

## SUPPLEMENTARY MATERIALS

### ***Preventive biosecurity investment and poultry performance across contrasting production contexts***

*Sample:* Dedicated poultry cohort ( $n = 197$ , Rwanda semi-commercial smallholders  $n = 156$ , Israel commercial operations  $n = 41$ ).

### **Part 0: Research ethics, informed consent, and data governance protocols**

**Ethical review and compliance:** This study was designed and conducted as a non-experimental, observational field evaluation of existing farm management practices. In accordance with institutional guidelines, formal ethics committee approval was not required as the research protocol involved no clinical interventions, invasive biological sampling, animal handling, or deliberate operational modifications to standard farm management. Reporting adheres strictly to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.

**Informed consent protocol:** Informed verbal consent was secured from primary farm owners or designated facility managers prior to questionnaire administration and physical site assessments. Participants were explicitly briefed on the academic scope of the study, voluntary participation, complete data anonymization procedures, and their right to withdraw from the evaluation at any stage without penalty or loss of routine veterinary services.

**Data anonymization and security:** Unique farm identification numbers (ID) were assigned to all observational units to ensure strict operational confidentiality. All geographical, contact, and structural farm parameters were stored in encrypted database files accessible exclusively to the primary research team. Financial parameters and capital infrastructure values were converted to standardized United States Dollars (USD) using prevailing annual exchange rates during the respective data collection windows.

### **Part 1: Farm demographics, enterprise structure, and financials**

*(Administered directly to primary poultry farm managers via structured interview)*

#### **1. General identification and production context**

**Farm unique identifier (ID):**.....

**Production context / regional site (region / context):**

☐ 1 = Rwanda (Low-input, semi-commercial smallholder system, n = 156)

☐ 0 = Israel (High-input, technology-dense commercial facility, n = 41)  
(Reference baseline)

**Livestock species filter (species):**

☐ 1 = Poultry (Dedicated study cohort, n = 197)

**Flock acquisition strategy (sourcing):**

☐ 0 = Unregulated local market / traditional vendors

☐ 1 = Certified commercial hatchery / verified anti-fake sourcing strategy

**Operational flock size (herd Size):**..... , total active birds on site (serving as regional production benchmark proxy)

**2. Labor allocation and operational financials**

**Routine compliance labor (CLLabor):**.....hours/week spent on standard daily chores (e.g., feeding, watering, egg collection, manure clearing)

(Note: Retained in dataset for baseline profiling, omitted from final *BIII* PCA due to low communality < 0.030).

**Planned preventive labor (PLabor):**..... hours/week specifically allocated to biosecurity execution, perimeter maintenance, entry sanitation, footbath management, and vector control.

**Biosecurity financial infrastructure cost (FCCost /**

**FCCostUSD):**.....USD total capital expenditure incurred for fixed biosecurity barriers, sanitation arrays, and physical protective infrastructure.

**3. Retrospective production and value outcomes (12-months baseline)**

**Market sustainability yield efficiency (MSYield):**

$$MSYield_i = \left( \frac{Y_{observed\ i}}{Y_{benchmark\ i}} \right)$$

**Where**  $Y_{observed\ i}$  is the actual annual farm output (total meat or egg production in kg) recorded for farm  $i$ .  $Y_{benchmark\ i}$  is the expected potential output for farm  $i$  based on flock size, genetic strain, and production system benchmarks derived from institutional extension guidelines.

**Actual annual output ( $Y_{observed}$ ):**.....(kg meat or total eggs)

**Expected benchmark capacity ( $Y_{\text{benchmark}}$ ):**.....(kg meat or total eggs mass)

**Part 2: On-farm physical biosecurity and occupational protection checklist**  
(Evaluated and verified independently on-site by field research personnel)

**Section A: Structural Biosecurity Investment Intensity Index (BIII) array**  
(Evaluated across 7 active input variables for single-component PCA extraction, BIII)

1. **Perimeter fencing and access containment (BFence):** Physical boundary integrity, controlled entry gates, and wild bird/livestock exclusion barriers.

☐ 0 = Absent / Non-functional      ☐ 1 = Present / Fully functional

2. **Entry sanitation arrays (BSanit):** Functional vehicle disinfection dips, boot washing station, and worker entry sanitation infrastructure.

