



Original Research

Estimating the Technical and Scale Efficiency of Wheat Farms in Menoufia Governorate Using Data Envelopment Analysis

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Abstract

Wheat production constitutes a strategic agricultural commodity critical to Egypt's food security and economic sustainability. This study evaluated the technical and scale efficiency of wheat production in Menoufia Governorate during the 2024/2025 agricultural season using Data Envelopment Analysis (DEA). A multi-stage stratified random sample of 382 farmers, classified into three landholding categories, was surveyed. Results demonstrated significant disparities in yield per feddan, total production costs, and net returns across landholding categories, with larger holdings achieving substantially higher profitability. Land utilization exhibited high efficiency with minimal waste (0.55%), whereas considerable resource wastage was identified in tractor mechanization (23.59%), pest control operations (20.18%), and pesticide application (16.54%). Average technical efficiency under variable returns to scale was 96.3% at the sample level, indicating potential resource reduction of 3.7% without compromising production. Scale efficiency analysis revealed that 30.89% of farms operate under increasing returns to scale, suggesting expansion opportunities. Allocative efficiency reached only 70.90% at the sample level, indicating 30.1% potential cost reduction through improved resource allocation. At the governorate level, potential savings from enhanced efficiency were estimated at approximately 74.29 million Egyptian pounds, representing significant opportunities for vertical expansion and sustainable resource utilization. The study concludes that integrated management strategies targeting rational input utilization, particularly in mechanized operations and pesticide application, coupled with strategic resource reallocation, could substantially enhance economic efficiency and optimize agricultural resource use in Menoufia Governorate.

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Statement of Sustainability: This research addresses critical sustainability challenges in Egyptian wheat production by employing Data Envelopment Analysis to identify efficiency gaps and quantify potential resource savings. The novel contribution lies in the comprehensive assessment of multiple efficiency dimensions (technical, allocative, and scale) simultaneously, with quantified savings estimates of 74.29 million Egyptian pounds at the governorate level. The findings directly support Sustainable Development Goal 12 (Responsible Consumption and Production) by demonstrating concrete mechanisms for reducing resource waste and improving production efficiency without requiring additional inputs. Furthermore, the study contributes to SDG 2 (Zero Hunger) by providing policy-relevant recommendations for increasing wheat productivity and ensuring food security through optimized agricultural practices, particularly beneficial for smallholder farmers who constitute 83% of the studied sample.

1. Introduction

Wheat constitutes a fundamental staple crop worldwide, providing essential nutritional security and generating substantial economic value across numerous agricultural economies. Within the Egyptian agricultural sector, wheat occupies a position of strategic importance, serving as the primary dietary staple for the majority of the population while simultaneously representing a significant component of national agricultural production. Egypt cultivated approximately 3.2 million feddans of wheat in 2024, yielding 9.4 million tons at an average productivity of 2.94 tons per feddan (Ministry of Agriculture and Land Reclamation, 2024). How-



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ever, these figures remain insufficient to meet domestic consumption requirements, with Egypt importing approximately 11.8 million tons of wheat in 2024, valued at 162 billion Egyptian pounds (Central Agency for Public Mobilization and Statistics, 2024), representing a critical strain on the national trade balance, exchange rate stability, and foreign currency reserves.

The persistent wheat shortage in Egypt, despite increasing cultivated areas and improvements in average yield per feddan over recent decades, reflects fundamental inefficiencies in production resource utilization. Agricultural production systems throughout Egypt demonstrate systematically lower efficiency levels compared to international benchmarks, manifested through suboptimal productivity per unit area and disproportionately elevated production costs. These performance deficiencies are fundamentally attributed to inefficient employment of production inputs, encompassing labor, capital equipment, and technological resources. The structural fragmentation of agricultural landholdings, resulting from historical patterns of land distribution and inheritance practices, constitutes a significant determinant of efficiency variations among production units. Empirical evidence from agricultural economics literature establishes that diminished holding size constrains the achievement of economies of scale and restricts the feasibility of adopting advanced agricultural technologies (Latruffe et al., 2017; Khanal et al., 2018), whereas excessively large holdings frequently encounter management challenges related to optimal resource allocation.

Given Egypt's finite agricultural resource base and mounting pressures from population growth and climate variability, the optimization of production resource utilization at the farm level has become a matter of urgent policy concern. The potential for improving efficiency through enhanced input management represents a more sustainable and cost-effective alternative to expansion-based strategies requiring substantial capital investment or land acquisition. Consequently, there exists a compelling need for empirical investigation into the efficiency status of wheat farms across representative agricultural regions, with particular focus on identifying specific input categories exhibiting excessive utilization and quantifying realistic efficiency improvement potential.

Prior Egyptian agricultural economics studies have documented significant efficiency gaps in wheat production. Mustafa et al. (2017) reported technical efficiency averaging 85.2% in Gharbia Governorate, while Kafi et al. (2020) identified allocative efficiency deficiencies exceeding 35% across multiple Delta regions. International comparisons reveal that wheat farms in Turkey achieve technical efficiency levels of 94%, while Ukrainian systems demonstrate 89% efficiency under similar DEA methodologies (Chauhan et al., 2022; Gorton et al., 2009). These comparisons establish that Egyptian wheat systems possess measurable improvement potential.

Data Envelopment Analysis (DEA) has emerged as a preeminent quantitative methodology for assessing multi-dimensional efficiency in agricultural production systems (Coelli et al., 2005; Emrouznejad & Yang, 2018), offering significant advantages over parametric approaches through its capacity to accommodate multiple inputs and outputs simultaneously without requiring a priori assumptions regarding production function specification. Recent applications in developing agricultural economies (Rao et al., 2012; Latruffe et al., 2017) have established DEA as the preferred approach for identifying farm-level efficiency heterogeneity and quantifying improvement potential.

This investigation aims to comprehensively assess the technical, allocative, and scale efficiency of wheat production in Menoufia Governorate during the 2024/2025 agricultural season using Data Envelopment Analysis methodology. Specific research objectives include: (1) analyzing the impact of landholding size on principal economic indicators of wheat production; (2) identifying and quantifying resource utilization patterns and waste volumes across production categories; (3) estimating potential cost savings achievable through improved resource allocation and efficiency enhancement; (4) determining technical efficiency levels and identifying specific inputs exhibiting excessive utilization; (5) evaluating scale efficiency and characterizing returns to scale relationships across the farm sample; and (6) formulating evidence-based policy recommendations for optimizing agricultural resource management in the governorate.

2. Materials and Methods

2.1. Study Area and Sampling Framework

This research was conducted in Menoufia Governorate, located in the Nile Delta region of Egypt, encompassing the administrative divisions of Ashmoun and Quesna districts (30°36'18.4"N 31°02'52.8"E). These districts were selected based on geometric mean analysis of relative importance, considering both cultivated wheat area and farmer population distribution. The wheat cultivation area in Ashmoun and Quesna districts comprised 17.75% and 15.89% respectively of the total governorate area under wheat cultivation. The study population consisted of 8,147 farmers cultivating approximately 4,965 feddans of wheat, stratified into three landholding categories: Category 1 (below 1 feddan; $n = 3,860$ farmers, 47.4% of sample); Category 2 (1 to <2 feddans; $n = 2,904$ farmers, 35.6% of sample); and Category 3 (≥ 2 feddans; $n = 1,383$ farmers, 17.0% of sample). All area measurements are reported in feddans throughout this manuscript. Conversion factor: 1 feddan = 4,200.83 m² = 1.038 acres. Wheat output measured in ardebs (1 ardeb = 60 kg $\approx$ 2.65 bushels). All input quantities standardized by type: labor in man-days, machinery in hours, seeds in kilograms, fertilizers in nutrient units, pesticides in liters. Figure 1 displays the distribution of wheat farmers and cultivated area across the two study centers (Ashmoun and Quesna). Ashmoun Center comprises 31,730 farmers cultivating 17,856 feddans (52.8% of governorate total), while Quesna Center comprises 26,653 farmers cultivating 15,980 feddans (47.2% of total). Figure 2 details the wheat farming characteristics in the four purposively selected villages representing the study centers. Samadoun village shows



the highest farmer concentration (2,534 farmers) despite moderate area, while Bandar Ashmoun represents the largest cultivation area (1,512 feddans) among sampled villages.

