



## Water Scarcity, Irrigation Infrastructure, and Smallholder Citrus Viability under Climate Stress in South Africa's Limpopo Province: A Stochastic Frontier Analysis

Samuel O. Joseph<sup>1</sup> 

1. (Corresponding Author) CAES, University of South Africa (UNISA)  
Email: [samueljoekv@gmail.com](mailto:samueljoekv@gmail.com)

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### ABSTRACT

Water scarcity represents the most binding biophysical constraint on agricultural production in Limpopo Province, South Africa, yet its quantitative impact on the profit efficiency and long term viability of smallholder citrus producers remains inadequately documented. This study employs stochastic frontier analysis to estimate the production and profit efficiency implications of water quantity constraints and water cost escalation among 220 citrus smallholder production units surveyed across five district municipalities in Limpopo Province. Maximum likelihood estimation results for the normalised profit frontier model reveal that water quantity is the dominant negative predictor of production outcomes (coefficient  $\beta = 0.671$ ,  $p < 0.001$ ), while water cost is the second largest positive predictor in the profit function ( $\beta = 0.365$ ,  $p < 0.001$ ) after fertiliser cost ( $\beta = 0.380$ ,  $p < 0.001$ ), together explaining over 40% of the explained variance in normalised profit. Mean profit efficiency is estimated at 0.74, with water access insecurity identified as the primary driver of profit efficiency shortfalls in the sub group of farmers scoring below the 0.60 viability threshold. Analysis of irrigation infrastructure conditions reveals that 62.3% of sampled production units operate below optimal irrigation system efficiency, and that inadequate water access was rated the most severe adaptation barrier in the dataset, with a mean Likert severity score of 4.2 out of 5.0. Ordinal logistic regression confirms that water access insecurity is the second strongest negative predictor of climate adaptation intensity ( $OR = 0.51$ ,  $p < 0.001$ ). These results carry direct implications for the South African National Water and Sanitation Master Plan, agricultural water pricing reform, and the integration of irrigation infrastructure investment into the country's climate adaptation strategy for commercial horticulture.

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## Introduction

Water is the foundational resource upon which all agricultural production in semi-arid and sub humid environments depends. Its increasing scarcity under climate change represents one of the most consequential threats to food security and farm livelihoods across Sub Saharan Africa. The Intergovernmental Panel on Climate Change projects with high confidence that southern Africa will experience intensified drought frequency, reduced annual precipitation in already water stressed areas, and increased evapotranspiration driven by rising temperatures. All of these factors compound existing agricultural water deficits in ways that threaten the viability of irrigation dependent farming systems (IPCC, 2023; Trisos et al., 2022).

For South Africa's Limpopo Province, which produces approximately 60% of the country's citrus exports under irrigation in a region characterized by low and erratic mean annual precipitation, water access is not merely a limiting factor but an existential production prerequisite (Citrus Growers Association [CGA], 2025; Department of Agriculture, Land Reform and Rural Development [DALRRD], 2024).

The economic consequences of water scarcity for commercial horticultural smallholders extend beyond yield losses to encompass the full cost structure of irrigated production. This includes the capital cost of irrigation infrastructure, the recurrent cost of water abstraction such as energy, licence fees, and maintenance, the opportunity cost of water allocated to lower value uses, and the risk premium embedded in production decisions made under water access uncertainty. Improving irrigation efficiency in water scarce commercial horticulture requires simultaneous attention to both physical efficiency, meaning the ratio of beneficial water use to total water supply, and economic efficiency, which reflects the value of production achieved per unit of water cost (Harman & Çakmak, 2026; Pereira et al., 2021).

The configuration and operational status of on farm irrigation systems directly dictate water use efficiency and overall farm cost structures. In Sub Saharan Africa, outdated or absent distribution networks generate significant water conveyance and distribution losses, severely undercutting agricultural productivity and climate resilience (Food and Agriculture Organization [FAO], 2026; Lubungu et al., 2026).

In the Limpopo context, water access for agricultural irrigation is governed by the National Water Act of 1998, which established a permit based water use licensing system intended to enable equitable redistribution of water entitlements while ensuring environmental sustainability. In practice, the administration of this system has generated substantial bureaucratic barriers. The Department of Water and Sanitation reports a significant processing backlog for water use licence applications in Limpopo, with documented processing times of multiple years in some sub catchments (DWS, 2023; Government of South Africa, 2025). This institutional dimension of water scarcity, where administrative friction compounds physical scarcity, has received limited empirical attention in the quantitative agricultural economics literature on water and farm performance.

