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Inefficiency of laying hens farms in Benin: an input directional distance function approach

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Abstract

Background In Benin, the productivity of poultry production systems is a major concern. This paper aims first to estimate the cost, technical and allocative inefficiencies of modern and traditional poultry production systems, and then to determine the factors that influence these types of inefficiencies.

Results The study reveals significant cost inefficiencies, with just 9% and 18% of traditional and modern systems, respectively, being cost-efficient, highlighting the necessity of distinguishing production systems due to different operational requirements, particularly for modern systems. Addressing these inefficiencies requires crucial measures such as providing training, accessible credit, and mortality rate reduction to boost local production, with tailored support for small-scale farmers.

Conclusions The poultry sector's intense competition and the decline in local production, particularly among small-scale farmers, are primarily linked to high domestic production costs and local farmers' poor performance. Our study unveils substantial cost inefficiencies in both traditional and modern poultry farming systems, emphasizing the imperative to differentiate interventions based on their distinct operational requirements.

Keywords Distance function, Bootstrapping, Cost inefficiency, Poultry

Introduction

In the livestock sector, many efforts are made to increase the efficiency of animal products such as milk, eggs, and meat in developing and developed countries [39]. In many households, poultry farming, a significant source of revenue generation for small farmers in developing countries, is undertaken by women and young people, offering them employment opportunities and contributing to the family's economic gains [8, 60]. Furthermore, the poultry sector plays a crucial role in enhancing household food security, bolstering the provincial economy, and contributing to the overall national economic well-being, as highlighted [37]. In particular, traditional poultry farming, also termed family poultry or "bicycle poultry", is an important source of meat but also provides organic fertilizers for agriculture in many developing countries [86]. Traditional poultry represents more than 80% of the total poultry population and a significant proportion of meat (25–70%) and egg (12–36%) production in chickens [85]. The poultry sector is dominated by conventional breeding, with 21,796,000 heads of animals in 2020 in Benin [28]. This activity is practiced by farmers to meet their nutritional needs and is considered a way to diversify their sources of income and is considered a livelihood safety net.

The poultry sector has been characterized by a recent increase in poultry and egg production in Benin, which is estimated at 10 22500 541 heads and 3598 tons of eggs commercialized in 2022 [28]. However, poultry

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productivity statistics are still rather low in Benin compared to countries in the Sub-Saharan African region. Benin has a particularly low level of egg products (0,16 kg/poultry), well below the world average [28]. Despite the low levels of productivity (~30–80 eggs per bird per year), these backyard production systems have been beneficial, as they provide supplemental income and insurance to vulnerable groups in society through the sale of eggs and birds using almost negligible inputs. The commercial poultry farming sector in Benin is growing and contributes approximately 5.7% to the national gross domestic product and 14.8% to the agricultural gross domestic product, and nearly 22% of the protein requirement coverage comes from poultry products [88]. Egg production is the main product of modern poultry farmers, with an average annual laying rate of 240 eggs per bird and an average weight of one egg equal to 60 g [28]. However, intensive poultry systems have a minimum flock size of 100 birds and operate as commercial farms with much higher productivity levels, ranging from 200 to 340 eggs per bird per year [24, 28, 71]. In West Africa, the demand for poultry products exceeds the domestic supply from traditional and modern poultry farming, so these countries are importers of poultry [9]. Due to population growth and increased urbanization, this deficit between demand and supply will probably increase in the future, as demand for poultry is expanding [14]. In this context, Benin is still unable to meet its animal protein consumption needs [43]. Estimated at 12 kg per capita per year, the level of animal protein consumption in Benin is below the minimum consumption threshold recommended by the Food and Agriculture Organization for developing countries (21 kg per capita per year) [43]. Poultry meat dominates the global import market, with at least 98% of total meat imported since 2004 in Benin [27], and the country imports approximately 160,000 tons of poultry meat at a cost of over 243 billion CFA francs [94].

Benin's egg production sector received in 2018, 14,561 tons of meat and 15,400 tons of eggs, sourced from farms of various sizes, including small, intermediate, and large [4, 32]. Intermediate commercial poultry farming in Benin, predominantly focusing on laying hens for egg production, has witnessed a recent surge in egg production [35]. Over the last decade, national egg production has grown by 35%, from 5,400 tons in 2001 to 15,400 tons in 2019 [35]. Poultry farming in Benin comprises traditional and modern systems, with traditional farming prevalent in rural households and modern farming geared towards economic gain through egg production [78]. Modern poultry farming, initially a meat source, now emphasizes table egg production, with an estimated 750,000 layers across 500 units providing potential annual production of nearly 195 million eggs [90]. However, backyard production remains the dominant system in Benin, relying on indigenous poultry to make it viable for small-scale farmers, given the cost constraints of exotic poultry production [95].

Despite the increasing demand for poultry worldwide and in West Africa in particular, one of the main constraints to the development of small- and medium-scale poultry farming is the high cost of production (mainly feed cost) [9]. Due to the lack of sanitary controls and technical constraints in processing and marketing, the production costs are higher in Africa due to the lack of an integrated and automated industrial poultry sector. Whether a farm is modern or traditional strongly influences the level of productivity of poultry farms. Modern farming requires high levels of productivity [45]. Currently, due to various obstacles in trades, farmers are required to pay more attention to production [36, 49, 59]. Technical efficiency is viewed as the ability to generate a greater output from a given level of input, and it reflects the extent to which the unit does not reach the production boundary, as expressed in cost or production functions [20, 69, 73]. As poultry farmers attempt to expand their capacity, there is a rising demand for factors of production at stable prices, such as feed, labor, water, and electricity [77]. In addition, farmers do not have easy access to low-cost inputs and technologies, including chicks and feed, and face high costs for veterinary services [86]. This raises serious questions about the production costs of local production. To illustrate, due to the soaring cost of production and reduced net returns from the chicken meat sector, many poultry farmers in Ghana have stopped producing broilers altogether and are focusing on layer production [30]. One way to reduce the concern of the cost of production is to improve production by making small-scale chicken farming more competitive and to improve the cost efficiency of farmers. In addition, Begum et al. [12] and Giroh et al. [38] argued that eliminating poultry farmer inefficiencies appears to be more cost-effective than introducing new technologies as a means of increasing farm household production and income.

Many previous studies conducted in Sub-Saharan Africa and the subregion have addressed some aspects of inefficiencies in poultry production. Several studies have been carried out to estimate economies of scale, determine the optimal intensity of input use, and improve existing management practices [43, 78]. In Benin, various studies have been conducted in the poultry sector, but these studies have addressed only a few aspects of economic analysis of the poultry sector [44, 87, 89]. On the efficiency of poultry farming, a few studies have been conducted in Benin [43, 86, 95], and these studies focused on the existence and magnitude of scale economy effects on poultry production in Benin and examined the sources of total factor productivity growth on poultry egg production in Benin. The majority of studies on the performance of poultry production units are limited to the computation of ratios and the comparative analysis of profits to judge the economic or technical benefits despite the difficulty of dissociating the effects of scale from the effects of technical management in the measurement of all factor productivity [17, 18, 50]. In addition, Athanassopoulos and Ballantine [7] showed that ratios are in themselves insufficient to correctly measure productive performance and that they must be usefully supplemented by other approaches, such as the DEA method [58, 98].