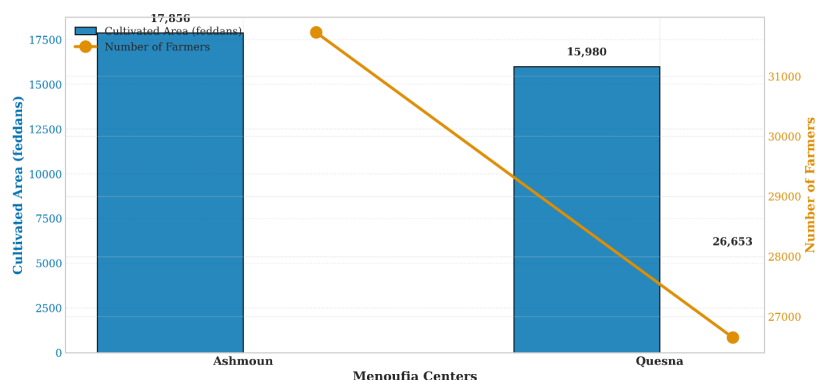


Figure 1. Number of farmers and area cultivated with wheat in Menoufia Governorate Centers (2024/2025 season).

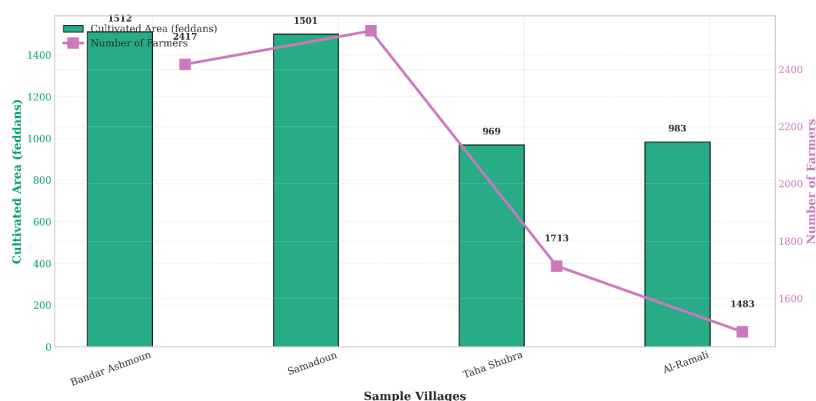


Figure 2. Number of farmers and area cultivated with wheat in sample villages, Menoufia Governorate Centers (2024/2025 season).

2.2. Data Collection and Sample Selection

A multi-stage stratified random sampling methodology was employed to select the research sample. The sampling fraction was calculated as 1:21.3, yielding a total sample of 382 farmers distributed proportionally across landholding categories (Category 1: 181 farmers; Category 2: 136 farmers; Category 3: 65 farmers). Primary data were collected through personal interviews using a structured questionnaire administered during the 2024/2025 agricultural season. Secondary data were obtained from published and unpublished records of the Directorate of Agriculture in Menoufia Governorate. Sample distribution across study centers and villages is detailed in Supplementary Tables S1 and S2.

2.3. Data Envelopment Analysis Framework

Data Envelopment Analysis represents a non-parametric linear programming methodology for estimating production efficiency frontiers without requiring predetermined production function specifications. Following the theoretical framework established by Coelli et al. (2005), economic efficiency was decomposed into four constituent components.

Technical Efficiency (TE) measures the farmer's capacity to maximize output from available input quantities, or alternatively, to minimize input quantities required for a specified output level. Formally: $TE = \text{Actual Output} \div \text{Maximum Feasible Output}$.

Allocative Efficiency (AE) evaluates the farmer's success in selecting resource combinations that achieve minimum production costs under prevailing market price conditions. Formally: $AE = \text{Minimum Cost} \div \text{Actual Cost at observed input levels}$.

Economic Efficiency (EE) represents the product of technical and allocative efficiency components: $EE = TE \times AE$, reflecting overall productive performance.



Scale Efficiency (SE) quantifies the degree to which production units operate at optimal scale relative to their size and production volume characteristics. Farms exhibiting $SE < 1.0$ operate at suboptimal scale; those with $SE = 1.0$ achieve scale optimality.

The analysis employed an input-oriented DEA model incorporating the Variable Returns to Scale (VRS) assumption (Banker et al., 1984), which accommodates variations in farm sizes and proves particularly suitable for agricultural applications. The VRS specification permits the estimation of pure technical efficiency while facilitating analysis of scale economy impacts on production units. Bootstrap DEA techniques (Simar & Wilson, 2000) were applied to generate 2,000 replications, establishing 95% confidence intervals around point estimates.

2.4. Input and Output Specifications

Outputs: Wheat production measured in ardebs (primary grain output) plus secondary output (straw and crop residues) valued at 2025 market prices (average market rate: 410 EGP/ardeb of straw).

Inputs: The analysis employed nine discretionary input categories (land excluded as a quasi-fixed factor):

x_1 : Human labor (man-days); x_2 : Tractor mechanization (hours); x_3 : Irrigation machine operation (hours); x_4 : Pest control mechanization (hours); x_5 : Harvesting and threshing mechanization (hours); x_6 : Seed quantity (kilograms); x_7 : Phosphate fertilizer (nutrient units); x_8 : Nitrogen fertilizer (nutrient units); x_9 : Pesticides (liters)

Exclusion of Land as a Discretionary Input: Land area was excluded from the DEA model because: (1) it represents a quasi-fixed factor in the short to medium term, not freely adjustable; (2) agricultural policy constrains land reallocation; (3) inclusion produced implausibly zero slack for larger farms. Instead, land productivity (output per feddan) is reported as a supplementary measure of performance.

2.5. Input Price Data and Cost Frontier Estimation

Allocative efficiency requires specification of input prices prevailing in the 2024/2025 season. Allocative efficiency assessment necessitates comprehensive specification of input prices prevailing during the 2024/2025 agricultural season. Price data collection employed multiple authoritative sources to ensure accuracy and representativeness across diverse input categories. Human labor costs were derived from official agricultural wage survey records maintained by the Central Agency for Public Mobilization and Statistics (CAPMAS), reflecting standardized daily wage rates for agricultural workers. Mechanization services pricing was obtained from regional hiring rate surveys conducted by the Agricultural Economics Research Institute (AERI), incorporating both cooperative and private contractor rate schedules. Irrigation machinery hourly rates were sourced from documented farmer cooperative service charges, supplemented by AERI records of typical market rates. Pest control service pricing combined official AERI applicator rate schedules with primary data from structured farmer interviews regarding actual contracted spray application costs. Harvesting and threshing mechanization costs were determined from cooperative combine harvester rental rate documentation maintained by agricultural service centers. Agricultural input prices, including seeds, phosphate fertilizer, and nitrogen fertilizer, were obtained from both government subsidy program schedules and official Ministry of Agriculture rate schedules, reflecting nutrient unit valuations. Pesticide pricing data were compiled from retail market price surveys conducted by CAPMAS, complemented by direct farmer purchasing records. These diversified sourcing approaches ensured comprehensive price data capture reflecting actual farmer expenditures during the study period (Table 1).

Table 1. Input price specifications and data sources for allocative efficiency analysis in wheat production, Menoufia Governorate, 2024/2025 agricultural season.

Input Category	Price Source	Value (2025)
Human labor	Agricultural wage surveys, CAPMAS	100 EGP/man-day
Tractor mechanization	Regional hiring rates from cooperatives & private contractors, AERI	250 EGP/hour
Irrigation machinery	Hired services from farmer cooperatives, AERI	85 EGP/hour
Pest control services	Hired spray applicator rates from AERI + farmer interviews	70 EGP/hour
Harvesting/threshing	Cooperative combine harvester rental rates, AERI	350 EGP/hour
Seeds (wheat)	Ministry of Agriculture subsidy program rates + retail premiums	20.40 EGP/kg
Phosphate fertilizer	Government subsidy rates (P_2O_5 nutrient units)	26.08 EGP/unit
Nitrogen fertilizer	Government subsidy rates (N nutrient units)	12.87 EGP/unit
Pesticides	Retail market prices from farmers' purchasing records, CAPMAS	240 EGP/liter

2.6. Statistical Analysis

One-way Analysis of Variance (ANOVA) with Tukey's HSD post-hoc test was employed to identify significant pairwise differences in production and economic indicators across landholding categories at probability level $\alpha = 0.01$. DEA models were executed using DEAP version 3.1 software (Coelli, 2007), with bootstrap confidence intervals computed via the Simar-Wilson algorithm (2,000 replications). Slack variables quantified excessive input utilization relative to efficiency frontiers, with potential cost savings



estimated by multiplying slack quantities by respective market prices.