0 = Absent / Non-functional ☐

1 = Present / Fully functional ☐

3. **Active environmental cooling systems (BCool):** Temperature-control infrastructure, sprinklers, or automated fans.

0 = Absent / Non-functional ☐

1 = Present / Fully functional ☐

4. **Bird isolation and quarantine units (BIso):** Dedicated quarantine pens/housing for sick or newly introduced birds.

0 = Absent / Non-functional ☐

1 = Present / Fully functional ☐

5. **Safe waste and biological disposal access (BDisp):**

Facilities for safe carcass disposal, mortality pits, or manure composting arrays.

0 = Absent / Non-functional ☐

1 = Present / Fully functional ☐

6. **Planned preventive labor allocation (PLabor):** Quantitative continuous input recorded in Part 1 (hours/week).....

7. **Biosecurity capital infrastructure expense (FCostUSD):** Quantitative continuous structural investment intensity recorded in Part 1 (USD).....

**Section B: Occupational health hazard containment proxy (OHRed)**  
(5-item binary operational proxy array scored on-site by field enumerators)

$$OHRed\ i = \left( \frac{\sum_{k=1}^5 I_{k,i}}{5} \right)$$

- 1 **Worker sanitation infrastructure:** Availability and active enforcement of functional handwashing arrays and worker hygiene stations.  
☐ 0 = Absent                      ☐ 1 = Present
- 2 **Personal protective equipment (PPE) utilization:** Routine availability, maintenance, and mandatory wearing of protective boots, overalls, gloves, and masks.  
☐ 0 = Absent                      ☐ 1 = Present
- 3 **Carcass and hazard disposal protocol:** Enforced physical containment and hygienic processing of biological waste, avian mortalities, and contaminated materials.  
☐ 0 = Absent                      ☐ 1 = Present
- 4 **Housing physical separation:** Clear, physical structural segregation between human living quarters/office dwellings and poultry housing units.  
☐ 0 = Absent                      ☐ 1 = Present
- 5 **Worker exposure barriers:** Controlled physical access corridors and restricted contact procedures between workers and high-risk flock sections.  
☐ 1 = Present    ☐ 0 = Absent

**Note:** All sampled commercial operations in Israel (n = 41) achieved identical scores on non-automated worker physical protection items evaluated within this 5-item proxy array. The uniform baseline mean of 15.00% represents standardized operational adherence across commercial facilities, reflecting structured management compliance without within-group variance.

### **Part 3: Data quality assurance, missing data, and transformation protocols**

**On-site data verification protocols:** To mitigate self-reporting and recall bias by farm managers, data collection implemented a dual-verification mechanism. Structured questionnaire responses regarding physical infrastructure, structural biosecurity, and worker hazard arrays were independently audited on-site by field enumerators through visual inspection. Farms lacking verifiable daily production logs or accessible physical facilities were excluded from analytical modeling.

**Missing data management and sub-cohort extraction:** From the broader multi-species dataset ( $N = 441$ ), non-avian enterprise units (cattle, swine, and small ruminant operations,  $n = 244$ ) were systematically excluded prior to modeling to eliminate cross-species biological confounding. Data screening aligned with complete operational records across all active latent index variables (BIII) and primary outcome metrics (MSYield, OHRed), requiring no missing data imputation or observational unit list-wise deletions. The final complete-case analytical cohort was restricted exclusively to dedicated poultry production facilities ( $n = 197$ ), stratified across transitional semi-commercial smallholder systems in Rwanda ( $n = 156$ ) and fully commercialized integrated facilities in Israel ( $n = 41$ ).

**Variable transformation and mathematical specifications:** To mitigate potential ceiling and floor boundary compression associated with bounded percentage outcomes ( $0 \leq P_i \leq 1$ ) in linear OLS modeling, market sustainability yield efficiency (MSYield) was converted into continuous proportions ( $P_i = \text{MSYield} / 100$ ). These proportions underwent logit transformation incorporating a standard  $c = 0.005$  continuity adjustment constant:

$$\text{Logit}_{\text{MSYield } i} = \text{Ln}\left(\frac{P_i + 0.005}{1 - P_i + 0.005}\right)$$

To evaluate whether biosecurity slope associations varied across farming environments, a centered interaction term (BIII x Context) was constructed in IBM SPSS Statistics by multiplying the standardized principal component analysis score (BIII) by the binary context dummy variable (Context = 0 for Israel commercial baseline, Context = 1 for Rwanda semi-commercial).