This paper aims to address two main concerns: what is the level of technical, economic and allocative inefficiency of poultry farmers in Benin? What are the factors that reduce the three types of inefficiencies? To address this first concern and improve the reliability of the estimate of efficiency compared to conventional DEA, this study uses the DEA bootstrap procedures proposed by Simar and Wilson [80, 81] to make statistical inferences about the estimates of technical efficiency. Moreover, this approach uses a computerized statistical technique to verify the accuracy of statistical estimates of repeated samples [56]. Our second research question of our paper is to explore the inefficiency determinants of poultry farms that reflect the maximum feasible proportionate reduction of inputs and expansion of physical outputs. We used a two-stage approach to determine inefficiency. In the first stage, the cost, allocative, scale, and pure technical inefficiency estimates are computed for each farmer and decomposed into technical and allocative inefficiency using a nonparametric method (data envelopment analysis) with the directional input distance function approach. In the second stage, the single truncated bootstrap [82] is used to regress the inefficiency estimates on environmental and organizational factors and build confidence intervals for coefficients. The remaining paper is organized as follows: "Method" section presents the conceptual framework, "Results and discussions" section provides information on the research data and variables, "Conclusion" section presents the results and discusses the findings, and "Limitations and future research recommendation" Section provides conclusions and policy implications.

Method

Conceptual framework

Input directional distance function

Chambers et al. [22, 23] introduced directional distance functions as additive alternatives to the concepts of distance functions using dual approaches. The distance functions help to estimate and describe the production process of technically efficient entities and to measure the deviations of the entities from the production frontier [17, 18]. Therefore, directional distance functions are more general representations of production technology since they encompass, in particular cases, more conventional distance functions [22]. In contrast to radial distance functions, directional distance functions provide difference measures rather than ratio measures of relative efficiency and do not impose proportional variations in inputs or outputs [23, 34, 54]. Behavioral assumptions are not required for estimating technical inefficiency measures, but they are required for estimating cost inefficiency measures. In this paper, poultry farmers are assumed to be cost-minimizing decision-making units (DMUs). Indeed, poultry production systems can lead farmers to increase the size of their operations. For the traditional system, family labor is the main source of labor used, which indicates that family labor is one of the main production constraints. In contrast, the modern system is faced with exogenously determined input and output prices and attempts to allocate inputs in such a way as to minimize costs in view of market competition. This behavior involves endogenously determined inputs. Minimizing the cost of an inefficient farmer generally requires modifying the input vector. Thus, in our case, the directional input distance function is an adequate representation of the production technology of the traditional and modern poultry farming systems. The input-based inefficiency measures employed in this article are generated using the directional variable input distance function approach proposed by Chambers et al. [22]. The short-run directional input distance function is formally defined as follows:

$$\overrightarrow{D_i}(x_v, y; g_{x_V})\Big|x_f = \sup_\beta\{\beta \in \Re : (x_v - \beta g_{x_V}, y) \in V(y)\} \quad (1)$$

If $(x_v - \beta g_{x_v}, y) \in V(y)$ for some values of β, $\overrightarrow{D_i}(x_v, y; g_{x_v})|x_f = -\infty$; otherwise, where β is a measure of technical inefficiency, $V(y)$ is the input requirement set, $y \in \Re^M_+$ is a vector of outputs, $x_v \in \Re^N_+$ is a vector of variable inputs, $x_f \in \Re^N_+$ **is** a vector of quasifixed inputs, and $g_{\mathbf{x_v}} \neq 0_N$ represents the directional vector.

In our study, we assume, like Kapelko and Lansink [47], that $\overrightarrow{D_i}(x_v, y; g_{x_v})|x_f$ is concave with respect to (x_v) given x_f and y; this implies that $\overrightarrow{D_i}(x_v, y; g_{x_v})|x_f$ is increasing in variable inputs (x_v) but decreasing in output (y); $\overrightarrow{D_i}(x_v, y; g_{x_v})|x_f$ measures the distance of (x, I) to the boundary of $V(y)$ in a preassigned direction (g_{x_v}). In addition, the input requirement set $V(y)$ is a closed and nonempty set, has a lower bound, is positive monotonic in x_v, is a strictly convex set, and outputs are freely disposable. The directional variable input distance can be interpreted as the number of times the input bundle g_{x_v} is overused in x_v [33, 79]. Exploring the relation between the input distance function of Shephard [75] and benefit function, Chambers et al. [22] propose the directional input distance function and show the duality between this function and the cost function [79]. Duality between the directional input distance function and the cost function allows an additive decomposition of cost inefficiency. Following [22, 23], cost inefficiency can be decomposed as follows:

$$\frac{w'x_v - C(y,w)}{w'g_{x_v}} = \overrightarrow{D}_i(x_v, y; g_{x_v})|x_f + AIE \quad (2)$$

where $C(y,w)$ is the cost function, $\overrightarrow{D}_i(x_v, y; g_{x_v})|x_f$ is the directional input distance function representing technical inefficiency (TIE) and AIE is a residual component indicating allocative inefficiency. The left-hand side of (2) is the cost inefficiency measure. Cost inefficiency (CIE) is measured by the difference between actual cost and minimum cost, normalized by the value of the directional vector. Equation (2) assumes constant returns to scale, so it does not identify scale inefficiency change [47].

Our study estimates the cost, allocative, scale, and pure technical inefficiency.

Data and variables

Data and study area

Benin is located between 6°30' and 12°30' north latitude and between 1° and 3°40' east longitude with variable agro-ecological zones. This study was carried out at the level of five (5) agricultural development hubs (ADH), namely, Hubs 2 and 3 located in the Sudanian zone, Hub 4 located in the Sudano-Guinean zone, and Hubs 5 and 7 located in the Guinean zone [2]. In our study, we chose locations based on the potential for poultry production in Benin. We randomly chose the districts of farmers in each ADH by considering the weight of these districts in the production of poultry in Benin. Furthermore, districts with low and high poultry production were included in the sample. The districts of Parakou, Banikoara, Kérou, Matéri, Toucountouna, Glazoué, Allada, Lokossa, Zogbodomey, and Lalo were retained as shown in Fig. 1. The data set consisted of a stratified random sample survey of 150 producers in the five agricultural development hubs (ADHs) where farmers produce poultry in Benin. Qualitative and quantitative data were collected. The data were collected using interview guides and structured questionnaires. The qualitative data collected information on the mapping of the poultry sector, the flows of different products obtained in poultry production, constraints and opportunities from key persons (extension agents) and presidents of local cooperatives. Regarding quantitative data, several types of data were collected, including the size of the flock, poultry production objectives, inputs, labor, purchase prices of raw materials, source of financing for activities, product sales prices, various production operations, and production equipment (quantity, price, and lifetime). The data collection period is from October to November 2018.