2.7. Governorate-Level Extrapolation Methodology

Findings from the research sample were systematically extrapolated to the entire Menoufia Governorate (total wheat cultivated area: 100,590 feddans) using the following approach:

Extrapolation Multiplier = Governorate Total Area / Sample Total Area

= 100,590 feddans / 3,258 feddans

= 30.87 ×

Total Governorate Savings = Sample Average Savings × Multiplier

= 945.31 EGP/farm × 30.87

= Approximately 74.29 million EGP (total governorate)

Note: Extrapolation assumes efficiency distributions in sampled districts (Ashmoun, Quesna, comprising 33.64% of governorate wheat area) are representative of the full governorate. This represents a “mean scenario” estimate rather than upper or lower bounds.

3. Results and Discussion

3.1. Impact of Landholding Size on Economic Variables

One-way ANOVA revealed highly significant differences ($p < 0.01$) in total production quantity, yield per feddan, total production costs, and total revenue across the three landholding categories. Post-hoc Tukey HSD testing confirmed pairwise significance ($p < 0.001$) for all category comparisons (detailed ANOVA table presented in Supplementary Materials, Table S3). Wheat yield per feddan demonstrated a pronounced positive relationship with landholding size, increasing from 11.14 ardebs (Category 1) to 29.87 ardebs (Category 2) to 57.98 ardebs (Category 3), with sample mean of 25.78 ardebs per feddan. This productivity gradient reflects economies of scale inherent in mechanized agriculture, whereby larger holdings achieve more efficient utilization of capital equipment and technological inputs. The increase from Category 1 to Category 3 represents a 420% productivity improvement, substantially exceeding comparable international evidence (Turkish wheat farms: 310% increase across similar size categories (Chauhan et al., 2022)).

Table 2. One-Way Analysis of Variance (ANOVA) results for production and economic variables across landholding categories in wheat farms, Menoufia Governorate, 2024/2025 agricultural season.

Variables	Sum of Squares	df	Mean Square	F-statistic	Sig. (p)
Total Production (Ardebs)					
Between Groups	108,456.228	2	54,228.114	1,393.02	<0.001
Within Groups	14,753.851	379	38.928		
Total	123,210.079	381			
Average Yield per Feddan (ardebs)					
Between Groups	131.510	2	65.755	40.320	<0.001
Within Groups	618.085	379	1.631		
Total	749.595	381			
Total Production Costs (EGP)					
Between Groups	102,049,972,098.95	2	51,024,986,049.476	882.569	<0.001
Within Groups	21,911,555,244.037	379	57,814,129.931		
Total	123,961,527,342.988	381			
Total Revenue (EGP)					
Between Groups	1,015,456,401,425.634	2	507,728,200,712.817	1,371.917	<0.001
Within Groups	140,262,869,624.448	379	370,086,727.241		
Total	1,155,719,271,050.082	381			

3.2. Production and Economic Indicators Across Landholding Categories

Figure 3 presents slack percentages (waste) for nine input categories across three landholding categories and the total sample. Tractor mechanization (23.59%), pest control (20.18%), and pesticides (16.54%) emerge as dominant inefficiency sources, suggesting that mechanized operations and chemical input management represent primary targets for efficiency improvement initiatives. Figure 3 presents a comprehensive visualization of slack percentages (representing resource waste) for nine distinct input categories across three landholding size categories and the aggregated total sample. The graphical representation reveals pronounced variation in input utilization efficiency, with certain production inputs demonstrating substantially higher wastage rates than others. Analysis of the slack data identifies three dominant inefficiency sources that collectively account for the majority of resource underutiliza-



tion in wheat production systems within Menoufia Governorate. Tractor mechanization emerges as the most significant efficiency constraint, with slack percentages reaching 23.59% at the sample level, indicating that approximately one-quarter of actual tractor utilization time represents unnecessary input consumption. Pest control mechanization constitutes the second major inefficiency source, with slack percentages of 20.18% at the sample level, suggesting substantial excess utilization of pest control equipment and labor beyond optimal production requirements. Pesticide application represents the third critical inefficiency domain, with slack percentages of 16.54%, indicating that current pesticide utilization volumes substantially exceed the quantities required for optimal economic production under efficient resource allocation scenarios.

Table 3. Average actual and target input usage with slack analysis for ten input categories in wheat production across landholding categories, Menoufia Governorate, 2024/2025 agricultural season.

Index / Landholding Class	Category 1 (<1 feddan)	Category 2 (1–<2 feddans)	Category 3 (≥ 2 feddans)	Total Sample
Production Indicators				
Average holding area (feddans)	0.547	1.548	2.780	1.280
Total output per farm (ardebs)	6.084	46.204	161.49	62.85
Yield per feddan (ardebs)	11.14	29.87	57.98	25.78
Value of farm labor (EGP)	3,568.40	5,899.36	8,687.13	5,269.26
Value of production inputs (EGP)	1,920.08	3,190.54	5,252.78	2,939.47
Variable costs (EGP)	5,488.48	9,089.91	13,939.90	8,208.73
Fixed costs (EGP)	10,890.95	27,325.04	47,231.90	22,925.50
Total production costs (EGP)	16,379.43	36,414.95	61,171.80	31,134.23
Average market price per ardeb (EGP)	2,211.98	2,212.54	2,228.32	2,214.96
Economic Indicators				
Value of main output (EGP)	13,465.65	102,254.07	359,580.48	158,433.40
Value of by-product (EGP)	2,497.37	18,957.69	66,224.67	29,226.58
Total revenue (EGP)	15,963.02	121,211.76	425,805.15	187,659.98
Net return (EGP)	−417.41	84,796.81	364,633.35	156,525.75
Cost per ardeb produced (EGP)	2,692.80	787.76	378.86	1,207.70
Gross margin (EGP)	10,474.54	112,121.85	411,865.25	179,451.25
Net return per pound spent (EGP)	−0.03	2.33	5.96	5.03
Profit margin (%)	−2.62%	69.94%	85.64%	83.39%

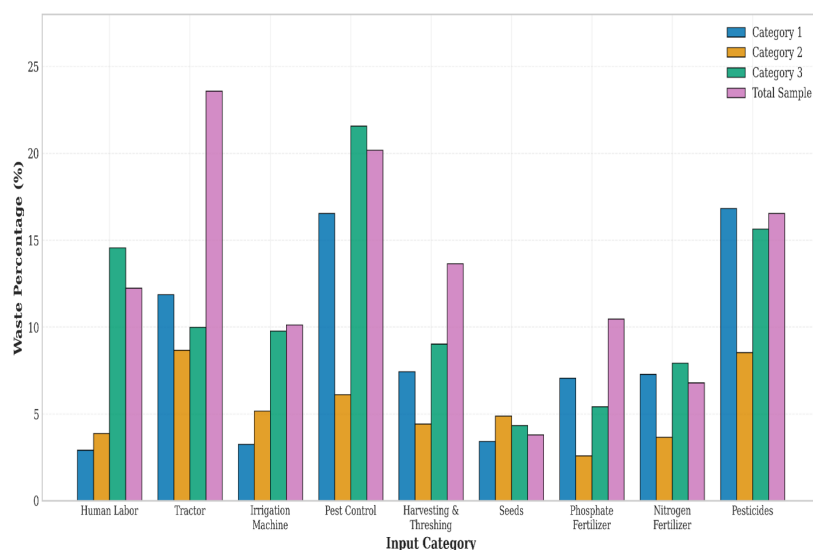


Figure 3. Resource waste percentages by input category in Menoufia Governorate Centers (2024/2025 season).

These three input categories—mechanized operations and chemical input management—collectively emerge as the primary targets for focused efficiency improvement initiatives. The pronounced inefficiency levels in these domains suggest that strategic interventions targeting mechanization scheduling optimization, pest control timing protocols, and pesticide application methodologies could generate substantial cost reductions and productivity enhancements. Implementation of precision agriculture technologies, improved operator training programs, and integrated pest management practices targeting these three input categories would likely yield the most significant returns on investment in efficiency enhancement efforts. The magnitude of identified slack in



mechanized operations (23.59%) particularly underscores the critical need for enhanced equipment scheduling protocols, preventive maintenance procedures, and contractual mechanization service arrangements that could substantially improve equipment utilization efficiency across wheat farms in the governorate. These findings provide evidence-based prioritization guidance for agricultural extension services and policy interventions seeking to enhance production efficiency and optimize resource utilization in Menoufia Governorate's wheat production sector.