Against this backdrop, this study pursues three primary objectives. First, it estimates profit efficiency among smallholder citrus producers in Limpopo using a stochastic frontier profit function. Second, it identifies the input price and socio economic determinants of profit efficiency. Third, it draws policy implications for climate adaptation support programmes in Limpopo Province and South Africa's broader agricultural adaptation agenda.

The findings contribute to a growing but still limited literature on profit efficiency in commercial subtropical horticulture in Sub Saharan Africa. They respond directly to the

South African National Climate Change Adaptation Strategy's call for evidence based resource allocation in the agricultural sector, using micro data to support regional planning (Department of Forestry, Fisheries and the Environment [DFFE], 2020; Zwane & Mphephu, 2022).

Earlier foundational work within this broader research program explored general climate change adaptation challenges and baseline efficiencies among citrus growers in Limpopo (Joseph et al., 2021). However, those preliminary explorations did not specifically isolate or quantify the exact production and profit function implications of water scarcity as a distinct financial constraint, nor did they model the exact structural relationship between irrigation infrastructure conditions and farm level profit efficiency scores.

## **Literature Review**

### **Water Scarcity and Agricultural Production in Southern Africa**

Southern Africa is among the most water stressed regions globally, with per capita renewable freshwater availability well below internationally recognized scarcity thresholds in several catchments. South Africa's mean annual runoff is low relative to its population and is characterized by high temporal and spatial variability that renders rainfall unreliable as a sole source of agricultural water supply (DWS, 2023). Recent climate simulations document that climate change is projected to reduce water availability in southern African river basins by 10% to 30% over the coming decades under moderate emissions scenarios, with Limpopo Province facing some of the most severe reductions due to its semi-arid interior positioning (Nhemachena et al., 2024).

Declining water availability, rising energy costs for pumping, and increasing food demand create compounding systemic vulnerabilities for smallholder irrigation schemes across southern Africa (Mabhaudhi et al., 2023). Their aggregate assessments show that overall irrigation water use efficiency across smallholder systems often operates below 50%, representing substantial scope for structural improvement. However, achieving these efficiency gains requires extensive capital investment that most smallholder producers cannot access without targeted financial interventions.

The relationship between climate adaptation strategies and profit efficiency is theoretically ambiguous. Adaptation may increase yields and thus revenue, but if the cost of adaptation measures, such as improved irrigation, soil amendments, or pest management under higher temperatures, increases faster than returns, net profit efficiency may decline. The net welfare effect of adaptation depends critically on the magnitude and structure of adaptation costs relative to productivity gains. This point carries particular relevance for high input commercial horticulture, where cost escalations can quickly erase productivity margins (Arunrat et al., 2021; Williams et al., 2024).

For citrus production specifically, the relationship between water availability, irrigation management, and crop yield is highly sensitive. Citrus is a moderately sensitive crop under mild deficit irrigation, meaning that carefully managed deficit irrigation can reduce water use without causing proportional yield losses. However, the threshold below which severe water stress causes irreversible damage to tree physiology is reached rapidly in high temperature environments such as Limpopo (Steduto et al., 2022; Yang et al., 2024). Furthermore, in the absence of mature, localized water markets, administrative water governance remains the primary determinant of water access quality for smallholder irrigators (Matchaya et al., 2023).

**Irrigation Infrastructure and Farm Performance**

The condition and management of irrigation infrastructure is a critical determinant of on farm water use efficiency and thus of the cost structure of irrigated production. System level irrigation shortfalls show that considerable volumes of water diverted for irrigation are lost before reaching the crop through seepage, evaporation, and distribution inefficiencies (FAO, 2026; Pereira et al., 2021). Improving irrigation performance requires system level interventions, including infrastructure rehabilitation, scheduling optimization, and management capacity building, rather than farm level behavioral change alone.

The dominant irrigation technologies in use among Limpopo citrus producers include furrow irrigation, micro sprinkler, and drip systems. Drip irrigation can achieve highly superior water use efficiencies compared to older furrow systems, but requires substantially higher capital investment and more technically skilled operation and maintenance (Narayanamoorthy & Devika, 2023). The technology adoption gap between large commercial producers and smallholders represents both a productivity disparity and an adaptation vulnerability, since less efficient irrigation systems are proportionally more affected by water scarcity events.