Empirical model specification

Estimation of the cost inefficiency model

To establish the dual relationship between the cost function and the directional input distance function, the short-run minimum cost of each farmer relating to the input requirement set is defined simply as in Chambers et al. [22] and Färe and Grosskopf [33]:

$$C^*(y,w) = \min_{,x_v} (wx_v) s.t D_T(x_v, y; g_{x_v}, g_y) \geq 0 \quad (3)$$

Estimating cost inefficiency requires calculating the optimal levels of variable inputs of each farmer. Consider a sample of K farmers and let y_k, x_{kv} and x_{kf} be, respectively, the vector of observed outputs (eggs, spent hens), variable inputs, and quasifixed inputs for farmer k and w the vector of input prices faced by all farmers. Labor is considered a fixed factor because family labor is the labor force most used by the producers concerned. To generate the cost inefficiency measure, the minimum cost for each farmer k, $k=1, \ldots, K$, is computed by running the following cost minimization problem (4) for each farmer i ($i \neq k$):

$$\min_{x_v} (wx_v) \quad (4)$$

s.t

$$y_{im} \leq \sum_{k=1}^{K} \lambda_k y_{km}, m = 1, \ldots M \quad (4.1)$$

$$\sum_{k=1}^{K} \lambda_k x_{kv} \leq x_{iv}, v = 1, \ldots V \quad (4.2)$$

$$\sum\nolimits_{k=1}^{K} x_{kf} \leq x_{if}, f = 1, 2, 3 \quad (4.3)$$

$$\sum_{k=1}^{K} \lambda_k = 1 \quad (4.4)$$

$$\lambda_k \geq 0 \quad (4.5)$$

$$x_v \geq 0 \quad (4.6)$$

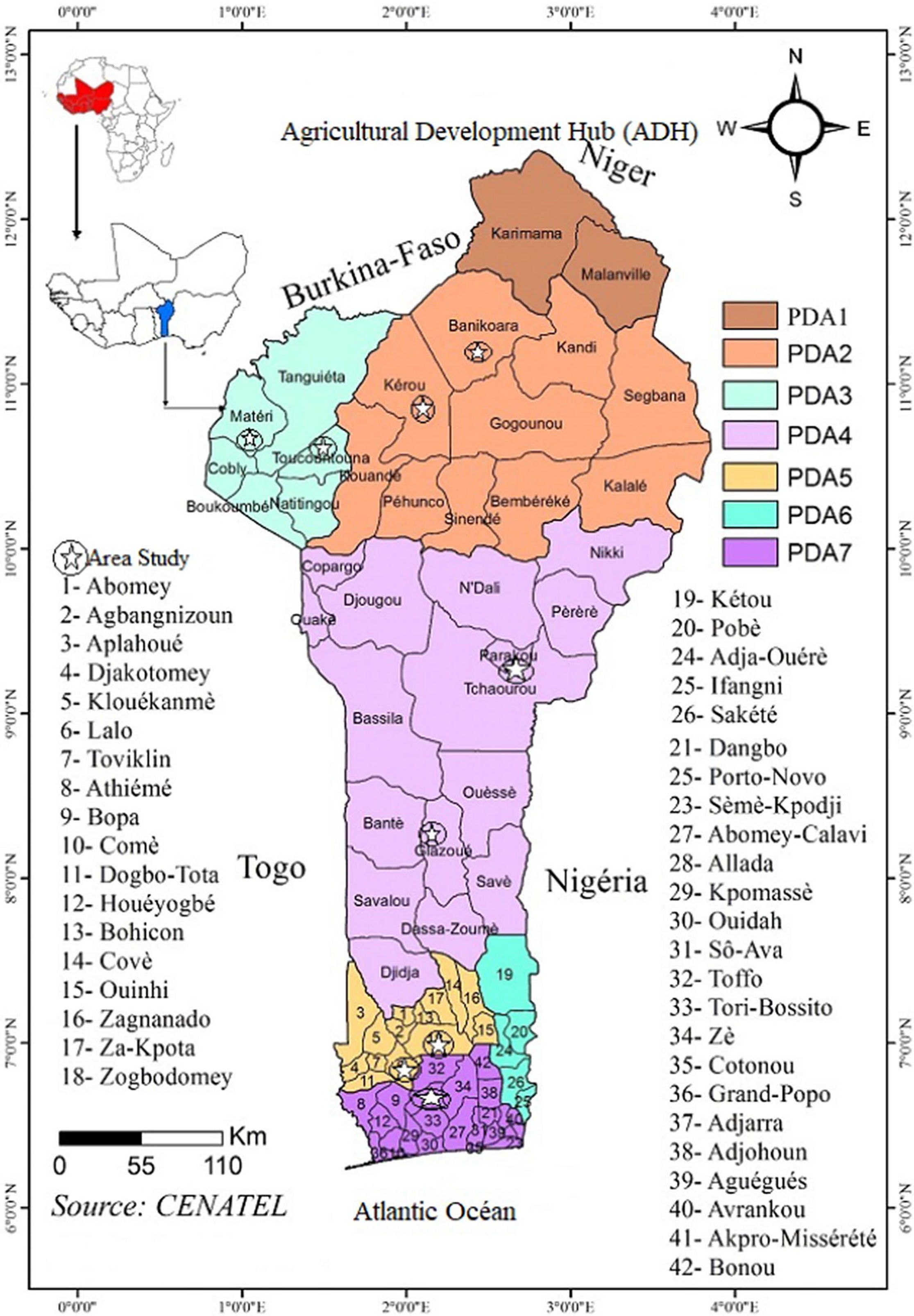

Fig. 1 Study area with district selected

where w is the price of the variable inputs and is supposed to be fixed exogenously. The remaining notations are as previously defined. Equations (4.1) and (4.2) impose some restrictions on the output and the variable input and express that the optimal solution is lower than or equal to (higher or equal to) the best practices observed. Equation (4.3) indicates that the levels of quasifixed inputs used are not higher than those of the analyzed farmer. Equation (4.4) supposes the VRS hypothesis, which ensures a finite solution for the optimal cost [19]. Equations (4.5) and (4.6) ensure the nonnegativity of optimal choice variables. CIE is a normalized deviation between the observed cost and the minimum cost. Therefore, CIE is a dimensionless measure. Note that the cost inefficiency of variable inputs (CIE) gives an indication of the high variable input cost due to the suboptimal choice of variable input. Hence, the cost inefficiency of the variable inputs can be all zero or all positive. A zero value of CIE (minimum cost = observed cost) indicates a cost-efficient farmer, and a strictly positive value characterizes the cost inefficiency of the farmer. The variable x_v^* represents the optimal variable input vector obtained by solving the linear programming model (4).

Estimation of technical inefficiency

Technical efficiency refers to the ability of a production unit to use best practices in the production process so as not to use more than the necessary quantity of a given set of inputs to produce the best level of production [21, 31]. The estimation of technical inefficiency with the directional distance function (DDF) introduced by Chambers et al. [23] attributes the potential increase in output and decrease in input together through a single parameter [6]. Consider the data of a production system and assume that there are $k = 1\ldots$, K poultry producers. Each farmer uses factors (variable and fixed) to produce two outputs (eggs and spent hens). Using DEA, the directional variable input distance function can be generated for each farmer i ($i \neq k$) through the linear programming model (5) as follows:

$$\vec{\mathrm{D}}\left(\mathrm{x_v}, \mathrm{y}; -\mathrm{x_v}, \mathrm{y}\right)|CRS = \max_{\beta\lambda} \beta \tag{5}$$

s.t

$$\mathrm{y_{im}} \leq \sum_{k=1}^{K} \lambda_k \mathrm{y_{km}}, m = 1, \ldots M \tag{5.1}$$

$$\sum_{k=1}^{K} \lambda_\mathrm{k} \mathrm{x_{kv}} \leq \mathrm{x_{iv}} - \beta \mathrm{x_{iv}}, v = 1, \ldots \mathrm{V} \tag{5.2}$$

$$\sum_{k=1}^{K} \lambda_\mathrm{k} \mathrm{x_{kf}} \leq \mathrm{x_{if}}, f = 1, 2, 3 \tag{5.3}$$

$$\sum_{k=1}^{K} \lambda_\mathrm{k} = 1 \tag{5.4}$$

$$\lambda_\mathrm{k} \geq 0 \tag{5.5}$$

In this equation, β is the directional variable input distance function and represents the pure technical inefficiency (PTIE). Although β is not sign constrained, its maximum value will always be nonnegative [6]. The variable $\mathrm{x_{i,}}$ which is multiplied by β to the right of (5.2), is the observed variable input at the level of each farmer. The vector λ_k is the intensity variable, indicating the importance of each technically efficient farmer compared to each inefficient farmer. It defines a point, which is a linear combination of points located on the border with respect to each point located outside the border, and it takes values between 0 and 1. On the other hand, each technically inefficient farmer is compared to technically efficient farmers. Equations (5.1), (5.2) and (5.3) indicate an order: the constraints of the output, the variable inputs and the quasifixed inputs, and they imply the high availability of the output, variable factors and fixed factors, respectively. Equation (5.4) indicates the convexity constraint, and Eq. (5.5) guarantees the nonnegativity of λ_k. The remaining notations are as previously defined.