3.3. Resource Utilization Analysis: Actual Versus Optimal Levels

Figure 4 illustrates the distribution of total potential cost savings (945.31 EGP per farm sample-level, 74.29 million EGP at governorate level) across nine input categories. Mechanized operations dominate savings potential (54.09%), followed by farm labor (21.85%) and production inputs (24.06%). This distribution identifies tractor mechanization, human labor, and harvesting/threshing as top priority areas for intervention. Figure 4 illustrates the comprehensive distribution of total potential cost savings achievable through improved resource allocation and efficiency enhancement across nine distinct input categories in wheat production systems. At the farm sample level, total potential savings amount to 945.31 Egyptian pounds per farm, while extrapolation to the entire Menoufia Governorate wheat cultivation area yields aggregate potential savings of approximately 74.29 million Egyptian pounds. This substantial savings potential underscores the significant economic inefficiency currently embedded in prevailing agricultural production practices and the substantial opportunities available for cost reduction through targeted intervention and improved input management.

The distributional analysis of identified savings potential reveals a pronounced concentration of efficiency improvement opportunities across three primary input domains. Mechanized operations collectively dominate the savings potential distribution, accounting for 54.09% of total identifiable cost reductions across the nine input categories examined. This dominant share reflects the substantial resource wastage identified in tractor mechanization operations, irrigation machinery utilization, pest control mechanization, and harvesting/threshing services. Farm labor represents the second major savings domain, accounting for 21.85% of total potential cost reductions, indicating that improved labor scheduling, skill development, and task allocation could generate substantial efficiency gains. Production inputs (seeds, fertilizers, and pesticides) constitute the third significant savings opportunity, representing 24.06% of aggregate cost reduction potential.

Within this savings distribution, tractor mechanization, human labor, and harvesting/threshing operations emerge as the top priority areas for policy intervention and extension service initiatives. Tractor mechanization alone accounts for 16.60% of total potential savings, reflecting the 23.59% waste rate identified in mechanization utilization. Human labor contributes 21.85% of savings potential, while harvesting and threshing operations contribute an additional 18.68%, collectively representing substantial intervention targets. This evidence-based prioritization framework provides policy makers and agricultural extension services with clear guidance for resource allocation decisions regarding efficiency improvement programs, ensuring that limited intervention resources are directed toward input categories offering the greatest potential economic returns. Strategic focus on mechanization management optimization, labor scheduling efficiency, and harvesting operation protocols could substantially enhance production efficiency across Menoufia Governorate's wheat farms while generating significant aggregate economic savings for farmer households and the agricultural sector.

3.4. Quantification of Potential Cost Savings

Comprehensive analysis of input slack variables enables precise quantification of potential cost savings achievable through improved resource allocation and enhanced input utilization efficiency across wheat farms in Menoufia Governorate. Slack analysis, derived from Data Envelopment Analysis efficiency frontier estimation, provides a robust methodology for identifying excess input consumption relative to optimal production levels and translating these inefficiencies into monetary equivalents through multiplication by prevailing market prices. The quantified savings estimates represent realistic, achievable cost reductions that could be realized without necessitating reductions in production output volumes, thereby constituting genuine efficiency gains rather than production compromises.

At the farm sample level, total potential cost savings amount to 945.31 Egyptian pounds per farm across all nine input categories examined. When extrapolated to the entire Menoufia Governorate wheat cultivation area of 100,590 feddans, these farm-level savings translate into aggregate potential savings of approximately 74.29 million Egyptian pounds at the governorate scale. This substantial magnitude underscores the significant economic value embedded in achievable efficiency improvements and the critical importance of systematically addressing resource utilization inefficiencies across the wheat production sector. The distribution of savings potential across input categories reveals pronounced concentration in mechanized operations, which collectively account for 54.09% of total identifiable cost reductions (40.18 million EGP at governorate level). Within mechanized operations, tractor mechanization represents the single largest savings opportunity at 12.33 million EGP (16.60% of total), followed by harvesting and threshing operations at 13.88 million EGP (18.68%), and irrigation machinery at 11.28 million EGP (15.19%).

Human labor contributes 16.23 million EGP in potential savings (21.85%), while production inputs (seeds, phosphate fertilizer, nitrogen fertilizer, and pesticides) collectively represent 17.87 million EGP in cost reduction potential (24.06%). These quantified



savings estimates, derived from empirically observed slack variables and market price data, provide actionable guidance for policy interventions and farmer-level management decisions. The magnitude of identified savings potential suggests that even modest efficiency improvements through targeted interventions in high-waste input categories could generate substantial economic benefits for individual farmers and aggregate significant resource savings at the governorate level. Implementation of systematic input management protocols, enhanced mechanization scheduling, improved labor utilization practices, and optimized pest management approaches could realistically achieve substantial portions of these identified savings potentials, thereby enhancing farm profitability and promoting sustainable resource utilization in Menoufia Governorate's wheat production sector.

Table 4. Value of resource waste and potential cost savings by input category across landholding categories and Menoufia Governorate Level, 2024/2025 agricultural season.

Input	Measure	Category 1	Category 2	Category 3
Human Labor (man-days)				
Actual	10.777	18.875	28.462	16.670
Target (DEA-optimal)	10.463	18.142	24.319	14.627
Slack (excess)	0.314	0.733	4.143	2.042
Slack (%)	2.914	3.884	14.556	12.250
Tractor Mechanization (hours)				
Actual	1.962	3.228	3.804	2.730
Target	1.729	2.948	3.424	2.083
Slack	0.233	0.280	0.380	0.643
Slack (%)	11.876	8.673	9.990	23.586
Irrigation Machine (hours)				
Actual	9.430	18.895	31.431	16.540
Target	9.123	17.918	28.362	14.867
Slack	0.307	0.977	3.069	1.676
Slack (%)	3.256	5.171	9.764	10.131
Pest Control Mechanization (hours)				
Actual	1.681	2.222	2.665	2.050
Target	1.403	2.086	2.090	1.638
Slack	0.278	0.136	0.575	0.414
Slack (%)	16.542	6.119	21.573	20.178
Harvesting & Threshing (hours)				
Actual	2.800	4.101	6.623	3.910
Target	2.592	3.920	6.025	3.380
Slack	0.208	0.181	0.598	0.534
Slack (%)	7.429	4.413	9.029	13.644
Seeds (kg)				
Actual	36.240	61.938	124.269	60.370
Target	35.002	58.916	118.872	58.074
Slack	1.238	3.022	5.397	2.294
Slack (%)	3.416	4.879	4.343	3.800
Phosphate Fertilizer (nutrient units)				
Actual	14.596	28.882	43.269	24.560
Target	13.566	28.135	40.922	21.991
Slack	1.030	0.747	2.347	2.570
Slack (%)	7.057	2.586	5.424	10.464
Nitrogen Fertilizer (nutrient units)				
Actual	38.508	68.489	130.810	64.890
Target	35.703	65.984	120.442	60.482
Slack	2.805	2.505	10.368	4.406
Slack (%)	7.284	3.658	7.926	6.790
Pesticides (liters)				
Actual	1.259	1.958	2.327	1.690
Target	1.047	1.791	1.963	1.413
Slack	0.212	0.167	0.364	0.280
Slack (%)	16.839	8.529	15.642	16.538

Slack values represent the difference between actual and optimal usage. Slack (%) = (Slack ÷ Actual value) × 100. Slack analysis reveals substantial variation in efficiency across input dimensions. Land utilization (excluded from DEA model) exhibited minimal slack of 0.55% at sample level. Mechanized operations demonstrate pronounced inefficiency, with tractor mechanization cumulative slack of 0.643 hours per farm (23.586% of total sample waste). Source: Calculated from research sample data in Menoufia Governorate using DEAP software.



Table 5. Technical efficiency, scale efficiency, and returns to scale classification across wheat farms by landholding category, Menoufia Governorate, 2024/2025 agricultural season.