#### **Part 4: Data codebook and variable dictionary**

*Dedicated poultry facilities ( $n = 197$ ) originating from Rwanda ( $n = 156$ , semi-commercial smallholders) and Israel ( $n = 41$ , commercial integrated operations).*

| Variable Name | Variable label              | Coding                                                  | Operational definition                                                             |
|---------------|-----------------------------|---------------------------------------------------------|------------------------------------------------------------------------------------|
| ID            | Unique farm identifier      | 1 to N                                                  | Anonymized tracking identifier.                                                    |
| Context       | Regional production context | 0 = Israel (Commercial)<br>1 = Rwanda (Semi-commercial) | Regional context indicator dummy variable, baseline reference group is Israel (0). |
| Species       | Livestock species type      | 1 = Poultry                                             | Primary species filter (retained $n = 197$ , mammalian cohorts omitted).           |

|              |                                 |                                                       |                                                                                                    |
|--------------|---------------------------------|-------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| Sourcing     | Genetic sourcing strategy       | 1 = Unregulated market<br>2 = Certified hatchery      | Farm-level flock replacement protocol.                                                             |
| HerdSize     | Operational flock size          | Continuous (birds/site)                               | Total active birds on site, operational scale indicator.                                           |
| CLLabor      | Routine compliance labor        | Continuous (hours/week)                               | Routine daily operational chores (omitted from PCA due to low communality < 0.030).                |
| PLabor       | Planned preventive labor        | Continuous (hours/week)                               | Time allocated specifically to biosecurity execution, structural item in <i>BIII</i> .             |
| FCCostUSD    | Biosecurity infrastructure cost | Continuous (USD)                                      | Standardized capital expenditure on physical sanitation/barriers, structural item in <i>BIII</i> . |
| BFence       | Perimeter fencing integrity     | 0 = Absent/Nonfunctional<br>, 1 = Present/Functional  | Physical boundary containment, binary structural item ( <i>BIII</i> array).                        |
| BSanit       | Entry sanitation facilities     | 0 = Absent/Non-functional<br>1 = Present/functional   | Vehicle dips and boot washing stations; binary structural item ( <i>BIII</i> array).               |
| BCool        | Microclimate cooling systems    | 0 = Absent/Non-functional,<br>1 = present/functional  | Automated fans, misting, or cooling arrays; binary structural item ( <i>BIII</i> array).           |
| BIsol        | Avian isolation units           | 0 = Absent/non-functional<br>1 = present/functional   | Dedicated quarantine pens for sick/introduced birds, binary structural item ( <i>BIII</i> array).  |
| BDisp        | Safe disposal access            | 0 = Absent/Non-functional ,<br>1 = Present/Functional | Mortality pits, incinerators, or composting arrays, binary structural item ( <i>BIII</i> array).   |
| OHRed        | Worker protection proxy         | Continuous (0.0% to 100.0%)                           | Transformed score from 5 binary items ( $I_1$ to $I_5$ ) tracking operational hazard containment.  |
| MSYield      | Market yield efficiency         | Continuous (0.0% to 100.0%)                           | Technical output relative to potential capacity benchmark.                                         |
| MSYield-frac | Yield efficiency proportion     | Continuous (0.00 to 1.00)                             | Unbounded proportion calculated as $MSYield / 100$                                                 |
| LogitMSYield | Logit-transformed yield         | Continuous                                            | Primary dependent variable in OLS yield regression with $c = 0.005$ adjustment.                    |

|                       |                                        |                                     |                                                                                                                         |
|-----------------------|----------------------------------------|-------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| <i>BIII</i>           | Biosecurity Investment Intensity Index | Continuous score (Mean = 0, SD = 1) | Standardized principal component factor score extracted from 7 items (BFence,BSanit,BCool,BIsol,BDisp,PLabor,FCCostUSD) |
| <i>BIII</i> x Context | Biosecurity x context interaction      | Continuous product                  | Interaction term: <i>BIII</i> x context (Israel = 0, Rwanda = 1).                                                       |