The assumption is only indicated when farmers operate at the optimal scale. However, due to imperfections in agricultural markets, farmers rarely exhibit CRS. Banker et al. [11] proposed an extension of the DEA model to take into account variable returns to scale. The introduction of the equation of the convexity constraint ($\sum_{k=1}^{K} \lambda_\mathrm{k} = 1$) in the above model (5) is necessary, allowing determination of the pure technical inefficiency (PTIE). In this case, returns to scale can be increasing (IRS), constant (CRS) or decreasing (DRS) successively [19, 83, 84].

Estimation of allocative inefficiency

Allocative efficiency refers to the choice of the optimal mix of inputs compatible with relative factor prices [31, 61]. On the other hand, variable cost efficiency is the ability of a farm to minimize its variable input costs [31]. Based on the aforementioned duality, the allocative inefficiency (AIE) is obtained by subtracting the total technical inefficiency (TIE), which is the sum of the pure technical inefficiency (PTIE) and the inefficiency of scale (SIE), from the cost inefficiency (CIE) as follows:

Table 1 Summary statistics of inputs and output prices ($1US = 551.13 Franc CFA in 2021)

Outputs	System				Overall	
	Traditional		Modern			
	Mean	SD	Mean	SD	Mean	SD
Eggs sold (FCFA/Birds)	3335.25	2734	3944.60	3292.55	3253.9	243.04
Spent hens (FCFA/Birds)	4151.36	3188.89	3960.38	2989.68	4069.8	3067.30
Price of Birds (FCFA/Birds)	1722.11	1212.99	1552.29	1236.11	1649.6	1212.90
Price of labor (FCFA/Birds)	2734.94	2613.99	2444.45	3539.09	2611	2577.70
Price of feeds (FCFA/Birds)	2146.81	1763.53	2945.22	1734.70	2060.70	1763.50
Price of vaccination (FCFA/Birds)	69.24	41.96	65.22	37.25	67.50	39.90
Price of veterinary care (FCFA/Birds)	60.44	42.69	57.64	37.17	59.20	40.30
Other costs (FCFA/Birds)	102.98	69.09	126.69	85.62	113.00	77.20
Depreciation of equipment (FCFA/Birds)	432.20	316.00	381.85	252.51	410.70	291.30
Depreciation of buildings (FCFA/Birds)	139.80	12.10	133.73	101.47	137.20	107.40
Interest on fixed capital (FCFA/Birds)	25.99	17.37	31.02	21.98	28.8	20.20

SD Standard deviation

$$AIE = CIE - TIE = CIE - PTIE - SIE \quad (6)$$

The value of the allocative inefficiency (AIE) is also greater than or equal to zero. The value of zero indicates that the farmer is allocatively efficient. On the other hand, a value greater than zero indicates that the farmer is allocatively inefficient. Scale inefficiency (SIE) is nothing more than the difference between the levels of technical inefficiency under the assumptions of nonincreasing returns to scale ($\sum_{k=1}^{K}\lambda_k \leq 1$) and nondecreasing returns to scale ($\sum_{k=1}^{K}\lambda_k \geq 1$).

Inefficiency score data

For the first stage, we distinguished two outputs (eggs and spent hens) and nine inputs, including laying poultry, labor, vaccination, veterinary care, other costs (electricity, water, waste), depreciation of buildings and equipment, and interest in fixed capital. The cost of spent hens was generated by calculating the total cost value of spent hens per bird. The cost of labor input consisted of family labor and paid labor, each measured at their effective costs. The cost of feeds was calculated as the total value of feed use per laying hen. The costs of vaccination and veterinary care consisted of the total value of drugs and medication of the poultry. The other costs included miscellaneous costs and water and electricity costs. The fixed costs incorporate the annual depreciation of equipment, such as managers and tanks, and the annual depreciation of buildings, such as poultry shelters. Table 1 shows the descriptive statistics of the inputs and outputs used to estimate the inefficiency scores.

Outputs and factors have been converted into monetary terms because of the aggregated data and to facilitate comparisons between producers. Factor and product prices were also aggregated in the profit maximization program.

Truncated bootstrap analysis of the determinants of inefficiency

In nonparametric efficiency analysis, two-step semiparametric approaches that combine DEA efficiency measurement with regression analysis that uses the estimated DEA efficiency as dependent variables are becoming popular [10]. These approaches are used to produce multiple pseudo samples by resampling with replacement of the empirical distribution of a set of observations. The first application of the two-step procedure is usually a censored (Tobit) regression used to account for the bounded nature of the DEA efficiency score, or simply OLS [82]. This naïve procedure is criticized by Simar and Wilson [82], mainly for two reasons. First, they pointed out the absence of a clear theory of the underlying data generation process, which would justify the naïve two-step approach. Second, they criticize the conventional inference that is pursued in most two-step applications, ignoring that the estimated DEA efficiency scores are calculated from a common sample of data [10]. Thus, Simar and Wilson [82] develop a two-step procedure that takes into account the problems mentioned above. The idea behind bootstrapping is to simulate a real sample distribution by mimicking the process that generates the data [52, 66, 83]. This study uses the algorithm of Simar and Wilson [82], which is a truncated regression with a parametric bootstrap procedure, and applies it in the case of the directional distance function to obtain consistent estimates of the coefficients obtained in the second step.

Table 2 Summary statistics of explanatory variables

Variables	Traditional		Modern		Overall	
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Years of expérience	44.86	11.21	42.27	10.61	43.75	11.00
Education (dummy 1 = yes; 0 = no)	0.58	0.50	0.64	0.48	0.61	0.49
Household size	8.69	3.60	8.22	5.08	8.49	4.29
Training	0.56	0.50	0.64	0.48	0.59	0.49
Contact with extension services (dummy 1 = yes; 0 = no)	0.70	0.46	0.77	0.43	0.73	0.45
Access to credit (dummy 1 = yes; 0 = no)	0.53	0.50	0.91	0.29	0.69	0.46
Number of farm workers	5.19	4.65	3.80	4.00	4.59	4.43
Main profession (dummy 1 = full time; 0 = part time)	0.67	0.47	0.67	0.47	0.67	0.47
Distance of the farm from nearest major market	6.15	9.16	5.62	6.61	5.92	8.15
Contract with input suppliers (dummy 1 = yes; 0 = no)	0.52	0.50	0.78	0.42	0.63	0.48
Membership in farmer association/cooperatives (dummy 1 = yes; 0 = no)	0.77	0.42	0.53	0.50	0.67	0.47
Mortality rate (%)	7.67	11.21	9.48	8.63	8.44	14.81

Std. Dev. Standard deviation

The single truncated bootstrap regression to identify the sources of inefficiencies is specified as follows:

$$\theta_i = Z_i\beta + \zeta_i \geq 0;\ \zeta_i \text{ follows } N\ (0, \sigma 2) \quad (7)$$

where θ_I is either cost inefficiency, pure technical inefficiency, allocative inefficiency, or the scale inefficiency obtained for producer i; Z indicates the exogenous variables; β represents the parameters to be estimated; and ζ is the error term.