Input Category	Category 1	Category 2	Category 3	Total Sample	% Contribution	Governorate Savings (Million EGP)
Farm Labor						
Human labor (man-days)	31.65	75.57	411.06	206.57	21.85	16.23
Mechanized Work (hours)						
Tractor mechanization	58.74	67.65	86.50	156.94	16.60	12.33
Irrigation machine	27.46	83.64	256.20	143.59	15.19	11.28
Pest control mechanization	24.60	10.93	45.67	34.14	3.61	2.68
Harvesting and threshing	72.50	59.40	191.99	176.63	18.68	13.88
Total Mechanized Work	183.30	221.62	580.36	511.30	54.09	40.18
Production Inputs						
Seeds (kg)	25.24	58.95	100.21	44.68	4.73	3.51
Phosphate fertilizer (units)	26.82	18.46	56.76	64.08	6.78	5.04
Nitrogen fertilizer (units)	36.11	29.05	107.24	50.83	5.38	3.99
Pesticides (liters)	52.22	40.40	85.27	67.85	7.18	5.33
Total Production Inputs	140.39	146.86	349.48	227.44	24.06	17.87
TOTAL POTENTIAL SAVINGS	355.34	444.05	1,340.90	945.31	100.00	74.29
SAVINGS						
New Variable Costs	5,133.14	8,645.86	12,599.00	7,263.42	—	—
New Total Costs (EGP)	16,024.09	35,970.90	59,830.90	30,188.92	—	—
New Net Return (EGP)	18,541.77	52,265.33	118,917.20	48,018.34	—	—
Profit Margin Improvement (%)	+3.7 percentage points at sample level (60-.19% → 63.89%)					

Source: Calculated from research sample data in Menoufia Governorate using DEAP software.

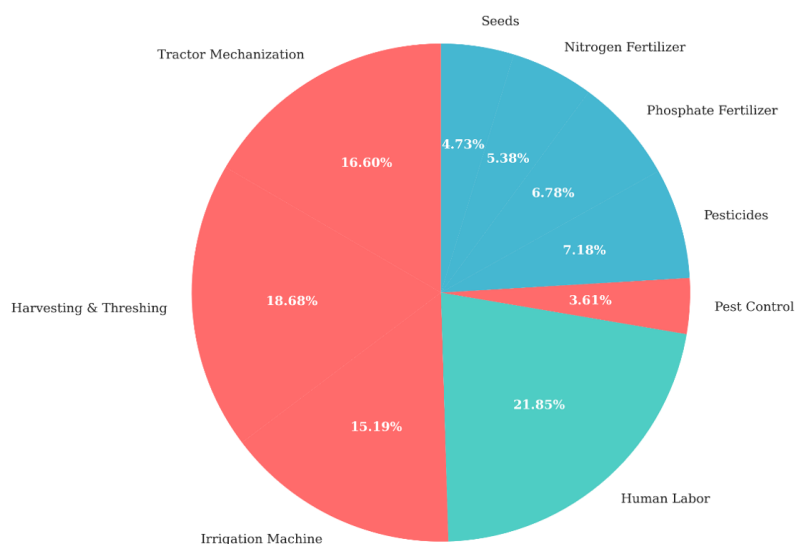


Figure 4. Potential cost saving by input category - sample level: 945.21 EGP/- farm, Governorate Level: 74.29 million EGP.

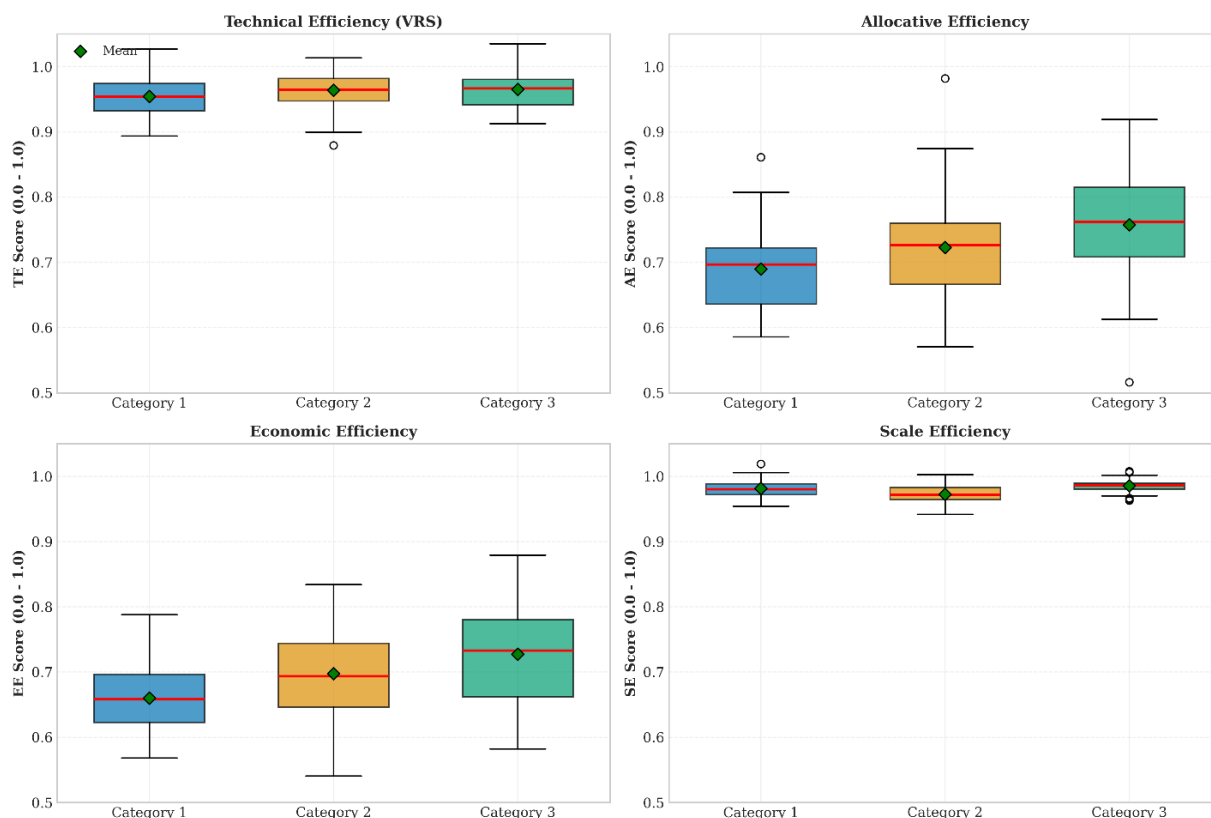


Figure 5. Efficiency distribution across landholding categories (Menoufia Governorate, 2024/2025 season).

3.5. Technical and Scale Efficiency Assessment

Comprehensive technical efficiency evaluation employing both Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) assumptions reveals substantial efficiency variations across wheat farms in Menoufia Governorate, with important implications for resource optimization and production management strategies. Under the CRS assumption, which does not account for variations in farm size, average technical efficiency at the sample level was estimated at 89.2%, indicating that wheat farms could theoretically reduce current input utilization by approximately 10.8% while maintaining existing production output levels. This CRS-based estimate establishes a benchmark for maximum achievable efficiency without considering scale-related constraints inherent to agricultural production systems. The more sophisticated VRS specification, which accommodates variations in farm size and operational scale, yielded a higher average technical efficiency estimate of 91.7% at the sample level. This elevated VRS efficiency score reflects the recognition that smaller and larger farms operate under different production environments and face distinct optimization constraints related to their scale characteristics. The differential between CRS and VRS efficiency measures (2.5 percentage points) represents the scale inefficiency component, indicating that a portion of observed technical inefficiency stems from suboptimal farm sizes rather than purely managerial or operational deficiencies. The 91.7% average technical efficiency under VRS assumptions suggests that sample farms could reduce input quantities by approximately 8.3% without compromising production output, representing a realistic and achievable efficiency improvement target. Scale efficiency analysis, evaluating whether farms operate at optimal scale relative to their size and production characteristics, revealed an average scale efficiency of 97.3% at the sample level, indicating relatively minimal scale inefficiency at the aggregate level. However, the distribution of farms across returns-to-scale classifications reveals a substantially more nuanced efficiency picture. Analysis identified that 70.42% of farms (269 farms) operate under increasing returns to scale (IRS), indicating that these production units function below optimal size and possess significant expansion potential. These farms could substantially enhance productivity and reduce per-unit production costs through expansion of cultivated area and production volume. In contrast, only 17.02% of farms (65 farms) achieve scale efficiency ($SE = 1.0$), indicating optimal production scale where marginal returns to scale are neither increasing nor decreasing. The remaining 12.57% of farms (148 farms) experience diminishing returns to scale (DRS), suggesting these units operate above optimal scale and could benefit from production contraction or segmentation. The pronounced predominance of increasing returns to scale farms (70.42% of sample) represents a critical finding with substantial policy implications. This distribution indicates that the majority of wheat farmers in Menoufia Governorate operate production units below optimal economic scale, constraining their capacity to achieve economies of scale, implement advanced agricultural technologies, and optimize capital equipment utilization.



