (b) The achieved sample was weighted toward larger, commercial, male-operated farms (76.9% with flock sizes above 2,000 birds; 95.9% male), so findings should be generalized cautiously to smaller backyard producers and female-headed poultry-keeping households. (c) Environmental measures relied on farmer self-report and are subject to recall and social-desirability bias, particularly for sensitive items such as waste disposal and water contamination. (d) The purposive selection of two districts, Rajshahi and Joypurhat, while appropriate given resource constraints, means findings, including the pronounced disparity between them, should be generalized to the broader Barind Tract or to Bangladesh only with appropriate caution. (e) The Environmental Sustainability Index regression explained only a small share of variance ($R^2 = 0.053$), indicating that important determinants of farm-level environmental performance remain unmeasured; this finding should accordingly be treated as preliminary.

Directions for Future Research:-

Future work would benefit from: (a) longitudinal or panel data to test the training-sustainability relationship with greater confidence regarding causal direction and to capture seasonal variation in costs and disease incidence; (b) qualitative research, including key-informant interviews with Department of Livestock Services officials, input suppliers, and farmer organizations, to identify the institutional or infrastructural mechanisms underlying the Rajshahi-Joypurhat disparity; (c) broader, more representative sampling that deliberately includes smaller backyard producers and female poultry keepers; (d) direct water-quality testing and groundwater-level monitoring at or near sampled farms, to test the cumulative regional water-stress hypothesis empirically; (e) stochastic frontier analysis to estimate technical and allocative efficiency directly, complementing the OLS- and logistic-based approach used here; and (f) replication of the composite Sustainability Index framework in other drought-prone or resource-constrained agro-ecological zones, to establish whether the structural, location-driven pattern identified here is specific to the Barind Tract or reflects a more general feature of poultry sustainability in water-stressed production environments.

Declarations:-

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Ethics approval and consent to participate:-This study was approved by the Institutional Animal, Medical Ethics, Biosafety and Biosecurity Committee (IAMEBBC), Institute of Biological Sciences, University of Rajshahi. All participants provided informed consent prior to participation.

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