Exogenous variables

The literature indicates that some factors that have an impact on the inefficiency of poultry egg farms include the sociodemographic and economic characteristics of the farmer, the level of education of the farmer, the characteristics of the farm, and the location of the farm. The variables often used in the literature to explain the inefficiencies are age of the farmer, educational status and experience of the farmer, farm size and the use of training and extension services [12, 74, 96]. In our study, we selected the exogenous variables according to the availability of data. These variables are also described in Table 2. The following variables were assumed to explain the variation in inefficiency scores (cost inefficiency, allocative efficiency, pure technical efficiency, and scale efficiency) (Table 3):

The age of farmers can have a positive or negative effect on inefficiency. This variable constitutes a possible source of variation in inefficiency between poultry farmers, as older farmers may or may not be suitable for new technologies [84]. The age of farmers can also negatively affect inefficiency, which may be due to experiences accumulated over time. Therefore, the older the farmer is, the greater his/her technical and economic efficiency [31]. The age of the farmers is likely to be an important variable explaining inefficiency differences since older farmers tend to help contain more animals on the farms than younger farmers do [26]. In this paper, a negative sign of the coefficient of this variable is, therefore, expected.

Education could have either a negative or positive influence on inefficiency [13, 46, 67, 68].

The main occupation is common for some rural households that engage in agricultural and off-farm activities to supplement their income for subsistence. This variable could be either positive or negative [67].

Household size is the main source of labor. Family labor is a good way of providing labor for the farm [15]. In addition, household size and technical efficiency are negatively and significantly related. A larger household may utilize family labor, which helps to reduce labor costs and creates a formidable basis for improved technical efficiency [55].

Training relative to participation in poultry management training is a skill-related factor included in the inefficiency determinant model. Birhanu et al. [16] showed that there is a negative and statistically significant association between training and technical inefficiency. The expected sign here is negative.

Contact with extension services is an institutional factor that has been used in different empirical studies on the efficiency of poultry systems. Extension services contribute to higher technical efficiency [93].

Table 3 Expected sign of determinants of inefficiency scores

Code	Variables	Expected Sign
exper	Years of experience	–
ninst	Education (dummy 1 = yes; 0 = no)	±
taill	Household size	+
form	Training	–
contat	Contact with extension services (dummy 1 = yes; 0 = no)	–
cred	Acces to credit (dummy 1 = yes; 0 = no)	–
nttrav	Number of farm workers	–
occupation	Main profession (dummy 1 = full time; 0 = part time)	–
distfem	Distance of the farm from nearest major market	+
accintra	Contract with input suppliers (dummy 1 = yes; 0 = no)	–
coop	Membership in farmer association/cooperatives (dummy 1 = yes; 0 = no)	–
tauxmorti	Mortality rate (%)	+

Access to credit is a variable that is often cited in the literature. Khan et al. [48] showed that easier access to credit reduces the inefficiency of poultry farms.

The number of farm workers is a factor that significantly affects inefficiency [16]. The expected sign for this variable is negative.

The mortality rate is a very important indicator in breeding. Bird mortality due to heat stress is an important economic loss for the producer [70]. Hence, the increased mortality rate of poultry and laying hens should have a positive effect on inefficiency.

Membership in farmer cooperatives in such a group is an important factor for effectiveness because it positively influences effectiveness. The expected sign is negative.

Experience represents the number of years of experience and generally confirms the expertise of production techniques. However, experience is predicted to have a negative sign.

The distance of the farm from the nearest major market is an important indicator of access to different markets. There is a positive and significant association between distance to all-weather roads and inefficiency terms [16].

Contracts with input suppliers are a factor that is closely linked to the performance and productivity of poultry farms because the unavailability of production inputs leads to an increase in production costs. The expected sign is negative.

Access to veterinary services is a very important factor because farmers who receive technical advice from veterinary officers tend to be less inefficient [30]. Therefore, information on the health status of birds on a farm from a veterinary officer can reduce the mortality rate of birds, resulting in the minimization of production costs related to bird mortality and ultimately a reduction in production costs [30].

Diagnostics tests

Regression diagnostics were performed to ensure that the data collected met the underlying assumptions of the truncated regression models. The data were tested for the presence of multicollinearity. It is expected that no regressor will be linearly correlated with any other. The tolerance value (1/VIF) and variance inflation factor (VIF) were used to assess the impact of multicollinearity. The tests showed that none of the VIF or tolerance values illustrate severe multicollinearity. A VIF value greater than 10 indicates strong multicollinearity [40]. Next, a heteroscedasticity test was performed on the data. Heteroscedasticity is a violation of one of the requirements of truncated regressions, in which the error variance is not constant. The Breusch–Pagan test was applied. Finally, the normality test of the residuals was also performed on each model. The results of the tests are presented in the appendix.

Results and discussions

Inefficiency measures

For each system (traditional and modern), the average scores of short-term cost inefficiency and its decompositions are presented in Table 4. The average value of cost inefficiency is 0.62 and 0.55 for farmers of the traditional system and modern system, respectively, which shows the presence of substantial cost inefficiencies. This

Table 4 Cost, pure technical, allocative and scale inefficiencies scores

Poultry farm systems	Mean of inefficiency							
	Cost		Technical		Allocative		Scale	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Traditional system (*n* = 86)	0.62	0.32	0.20	0.14	0.45	0.23	0.42	0.35
Modern system (*n* = 64)	0.55	0.36	0.16	0.17	0.40	0.25	0.15	0.12

SD Standard deviation

implies that traditional farmers and modern farmers can, respectively, save 38% and 45% on their variable costs by improving their technical and allocative performance. Only 19% and 8% of traditional and modern poultry systems, respectively, are cost efficient (i.e., CIE = 0). Thus, most of the farmers present sources with a high percentage of inefficient costs. On average, the decomposition of cost inefficiency shows that allocative and then pure technical inefficiencies are the major components of cost inefficiency. Etuah et al. [30] indicated that 77% of farms have an inefficiency score of less than 20%. However, only approximately 5% of the broiler farms have a score above 30%. This indicates that a majority of the farms are operating close to their cost efficiency frontier. A comparison of the two systems shows that the traditional system is more cost inefficient than the modern system for the main reason that the modern system is more exigent in terms of investment and respect of sanitary norms (vaccination, medication) to reach an acceptable profitability contrary to the traditional system, which is less exigent and whose animals are, for the majority, in semi-divagation, not allowing optimal performance for profitability (Table 5).

Pure technical efficiency (i.e., PTIE = 0) applies to 16% of farmers (14 out of 86) in the traditional system and 25% of farmers in the modern system (16 out of 64) (Fig. 2). This implies that few poultry farmers operate with technical efficiencies. The proportion of pure technical efficiency is greater among farmers in the modern system than among farmers in the traditional system. The pure technical inefficiency scores average 0.20 and 0.16 for traditional and modern systems, respectively. Therefore, it is possible to reduce the variable input costs by 20% and 16% for traditional and modern systems, respectively. Hassan et al. [42] revealed substantial inefficiencies in poultry egg production in Ghana. There is, therefore, an existing scope for reducing the cost of production and hence obtaining egg output gain through efficiency improvement, which tallies with our obtained results. Similarly, Mahjoor [53] obtained a high efficiency score of 0.83. These results indicate that the technical efficiency of poultry broiler production in this region is relatively high; however, there are still opportunities to increase the productivity and income of broiler farmers. This high degree of technical efficiency of poultry farms suggests that very little marketable output is sacrificed to resource waste [100].