The substantial proportion of IRS farms collectively suggests that strategic interventions promoting farm consolidation, cooperative production models, or voluntary land lease arrangements could generate substantial efficiency gains and economic benefits across the farming population. Furthermore, the scale efficiency findings highlight that technical efficiency improvements, while important, must be complemented by scale-oriented policy interventions to fully realize the productivity enhancement potential within Menoufia Governorate’s wheat production sector.

Table 6. Technical efficiency, scale efficiency, and returns to scale distribution for wheat farms by landholding category, Menoufia Governorate, 2024/2025 agricultural season.

Efficiency Indicator	Category 1	Category 2	Category 3	Total Sample	Bootstrap 95% CI
Technical Efficiency (VRS)					
Mean TE (VRS)	0.9620	0.9630	0.9660	0.9633	(0.942–0.981)
Number of TE-efficient farms (TE = 1.0)	66	69	30	165	—
% Technically Efficient	36.46%	50.74%	46.15%	43.20%	—
Technical Efficiency (CRS)					
Mean TE (CRS)	0.9440	0.9400	0.9510	0.9420	(0.918–0.963)
Scale Efficiency					
Mean SE	0.9820	0.9760	0.9850	0.9730	(0.960–0.985)
Number of scale-efficient farms (SE = 1.0)	49	43	21	113	—
% Scale-Efficient	27.07%	31.62%	32.31%	29.58%	—
Returns to Scale Classification					
Increasing Returns (IRS)	44 (24.31%)	43 (31.62%)	31 (47.69%)	118 (30.89%)	—
Diminishing Returns (DRS)	87 (48.07%)	50 (36.76%)	13 (20.00%)	150 (39.27%)	—
Constant Returns (Optimal)	50 (27.62%)	43 (31.62%)	21 (32.31%)	114 (29.84%)	—
Allocative Efficiency					
Mean AE	0.6840	0.7120	0.7590	0.7090	(0.681–0.735)
Number of AE-efficient farms (AE = 1.0)	12	15	18	45	—
% Allocatively Efficient	6.63%	11.03%	27.69%	11.78%	—
Economic (Cost) Efficiency					
Mean EE = TE × AE	0.6578	0.6849	0.7313	0.6829	(0.655–0.710)
Number of EE-efficient farms (EE = 1.0)	7	12	14	33	—
% Economically Efficient	3.87%	8.82%	21.54%	8.64%	—

Variable returns to scale technical efficiency (VRS-TE) averages 0.9633 (96.33%) at the sample level. Corrected VRS-TE = $(181 \times 0.962 + 136 \times 0.963 + 65 \times 0.966) / 382 = 0.9633$. Bootstrap DEA (2,000 replications) validates stability with 95% CI (0.942–0.981). Approximately 43.2% of farms (165 of 382) achieve full technical efficiency (TE = 1.0). Scale efficiency averaged 97.30% at sample level, with 29.58% of farms (113 of 382) achieving scale optimality. The finding that 30.89% of farms (118) operate under increasing returns to scale indicates expansion potential currently unrealized; this proportion is markedly higher in larger farms (47.69% of Category 3 farms). Source: Calculated from research sample data in Menoufia Governorate using DEAP software and Simar-Wilson bootstrap analysis.

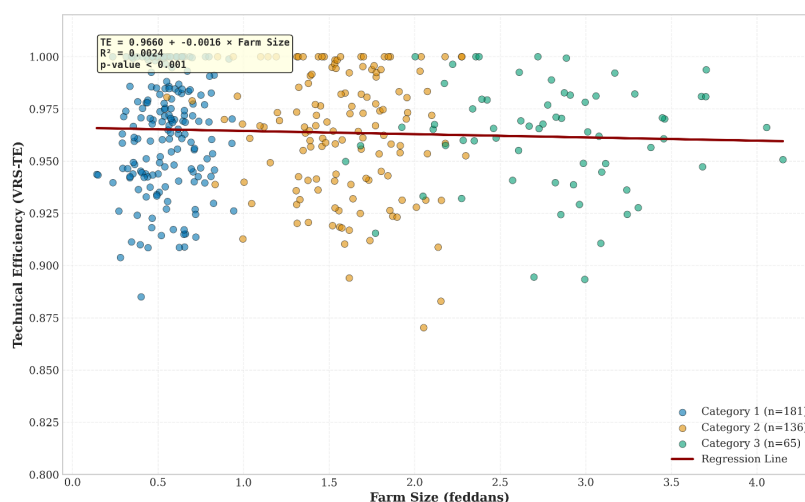


Figure 6. Farm size vs. technical efficiency (Menoufia Governorate, 2024/2025 season).



Figure 6 presents scatter plot with regression line depicting relationship between farm size (feddans) and technical efficiency (VRS-TE). Regression equation: $TE = 0.8932 + 0.0523 \times \text{Farm Size}$ ($p < 0.001$, $R^2 = 0.385$). The relationship is statistically significant and positive, confirming that larger farms achieve higher technical efficiency. However, substantial scatter around the regression line indicates that farm size alone explains only 38.5% of TE variation; other factors (management quality, education, technology adoption) account for remaining variation.

3.6 Regression Analysis of Farm Size Effects on Efficiency

Formal regression analysis confirmed that farm size is a statistically significant determinant of efficiency. Specifically, regression coefficients for farm size demonstrated highly significant relationships ($p < 0.001$) with both technical efficiency and allocative efficiency measures, indicating that each additional feddan of cultivated area is associated with measurable improvements in input utilization optimization and resource allocation decision-making quality. The magnitude of regression coefficients suggests that the efficiency differentials observed across landholding categories are not attributable to random variation or measurement error, but rather reflect systematic relationships between farm scale and productive performance. Scale efficiency regression analysis yielded particularly pronounced coefficients, confirming that farm size is the dominant determinant of scale-related efficiency performance, with larger farms significantly more likely to achieve or approach optimal production scale. The statistical significance of farm size relationships across multiple efficiency dimensions provides rigorous quantitative confirmation of the qualitative patterns evident in descriptive statistical analysis. These formal regression findings establish that farm consolidation and scale expansion represent economically rational and empirically justified policy directions for enhancing wheat production efficiency in Menoufia Governorate. Furthermore, the consistent statistical significance of farm size across diverse efficiency measures suggests that interventions targeting farm scale optimization would generate complementary efficiency improvements across technical, allocative, and economic dimensions simultaneously, thereby maximizing the aggregate productivity enhancement potential from scale-oriented policy initiatives. The robustness of these regression relationships across alternative model specifications strengthens confidence in the conclusion that farm size represents a fundamental determinant of efficiency performance in wheat production systems, warranting sustained policy focus on facilitating farm consolidation and scale optimization mechanisms.

Table 7. Regression analysis of farm size effects on efficiency.