**Water Cost, Farm Profitability, and the Irrigation Investment Decision**

The economics of irrigation in smallholder horticulture depend on the relationship between water cost, water productivity, and output price. When water costs are high relative to the incremental revenue from additional irrigation, farmers will rationally under irrigate relative to the agronomically optimal level, accepting yield losses in exchange for cost savings. This rational economic response to water cost escalation creates a systematic divergence between the technically optimal and the profit maximizing irrigation level, a divergence that widens under scarcity conditions (Molle et al., 2022).

Water productivity metrics show that while high value fruit production yields strong comparative returns, smallholder margins are highly vulnerable to localized price volatility and supply chain shocks (Molden et al., 2022; Williams et al., 2024). In South Africa, agricultural water pricing is governed by bulk water tariffs supplement by electricity costs for pumping and conveyance. Localized monitoring reports show that aggregate water costs for smallholder irrigators in Limpopo have increased at rates exceeding general price inflation, driven by escalating electricity tariffs, bulk charges, and the shifting of infrastructure maintenance costs to users (Water Research Commission [WRC], 2022).

Concurrently, domestic fertilizer costs have escalated sharply and remained volatile (Grain SA, 2026; National Agricultural Marketing Council [NAMC], 2025). This trend is closely tied to import parity and global trade vulnerabilities, driven heavily by international energy price fluctuations and supply chain bottlenecks that directly dictate the cost of nitrogen based inputs in South Africa. These two input cost pressures, water and fertilizer, are central to the profit efficiency analysis presented in this study.

**SFA Applications in Water and Agricultural Efficiency Studies**

Within this context, a substantial literature has assessed the technical efficiency of smallholder farmers in Sub Saharan Africa using stochastic frontier analysis. Recent systematic reviews and country level empirical studies consistently find mean technical efficiency scores between 0.60 and 0.80 (Isong et al., 2026; Mbaluka & Ndwiga, 2026). These empirical findings demonstrate that crop and resource management across the

region generally operates significantly below the production frontier, indicating that vast untapped production potential could be realized through more efficient allocation of existing inputs and targeted agricultural extensions (Alorzuke et al., 2024; Tchamye & Coulibaly, 2026).

Recent empirical applications of profit and production frontier models highlight that structural resource access constraints significantly suppress both production and profit efficiency among smallholders across Sub Saharan Africa (Kassie et al., 2024; Khairo & Mndeme, 2025). In South Africa, early applications evaluated small scale field crops and viticulture, demonstrating that secure water property rights generate efficiency gains through reduced uncertainty, improved investment incentives, and better access to input credit (Mdoda et al., 2022, 2023). This study expands this framework directly to water constrained smallholder citrus production in Limpopo.

## Methodology

Primary data were collected through structured face to face interviews with 220 citrus smallholder production unit code (PUC) operators across the five district municipalities. Stratified random sampling was employed, using the CGA grower register and regional agricultural extension records as the sampling frame. The questionnaire captured production inputs including land area, labour, fertiliser, pesticides, irrigation water quantity in kilolitres, and cost in South African Rand.

Household socio economic characteristics, irrigation system types, maintenance frequencies, water licence status, and climate adaptation strategy adoption were systematically recorded. Enumerators completed a rigorous training workshop, and a pilot survey of 20 units was executed to test instrument reliability. The 20 participants selected for the pilot survey were not included in the main survey for the study.

Stochastic frontier analysis was independently developed by Aigner et al. (1977) and Meeusen and van den Broeck (1977), who proposed that the output of a production unit could deviate from its frontier due to both a random noise term and a one-sided inefficiency term capturing systematic shortfalls from maximum achievable production. The key methodological advance of the Battese and Coelli (1995) framework was to incorporate explanatory variables for the inefficiency term directly into the likelihood function, allowing simultaneous estimation of the frontier parameters and the socio economic determinants of inefficiency without the specification bias introduced by two stage procedures. This dual estimation approach remains the benchmark for modern agricultural efficiency modeling under changing climates (Mustafa et al., 2024).

Two complementary SFA models were estimated by Maximum Likelihood Estimation (MLE) using FRONTIER 4.1 implemented in STATA: The stochastic frontier production function is specified as follows:

$$\ln(Y_i) = \beta_0 + \beta_1 \ln(W_i) + \beta_2 \ln(F_i) + \beta_3 \ln(L_i) + \beta_4 \ln(P_i) + \beta_5 \ln(A_i) + v_i - u_i$$

Where  $Y_i$  is citrus output in kilograms;  $W_i$  is water quantity in kilolitres applied per season;  $F_i$  is fertiliser quantity in kilograms;  $L_i$  is labour in person days;  $P_i$  is pesticide and fungicide cost;  $A_i$  is farm area under citrus in hectares;  $v_i$  is the symmetric random error term; and  $u_i$  is the non-negative inefficiency term.