The average allocative inefficiency scores are 0.45 and 0.40 for traditional and modern systems, respectively, meaning that on average, traditional poultry farmers are less successful at choosing the appropriate mix of variable inputs at the existing price levels than modern poultry farmers. Then, the proportion of the allocative efficiency shows that only approximately 15% (13 out of 86) of traditional farmers and 19% (12 out of 64) of modern poultry farmers are efficient (i.e., AIE = 0) (Fig. 2). The majority of farmers are not allocatively efficient. This suggests that these poultry farmers (the majority) in both poultry farming systems can substantially reduce their variable costs by choosing a mix of variable inputs given their prices, i.e., reduce the use of expensive variable inputs and increase the use of cheap variable inputs. Contrary to our results, Chukwuji et al. [25] reported that farmers are efficient in the allocation of their resources except in the case of fixed capital items. Traditional systems seem to be more inefficient than modern systems. This result could be explained by the nontracking mechanisms of traditional systems, where the majority of animals are stray, unlike in modern systems. Kouadio et al. [51] suggested that the difference in production between the traditional system and the extensive system occurs because, in the modern semi-intensive system, the hens benefit from adequate management conditions (balanced diet at will, watering and suitable housing with a good level of hygiene). On the other hand, the life cycle time of wandering hens is longer, but the losses are more important.

Determinants of cost, pure technical inefficiency and allocative inefficiency

The second stage uses the inefficiency scores (cost, allocative, pure technical) and regresses them on the nondiscretionary variables. We present the results of the bootstrap regression truncated at 95% bootstrap confidence intervals using L = 2000 replications as suggested by Simar and Wilson [82] for each poultry system (traditional

Table 5 Second-stage coefficients and bootstrap confidence intervals at 5% (L = 2,000)

Variables	Traditional system			Modern system		
	Coef	**Std**	**[BSCI, 95%]**	**Coef**	**Std**	**[BSCI, 95%]**
Cost inefficiency						
Year of experience	−0.006***	0.002	[0.003; 0.010]	−0.003	0.004	[−0.002; 0.010]
Education	−0.229***	0.050	[−0.327; −0.131]	0.099	0.088	[−0.091; 0.209]
Household size	0.036	0.009	[0.017; 0.054]	0.017	0.016	[−0.024; 0.031]
Training	−0.088**	0.052	[−0.189; 0.013]	−0.201**	0.095	[−0.346; 0.105]
Contact with extension services	−0.136*	0.057	[−0.248; −0.024]	−0.097**	0.128	[−0.430; 0.220]
Access to credit	−0.031	0.051	[−0.131; 0.070]	−0.300***	0.153	[0.309; 1.071]
Number of farm workers	−0.007	0.005	[−0.017; 0.003]	0.011	0.009	[−0.010; 0.021]
Main profession	−0.363	0.051	[−0.463; −0.263]	−0.061***	0.110	[−0.143; 0.239]
Distance of the farm from nearest major market	0.003**	0.003	[−0.008; 0.002]	0.003	0.009	[−0.006; 0.023]
Contract with input suppliers	−0.220	0.065	[0.093; 0.348]	−0.158**	0.130	[−0.193; 0.288]
Membership in farmer association/cooperatives	−0.159	0.064	[−0.285; −0.032]	−0.060***	0.087	[−0.289; 0.008]
Mortality rate (%)	0.000	0.002	[−0.004; 0.004]	0.005**	0.002	[−0.009; 0.006]
_cons	0.621***	0.148	[0.331; 0.912]	0.488	0.279	[−0.667; 0.487]
/sigma	0.167***	0.014	[0.140; 0.194]	0.216***	0.023	[0.172; 0.260]
	Wald chi2(12) = 243.06***			Wald chi2(12) = 72.14***		
Pure technical inefficiency						
Year of experience	0.001	0.001	[0.000; 0.002]	−0.002***	0.001	[0.001; 0.003]
Education	−0.017	0.015	[−0.047; 0.013]	−0.034 ***	0.017	[0.010; 0.060]
Household size	−0.007***	0.003	[0.002; 0.013]	−0.024	0.003	[0.022; 0.030]
Training	−0.050***	0.015	[−0.080; −0.020]	−0.036*	0.017	[−0.046; 0.006]
Contact with extension services	−0.050	0.017	[−0.082; −0.017]	−0.033***	0.022	[−0.047; 0.018]
Access to credit	−0.022	0.015	[−0.051; 0.008]	−0.001	0.023	[−0.037; 0.031]
Number of farm workers	−0.002	0.002	[−0.005; 0.001]	−0.001	0.002	[−0.006; 0.000]
Main profession	−0.029*	0.015	[−0.058; 0.000]	−0.034***	0.019	[−0.093; −0.034]
Distance of the farm from nearest major market	0.002***	0.001	[0.001; 0.003]	0.003**	0.002	[−0.005; 0.001]
Contract with input suppliers	−0.080	0.018	[−0.116; −0.044]	−0.062	0.022	[−0.100; 0.036]
Membership in farmer association/cooperatives	−0.071	0.019	[−0.108; −0.034]	−0.035*	0.015	[−0.029; 0.017]
Mortality rate (%)	0.008**	0.001	[−0.001; 0.001]	0.001***	0.000	[0.000; 0.001]
_cons	0.297***	0.044	[0.210; 0.384]	0.031	0.047	[−0.080; 0.065]
/sigma	0.049***	0.004	[0.041; 0.057]	0.033***	0.003	[0.027; 0.040]
	Wald chi2(12) = 532.33***			Wald chi2(12) = 1408.20***		
Allocative inefficiency						
Year of experience	−0.006***	0.002	[0.002; 0.009]	−0.004	0.004	[−0.003; 0.010]
Education	−0.206***	0.053	[−0.309; −0.103]	0.056	0.100	[−0.150; 0.177]
Household size	−0.022**	0.010	[0.002; 0.041]	−0.016 *	0.019	[−0.064; 0.002]
Training	−0.047	0.055	[−0.154; 0.061]	−0.238 **	0.112	[−0.399; 0.115]
Contact with extension services	−0.075	0.061	[−0.195; 0.046]	−0.136**	0.149	[−0.507; 0.153]
Access to credit	0.032	0.055	[−0.075; 0.140]	−0.322***	0.190	[0.292; 1.508]
Number of farm workers	−0.004	0.006	[−0.015; 0.007]	0.009	0.010	[−0.013; 0.021]
Main profession	−0.302***	0.054	[−0.409; −0.196]	0.196	0.132	[−0.059; 0.377]
Distance of the farm from nearest major market	−0.004	0.003	[−0.010; 0.001]	0.007	0.010	[−0.005; 0.030]
Contract with input suppliers	0.330	0.071	[0.190; 0.470]	−0.104*	0.153	[−0.159; 0.413]
Membership in farmer association/cooperatives	−0.096	0.068	[−0.229; 0.037]	−0.013	0.099	[−0.263; 0.073]
Mortality rate (%)	0.001**	0.002	[−0.003; 0.005]	0.006**	0.003	[−0.012; 0.004]
_cons	0.327**	0.154	[0.025; 0.629]	0.540	0.337	[−1.012; 0.535]
/sigma	0.172***	0.015	[0.143; 0.201]	0.228***	0.027	[0.175; 0.281]
	Wald chi2(12) = 79.69***			Wald chi2(12) = 23.46***		