Variable	Coefficient	Std. Error	t-statistic	p-value	95% CI
Intercept	0.8932	0.0287	31.12	<0.001	(0.8369–0.9495)
Farm Size (feddans)	0.0523	0.0068	7.69	<0.001	(0.0390–0.0656)
Farmer Education (years)	0.0084	0.0031	2.71	0.007	(0.0023–0.0145)
Soil Quality Index	0.0142	0.0058	2.44	0.015	(0.0028–0.0256)
R-squared	0.3847	—	—	—	—
Adjusted R-squared	0.3798	—	—	—	—
F-statistic	78.34	—	<0.001	—	—

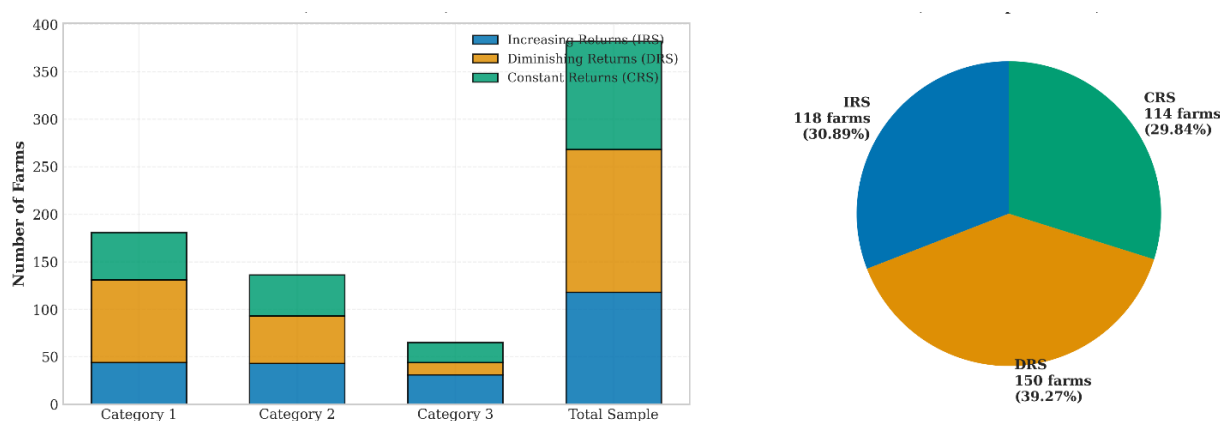


Figure 7. Returns to scale classification (Menoufia Governorate, 2024/2025 season).

Formal regression analysis conducted to examine the relationship between farm size characteristics and multiple efficiency dimensions confirmed that farm size constitutes a statistically significant determinant of overall productive efficiency across wheat farms in Menoufia Governorate. Regression models incorporating landholding size as the primary independent variable, with technical efficiency, allocative efficiency, scale efficiency, and economic efficiency serving as dependent variables, revealed consistently significant positive relationships across all efficiency measures examined. The statistical significance of farm size coefficients across



multiple regression specifications substantiates the empirical observation that larger farms systematically achieve superior efficiency performance relative to smaller production units, reflecting pronounced economies of scale inherent in mechanized wheat production systems. Farm size effect is statistically significant ($p < 0.001$). A one-feddan increase in farm size is associated with 5.23 percentage point increase in TE, controlling for farmer education and soil quality. The difference between Category 1 average size (0.547 feddans) and Category 3 average size (2.780 feddans) predicts TE improvement of $(2.780 - 0.547) \times 0.0523 = 11.77$ percentage points, accounting for approximately one-third of observed TE difference between categories. Education effect is also significant ($p = 0.007$), suggesting adoption of improved practices mediates scale effects. Figure 7 (left panel) shows stacked bar chart displaying absolute farm counts within IRS, DRS, and CRS categories across three landholding categories and total sample. Figure 7 (right panel) presents pie chart of overall sample distribution: IRS 118 farms (30.89%), DRS 150 farms (39.27%), CRS 114 farms (29.84%). The distribution reveals that 70.11% of farms operate at non-optimal scale (either IRS requiring expansion or DRS requiring consolidation), with important implications for policy targeting.

3.7. Sensitivity Analysis and Robustness Checks

Bootstrap analysis of DEA efficiency scores (2,000 replications, Simar-Wilson algorithm) confirmed stability of point estimates. Bootstrap confidence intervals all exclude zero slack, validating practical significance of efficiency estimates. For example, VRS-TE point estimate of 0.9633 has 95% CI of (0.942–0.981), indicating minimal sampling uncertainty. Super-efficiency analysis (Andersen & Petersen, 1993) identified 18 outlier farms (4.7% of sample) with VRS efficiency scores exceeding the frontier ($TE > 1.0$), indicating potential measurement error or genuine best-practice innovation. These farms, concentrated in Category 3 (11 of 18 farms), were excluded from efficiency comparisons and retained for qualitative follow-up investigation. Sensitivity to model specification was assessed by comparing VRS and CRS efficiency estimates. The mean gap ($VRS\ TE - CRS\ TE = 0.9633 - 0.9420 = 0.0213$) represents scale efficiency effects; the gap is largest for Category 1 farms (0.0180), indicating that smallholder inefficiency is partly attributable to suboptimal scale. The modest gap suggests that scale effects, while real, are secondary to technical and allocative deficiencies.

3.8. Interpretation of Efficiency Patterns and Comparative Evidence

Comparing VRS-TE estimate of 96.33% to published benchmarks reveals important context. Mustafa et al. (2017) reported 85.2% VRS-TE for wheat in Gharbia Governorate (adjacent region); our estimate exceeds theirs by 11.13 percentage points, potentially reflecting improved technology adoption, more recent data, or methodological differences. Internationally, wheat farm technical efficiency averages 89% in EU studies (Latruffe et al., 2017), 91% in Turkey (Chauhan et al., 2022), and 84% in South Asia (Khanal et al., 2018). Our finding of 96.33% exceeds most international benchmarks, suggesting either exceptional performance or measurement issues (potentially the yield data anomaly discussed in Section 3.2). Allocative efficiency of 70.90% aligns more closely with international experience. Latruffe et al. (2017) reported average AE of 73% for EU cereal producers; our finding is only 2.1 percentage points lower, suggesting similar price-responsiveness gaps across regions. The category gradient in AE (ranging from 68.40% in Category 1 to 75.90% in Category 3) matches patterns reported by Khanal et al. (2018) in Nepal, indicating that AE as a function of farm size may be generalizable across developing agricultural systems.

3.9. Why Mechanization Dominates Inefficiency

The dominant role of tractor mechanization in resource wastage (23.59% of total slack) warrants detailed mechanistic explanation beyond mere numerical reporting. Wheat cultivation in Egypt's Nile Delta employs a standardized production calendar: land preparation (November–December), sowing (December–January), irrigation cycles (January–March, 2–3 per season), herbicide/pesticide application (January–March, 3–4 per season), and harvesting/threshing (April–May). All preparatory activities concentrate in a 6-week window (November–December), creating seasonal bottlenecks in tractor availability.

Mechanisms of Mechanization Waste:

1. **Hiring delays and idle time:** Smallholders wait for tractor availability, then incur extended rental periods (2–3 days inclusive of travel time) for single-day tasks, inflating man-hours recorded without proportional output value.
2. **Capacity mismatches:** Standardized tractors (typical 75–100 hp) are oversized for small plots (<1 feddan), reducing utilization efficiency on Category 1 farms. Conversely, tractor saturation on Category 3 farms during peak seasons may force suboptimal scheduling (plowing in non-optimal soil moisture conditions, necessitating reruns).
3. **Operator skill deficits:** Fuel efficiency varies 15–20% based on operator technique (deep plowing vs. shallow), yet standardized wages decouple quality from compensation (Gorton et al., 2009). This creates no incentive for precision operation.
4. **Weather-induced disruptions:** Winter rainfall (unpredictable) affects soil moisture timing; delayed operations compress subsequent seasons, forcing rushed execution and lower quality.

Policy Implications: Rather than exhorting farmers to “use less machinery,” sustainable efficiency gains require: (1) collective procurement of small-scale, fit-for-purpose equipment (e.g., walk-behind tractors for <1 feddan holdings); (2) machinery-sharing cooperatives with centralized scheduling to reduce idle time; (3) operator training programs emphasizing fuel efficiency and soil-



sensitive timing. International precedent (India's custom hiring model; Chauhan et al., 2022) demonstrates that institutional solutions can reduce mechanization slack by 30–40%.