***Significance at the 1% level. **Significance at the 5% level. *Significance at the 10% level and modern) in Table 4. The determinants of cost inefficiency under both systems are strongly significant at the 1% level. Farmer experiences negatively and significantly affected cost efficiency at the 1% level only for the traditional system, as expected. The negative coefficient of experience is significant at 1%, suggesting that farmers with more years of experience tend to be less cost-inefficient. This result is similar to that of Ajiboye et al. [5], who reported that years of experience in poultry farming has a reducing effect on efficiency. This could be due to the overreliance on acquired experiences at the expense of innovation. In addition, years of experience allow farmers to gain more knowledge about their resources and practices, resulting in good use of production inputs and reduced costs [30]. In the same way, Tuffour and Oppong [91] stated that the more experienced farmers are, the more profitable the producer becomes. This result also tallies with the findings suggested by Udoh and Etim [92] that high experience significantly improves the efficiency of poultry production. The mortality rate was positive and statistically significant at 1% for both systems. For the traditional system, the coefficient of the negative and significant education variable at the 1% level indicates that a higher level of education reduces cost inefficiency. This result is consistent with the studies by Etuah et al. [30] and Abdulai and Huffman [1]. For both traditional and modern systems, the training variable is negative and significant at the 5% level. This suggests that poultry farmers who have had the opportunity to receive training in livestock management tend to reduce their farm inefficiency. Thus, participation in poultry management training is a skill-related factor. These results highlight the critical role of smallholder capacity building in improving production and productivity. Empirical studies have also documented the positive roles of skills and experiences in the technical efficiency of smallholders [16, 63]. The same is true for the extension service contact variable, which is negative and significant at the 10% and 5% levels for traditional and modern systems, respectively. This indicates that contact with extension services reduces the cost inefficiency of operators. This can be explained by the fact that the advice given during the visits of the extension services can give useful indications to the operator. Thus, accurate and timely information, especially regarding the health status of birds on a farm, provided by a veterinary or extension agent, has the potential to reduce bird mortality. Such a reduction results in the minimization of production costs associated with bird mortality and a potential reduction in cost inefficiencies [30]. The contract with input suppliers has a negative and significant effect on technical inefficiency. This means that farmers who have a contract for the delivery of production inputs (feed, medicine, etc.) tend to reduce their cost inefficiency and consequently favor a minimization of production costs. In addition, the variable access to credit is negative and significant at the 1% level for the modern system. For instance, an increase in the amount of credit accessed will enhance the acquisition of more production inputs required for production expansion [3]. The main occupation variable is also negative and significant at the 1% level. It appears that the more the producers have breeding as the main activity, the more the inefficiency of the costs is reduced. This agrees with the finding of Rahman [72] that those who do less off-farm work tend to be more efficient. In addition, membership in a cooperative is negative and significant at the 1% level, indicating that poultry farmers who are members of a cooperative tend to reduce inefficiencies. The animal mortality rate has a negative positive effect on farmers' cost inefficiency, as the mortality rate increases, the inefficiency of the farm increases. Pure technical inefficiency is negatively and significantly affected by experience and education for the modern system. The negative coefficient for years of experience suggests that farmers with more years of experience tend to be less technically inefficient. This sign is explained mainly because poultry activity is subject to multiple hazards that poultry farmers cannot control given the duration of their activity [78]. For the modern system, pure technical inefficiency is negatively and significantly affected by education. This implies that as the level of education increases, technical inefficiency decreases, which can be explained by the fact that education facilitates the adoption and use of improved technological innovations. This result is consistent with those obtained by Weir [97] and Oji and Chukwuma [65]. For traditional systems, household size has a negative effect on technique inefficiency for modern systems. Family labor is a good way to provide labor on the farm. Therefore, we expect poultry farmer productivity to increase with the availability of (family) labor [15]. Thus, for both systems (traditional and modern poultry systems), distance has a positive and significant

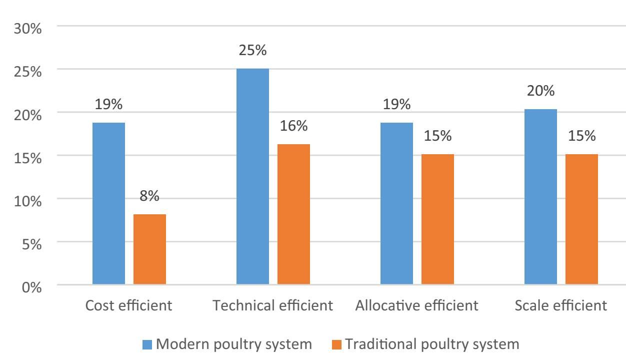

Fig. 2 Proportion of efficient farms by system

effect on technical inefficiency. The implication is that the greater the distance is, the greater the inefficiency. Long distances require more fuel for transportation, which leads to an increase in the cost of production. However, the situation is reversed for large broiler operations because a long distance to the main road means increased safety for the operations, and the cost of the increased distance can be ignored if the cost is counted per bird. Additionally, access to the extension service has a negative and significant effect on inefficiency, which reflects that the information received by the agents was applied and resulted in improved husbandry techniques. This result is in line with Odunlami et al. [62]. The mortality rate has a positive and significant effect on technical inefficiency for both systems (traditional and modern poultry systems). Similarly, Dogan et al. [29] showed that chick and hen mortality rates have a negative effect on technical efficiency. One reason is that high hen mortality rates, usually due to seasonal diseases affecting the farms, significantly reduce production.

Both models of allocative inefficiency are strongly significant for the traditional and modern systems. The estimated coefficient for year experience is statistically significant at the 1% level and is negatively related to the measure of allocative inefficiency in the traditional system model. However, for the modern system, farm location affects allocative inefficiency. Additionally, education has a negative effect on inefficiency at the 1% level. This suggests that education can reduce the allocative inefficiency of poultry farmers. This is in the same line with Ullah et al. [93], who argued that educated farmers in broiler production are more allocative efficient than those farmers who do not fall into this category. For both systems (traditional and modern poultry systems), household size has a negative and significant effect on inefficiency. This implies that a large family size is relevant to poultry production because family labor constitutes the bulk of labor supply in poultry production [76]. For modern systems, training has a negative and significant effect on allocative inefficiency. This means that the more training poultry farmers receive in livestock management, the more they reduce their inefficiency in resource allocation. Access to credit is negative and significant at 1% for the modern system. Thus, access to credit provides the farmer with a means to expand and improve his or her operation. It also determines the ease with which he adopts new practices and technologies in his business. Therefore, access to credit has a negative effect on inefficiency. Wozniak [99] corroborates this fact by reporting that credit thus increases net income from fixed inputs, market conditions and individual characteristics, while the credit constraint decreases farmers' efficiency by limiting the adoption of high-yielding varieties and the acquisition of information necessary to increase productivity. Finally, the mortality rate has a positive and significant effect for traditional and modern systems on allocative inefficiency. Hence, higher death rates in reared broiler birds tend to lead to allocative inefficiencies [57].