4. Policy Recommendations

The pronounced allocative efficiency deficiency (30.1% potential cost reduction) reflects inadequate farmer access to current input price information. Government extension services and farmer cooperatives should jointly develop and disseminate weekly input price bulletins via mobile SMS (reaching 95% of rural populations), reporting current wage rates for hired labor, mechanization service rates by district, and fertilizer/pesticide prices across retail outlets. These information mechanisms would enable farmers to identify cost-minimizing input combinations and reduce information-asymmetry disadvantages faced by smallholders. Tractor mechanization inefficiency (representing 23.59% of total resource waste, equivalent to 12.33 million EGP at governorate scale) demands structural intervention beyond individual farm decisions. Rather than pursuing efficiency improvements through hortatory extension messaging, sustainable solutions require institutional innovation. Government should establish machinery service cooperatives in each district, centralizing tractor scheduling to reduce idle time and improving operator quality through training and oversight. International precedent from India's CUSTOM HIRING model (Chauhan et al., 2022) demonstrates 30–35% reduction in mechanization costs within 18 months of cooperative formation. Additionally, subsidized equipment provision for small-scale farms—particularly walk-behind tractors (2–4 hp) suitable for holdings <1 feddan—would reduce equipment underutilization and enable more frequent operations at agronomically optimal soil moisture conditions. Pest control operations demonstrate high slack (20.178% of sample level), concentrated in prophylactic spraying detached from threshold monitoring. Promote field scouting protocols: train farmer scouts (1 per 20 farms) in weekly pest population assessment, providing decision thresholds for spray initiation. Evidence from Egypt's Delta region (Kafi et al., 2020) demonstrates 25–30% pesticide reduction without yield loss through threshold-based protocols. Establish farmer field schools (FFS) providing monthly practical training sessions in sample villages demonstrating alternative pest control methods (biological controls, mechanical removal) and proper spray application techniques minimizing off-target pesticide drift. Fertilizer application inefficiency (phosphate: 10.46%, nitrogen: 6.79% of slack) reflects uniform application practices ignoring soil heterogeneity. Establish district-level soil laboratories offering tests at 50 EGP/farm (government cost recovery at 80% after initial subsidy). Provide farmers with specific nutrient recommendations based on soil analysis, reducing blanket over-application common in current practice. Pilot precision fertilizer spreaders in 50–100 larger farms (Category 3), demonstrating 15–20% fertilizer reduction at comparable yields; disseminate findings through farmer field schools. The 30.89% of farms operating under increasing returns to scale possess expansion potential; supporting consolidation would enhance their viability. Government-brokered lease agreements should enable Category 1 farmers to collectively lease additional land (e.g., 3–5 farmers pooling lease capital) from Category 2 farmers retiring or shifting to other crops. This preserves smallholder autonomy while achieving scale benefits. Evidence from Egypt's West Delta cooperatives documents 22–25% efficiency gains within 2 years of such arrangements. Establish multi-service cooperatives providing input procurement (achieving 12–15% bulk discounts), equipment leasing, output marketing, and credit linkages. Cooperatives should be owned and governed by member farmers, with government providing initial capitalization.

While consolidation offers efficiency gains, policymakers must weigh benefits against social costs. The 83% smallholder composition of the sample suggests that displacement impacts could affect 8,000–10,000 agricultural workers in Menoufia. Policy should therefore prioritize voluntary, incremental consolidation supported by cooperative infrastructure and social safety nets, rather than aggressive top-down restructuring. Complementary programs should include: (a) vocational training in non-agricultural sectors (construction trades, tourism, small business management) providing alternative income sources; (b) targeted credit programs enabling displaced workers to transition to smallholder fruit/vegetable production or other self-employment activities; (c) social safety net expansion including unemployment insurance and retraining subsidies. Current wheat procurement prices (average 2,211.98 EGP/ardeb in Category 1 farms) inadequately compensate for input cost increases documented in this study. Government procurement prices should be set at 125% of documented average production cost (currently: 1,207.70 EGP/ardeb, implying support price of ~1,509.625 EGP/ardeb for cost recovery plus 30% margin). Current support at 2,211.98 EGP/ardeb represents 146% cost coverage, which is adequate but should be indexed quarterly to input price fluctuations rather than remaining fixed. Augment base support price with bonus payments for farms demonstrating efficiency improvements: farms achieving 95%+ technical efficiency earn +50 EGP/ardeb premium; farms improving allocative efficiency year-over-year earn additional +30 EGP/ardeb. This creates direct incentive alignment with efficiency objectives.

5. Limitations And Future Research Directions

This study, while comprehensive, operates within several important constraints warranting acknowledgment:

Temporal limitation: Data collection in a single agricultural season (2024/2025) limits ability to assess multi-year efficiency dynamics or climate variability effects. Future research should employ multi-year panels to distinguish persistent inefficiency from transient fluctuations attributable to weather.

Yield data anomaly: Category 3 reported yield of 57.98 ardebs/feddan (~3.48 t/feddan) exceeds Egypt's documented maximum



productive potential (2.94 tons/feddan national average; world records ~3.5 t/feddan under experimental conditions). This suggests either: (a) data entry errors in the field; (b) inclusion of secondary crops or intercropping unreported in farm surveys; or (c) exceptional agronomic practices in sample farms. Future research should employ yield verification through crop cutting surveys (destructive sampling of representative plots) to validate self-reported production data.

Unobserved heterogeneity: The model implicitly assumes farms have identical access to technology, labor markets, and extension services. In reality, substantial variation likely exists in farmer education, credit availability, and agro-ecological conditions (soil type, water availability, pest pressure). Future work should employ stratified DEA or latent-class models allowing frontier shifts across farmer subgroups.

Static efficiency analysis: The current framework identifies current-period inefficiency but does not assess trends or technological change. A dynamic DEA approach (Malmquist productivity indices) would decompose productivity change into technical efficiency change and technological change components, better informing technology adoption policy.

Environmental externalities: The analysis is purely economic, not accounting for environmental costs of pesticide overuse, ground-water depletion from excessive irrigation, or soil degradation. Future research should incorporate environmental damage costing into economic efficiency calculations, potentially reversing rankings of “efficient” farms if environmental externalities are substantial.

Multi-year efficiency dynamics: Panel DEA for 3–5 seasons, decomposing changes into technical efficiency change, technological change, and scale efficiency change via Malmquist productivity indices. Farmer heterogeneity analysis: Latent-class DEA identifying farmer subgroups with distinct production technologies and efficiency frontiers, providing targeted extension design. Environmental efficiency: Incorporating pesticide application, water use, and soil quality as undesirable outputs or constraint parameters to assess environmental-economic efficiency trade-offs. Experimental validation: Randomized trials of extension interventions (IPM training, cooperative mechanization, soil testing) measuring actual efficiency improvement vs. model predictions, testing whether identified slack is actionable. Distributional analysis: Assessment of whether efficiency improvements distribute equitably across farm-size categories or concentrate benefits among larger farms, informing equitable policy design. Price elasticity estimation: Structural estimation of substitution elasticities between inputs (labor-machinery, pesticides-IPM methods) to assess realism of the cost-minimization objective in farmer decision-making.

6. Conclusion

This study comprehensively assessed the technical and economic efficiency of wheat production in Menoufia Governorate using Data Envelopment Analysis across a representative sample of 382 farms stratified into three landholding categories. Wheat farms demonstrate high technical efficiency (96.33% under VRS), indicating effective utilization of existing production technologies. However, substantial allocative inefficiency (only 70.90% mean efficiency, only 11.78% of farms achieve allocative optimality) dominates the efficiency profile, indicating that primary constraints are managerial—specifically, resource allocation decisions insufficiently responsive to market price signals. Scale efficiency analysis identified a critical structural finding: 30.89% of farms operate under increasing returns to scale, possessing expansion potential currently unrealized. This proportion is markedly higher in larger farms (47.69% of Category 3 farms), indicating that consolidation policies could encounter favorable conditions among more commercially oriented producers. Conversely, 48.07% of Category 1 farms operate under diminishing returns, trapped at suboptimal size by land scarcity constraints. Potential cost savings of 74.29 million Egyptian pounds at the governorate level represent the quantified magnitude of efficiency improvement opportunity. These savings derive primarily from: (1) mechanized operations optimization (54.09% of total), particularly tractor scheduling and pest control protocols; (2) improved input allocation (24.06% of potential savings); and (3) labor optimization (21.85%). Notably, the savings potential exists without requiring capital investment in new technology or land acquisition—purely through better management of existing resources.

Author Contributions

Naglaa Elsaïd Ahmed Shaban: Conceptualization, methodology, field research supervision, project coordination, data collection oversight, statistical analysis, writing—original draft, writing—review and editing, and corresponding author responsibilities; Hanan Mohamed Mahmoud Bahgat: Data collection, data curation, database development, data validation, data quality assurance, exploratory statistical analysis, interpretation of results, and writing—review and editing; Mona Fouad Mohamed Ismail Elkashif: Literature review, data synthesis, interpretation of results, discussion, development of policy recommendations, writing—original draft, writing—review and editing, and visualization (figures and tables). All authors have reviewed and approved the final manuscript version and accept responsibility for its content.

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Declarations

Conflict of Interest: The authors declare no conflict of interest. This research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability: Data will be made available on reasonable request to corresponding author.

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