Conclusion

In recent years, the poultry sector has faced intensified competition, coupled with the ongoing decline of local production, particularly at a small scale. These challenges are widely ascribed to the elevated costs of domestic production and the suboptimal performance of local farmers, aligning with findings in the literature [64]. Our study seeks to contribute to this discourse by delving into the performance of poultry farms, employing a nuanced approach that computes cost inefficiency scores decomposing them into the contributions of technical inefficiency and allocative inefficiency for both traditional and modern poultry farming systems. According to our first research question, this study revealed substantial cost inefficiencies within the sampled traditional and modern poultry farms, mirroring observations made in previous studies on inefficiencies in agricultural production [12, 30]. Specifically a low cost efficiency is observed, only 9% and 18% of traditional and modern systems, respectively, demonstrated cost efficiency, reinforcing the pressing need to distinguish between production systems due to their divergent operational requirements. This refers to the observations of Gupta et al. [41] on the importance of tailoring interventions to specific farming practices.

Exploring the determinants of inefficiencies, our findings align with existing literature, emphasizing the crucial role of training for poultry producers and contact with extension agents in reducing cost, technical, and allocative inefficiencies [16, 30, 63]. The significance of access to credit as a determinant of cost inefficiency is corroborated by studies emphasizing the role of credit facilitation in enabling farmers to invest in production materials and enhance productivity [3]. Moreover, the negative influence of the mortality rate on all types of inefficiency resonates with previous research highlighting the multifaceted impact of mortality on agricultural production [30, 57]. This underscores the importance of targeted measures to reduce mortality rates in poultry farming, advocating improved health and biosecurity practices in livestock management. In light of these insights, our study recommends targeted programs or projects for both modern and traditional poultry farmers. Such initiatives should not only aim to boost local production but also emphasize better access to credit for small-scale farmers. Technical support, as suggested by our findings, should be a central component of these interventions to ensure sustainable improvements in the poultry sector. Finally, our study contributes to the ongoing discourse on poultry farming by aligning with and extending insights from existing literature. By integrating these findings, we advocate for tailored interventions that acknowledge the distinct needs of traditional and modern poultry farming systems, leveraging training, credit access, and targeted support to enhance efficiency and bolster local production in the face of heightened competition.

Limitations and future research recommendation

One significant limitation of this study is the relatively small sample size, which may introduce a degree of uncertainty and limit the generalizability of the results. While the findings provide valuable insights into the inefficiencies within the sampled poultry farming systems, caution should be exercised in extrapolating these results to a broader population. A larger and more diverse sample could enhance the robustness and external validity of the study.

Moreover, a notable area for future research lies in the incorporation of risk considerations into inefficiency measurement. The current study did not explicitly account for the influence of risk on farmers' decision-making processes, potentially overlooking a crucial factor affecting productivity. Farmers who prioritize risk avoidance strategies might exhibit different production behaviors compared to those embracing risk, leading to variations in productivity and production costs. Addressing this aspect in future research would contribute to a more comprehensive understanding of the factors influencing inefficiencies in poultry farming. Furthermore, exploring how farmers' risk attitudes interact with efficiency outcomes can provide valuable insights for developing targeted interventions to address inefficiencies and enhance overall sectoral performance.

Finally, while the current study sheds light on certain inefficiencies within poultry farming systems, acknowledging and addressing the limitations, particularly the sample size, will be essential for refining the understanding of inefficiency determinants. Future research endeavors should prioritize larger and more diverse samples, as well as incorporate risk considerations to offer a nuanced perspective on the multifaceted nature of inefficiencies in poultry production.

Appendix 1

Algorithm 1 of Simar and Wilson [82]

The following four steps summarize the procedure of Algorithm 1 of Simar and Wilson [82] used in our case here:

1. Use the original data to estimate the technical inefficiency $\widehat{\theta}_i$ of each producer ($i=1,\ldots,n$) in GAMS.
2. Use the maximum likelihood method to estimate $\widehat{\beta}$ of β in the truncated regression of $\widehat{\theta}_i$ on exogenous factors Zi considering the observations $m < n$, where $\widehat{\theta}_i > 0$:$\widehat{\theta}_i = Z_i\beta + \varepsilon_i > 0$
3. Loop the following three substeps (a, b et c) L times to obtain a set of L bootstrap estimations $\widehat{\beta}^*$ of β:

    a. In the new sample $i=1,\ldots,m$, drop for each producer the error term ε_i of the normal distribution $N(0, \widehat{\sigma}_\varepsilon^2)$, for which it is assumed a left truncation at $(0 - Z_i\widehat{\beta})$ since $(0 - Z_i\widehat{\beta}) < \varepsilon_i$. The process to carry out this step is indicated in the appendix of Simar and Wilson [82].
    b. Again, for each producer $i=1,\ldots,m$, compute $\widehat{\theta}_i^* = Z_i\widehat{\beta} + \varepsilon_i$.
    c. Use the maximum likelihood method to estimate the truncated regression of $\widehat{\theta}_i^*$ on Zi, giving a bootstrap estimate $(\widehat{\beta}^*)$.

4. Finally, use the obtained bootstrap values $\widehat{\beta}^*$ and the original estimate $\widehat{\beta}$ to build confidence intervals for each element of β. If the distribution $(\widehat{\beta}_j - \beta_j)$ was known for each element j of β, it would be trivial to find the values a_α and b_α such that:

$$Pr\left[-b_\alpha \le \widehat{\beta}_j - \beta_j \le -a_\alpha\right] = 1 - \alpha; 0 \le \alpha \le 1 \quad ; \alpha = 0.05, \text{for example } (8).$$

As the distribution $(\widehat{\beta}_j - \beta_j)$ is unknown for each element j of β, the element j of each bootstrap value $\widehat{\beta}^*$ is used to find the values a_α^* and b_α^* such that:

$$Pr\left[-b_\alpha^* \le (\widehat{\beta}^* - \widehat{\beta}_j) \le -a_\alpha^*\right] \approx 1 - \alpha; 0 < \alpha < 1 \quad ; \alpha = 0.05, \text{for example } (9).$$

With a large number of estimates (for instance, L = 2000 replications), the substitution of a_α, b_α by a_α^*, b_α^* in (8) leads to an estimated confidence interval $\left[\widehat{\beta}_j + a_\alpha^*, \widehat{\beta}_j + b_\alpha^*\right]$

Appendix 2

Multilinearity test

Variables	Modern system model		Traditional system model	
	VIF	1/VIF	VIF	1/VIF
taill	5.94	0.168411	3.26	0.306351
distfem	3.09	0.323485	2.88	0.347521
contat	2.66	0.376097	2.24	0.446871
occupation	2.64	0.378823	2.05	0.488524
accintra	2.58	0.387543	1.98	0.505844
form	2.01	0.497824	1.80	0.554235
coop	1.64	0.609271	1.79	0.558328
ninst	1.50	0.667463	1.78	0.562442
exper	1.29	0.772248	1.66	0.601753
nttrav	1.17	0.856411	1.45	0.690608
tauxmorti	1.13	0.888486	1.31	0.763076
cred	1.12	0.891915	1.22	0.817877
Mean VIF	2.23		1.95	

Appendix 3
Heterogeneity test

Poultry Systems	Test	chi2(1)	Prob > chi2	Decision
Modern poultry system model	Breusch–Pagan/Cook-Weisberg test	0.04	0.004	Reject null hypothesis
Traditional poultry system model		0.71	0.006	Reject null hypothesis
Modern poultry system model	Normality test	0.58	0.003	Accept null hypothesis
Traditional poultry system model		6.56	0.000	Accept null hypothesis

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Author contributions
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Availability of data and materials
The datasets are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no conflicts of interest.

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