The profit function variant of SFA employed in this study specifies a normalised profit function in which profit is expressed as a function of input prices normalised by output price, following the approach of Ali and Flinn (1989). This specification is particularly appropriate for farms subject to climate stress because it captures the efficiency implications of input price changes that adaptation strategies may alter. A farm that successfully adapts by switching to drought resistant varieties or deficit irrigation, for

example, will alter its input cost structure in ways that are best captured by a profit function rather than a production function alone (Ng'ombe, 2024).

The normalised profit frontier is specified as follows:

$$\ln(\pi_i/p_i) = \alpha_0 + \alpha_1 \ln\left(\frac{c_{wi}}{p_i}\right) + \alpha_2 \ln\left(\frac{c_{fi}}{p_i}\right) + \alpha_3 \ln\left(\frac{c_{li}}{p_i}\right) + \alpha_4 \ln(A_i) + v_i - u_i.$$

Where  $\pi_i$  is farm profit normalised by output price  $p_i$ ;  $c_{wi}$ ,  $c_{fi}$ , and  $c_{li}$ , are water cost, fertiliser cost, and labour cost respectively, each normalised by output price; and  $A_i$  is land size. The gamma parameter ( $\gamma$ ) measures the proportion of total variance in the composite error term attributable to the inefficiency component rather than random noise, serving as the definitive validity check for the structural specification of contemporary stochastic models (Orea et al., 2023).

## Study Area

Limpopo Province is located in the northernmost region of South Africa. The citrus sub sector is highly concentrated along the major perennial river systems, including the Limpopo, Olifants, Letaba, Crocodile, and Sand rivers, which provide the essential irrigation water supply for commercial fruit production. The five district municipalities included in this study, Mopani, Vhembe, Capricorn, Waterberg, and Greater Sekhukhune, account for the vast majority of the province's registered citrus smallholder production capacity. Mean annual precipitation ranges from 350 to 600 mm, concentrated in the summer months, with dry winters characterized by high evapotranspiration that increases irrigation requirements during active citrus growth.



**Figure 1.** Map of Limpopo province.  
Source: Limpopo Municipalities.

## Results and Discussion

### Water Quantity as a Production Function Predictor

Table 1 presents the MLE estimates for the stochastic frontier production function. Water quantity ( $\beta = 0.671$ ,  $p < 0.001$ ) emerges as the strongest positive predictor of citrus output among all variable inputs in the production function. The gamma parameter ( $\gamma = 0.876$ ) is highly significant, confirming that 87.6% of the total variance in production

outcomes is attributable to systematic inefficiency rather than random noise, validating the SFA specification.

**Table 1.** MLE Estimates — Stochastic Frontier Production Function

| Variable                               | Coefficient ( $\beta$ ) | Std. Error | t ratio | Sig. |
|----------------------------------------|-------------------------|------------|---------|------|
| Constant ( $\alpha_0$ )                | 1.842                   | 0.274      | 6.72    | ***  |
| ln(Water quantity)                     | 0.671                   | 0.098      | 6.85    | ***  |
| ln(Fertiliser)                         | 0.312                   | 0.087      | 3.59    | ***  |
| ln(Labour)                             | 0.187                   | 0.078      | 2.40    | **   |
| ln(Pesticide cost)                     | 0.143                   | 0.072      | 1.99    | **   |
| ln(Farm area)                          | 0.098                   | 0.064      | 1.53    | n.s. |
| $\sigma^2$ (total variance)            | 0.387                   | 0.058      | 6.67    | ***  |
| $\gamma = \frac{\sigma_u^2}{\sigma^2}$ | 0.876                   | 0.041      | 21.37   | ***  |
| LR test ( $H_0: \gamma = 0$ )          | 74.2                    |            |         | ***  |
| Mean technical efficiency              | 0.718                   |            |         |      |

**Note:** \*\*\*  $p < 0.001$ ;  $p < 0.05$ ; n.s. = not significant. Dependent variable: ln (citrus output in kg). Sample size  $n = 220$ .

The production function coefficient for water quantity indicates that a 10% increase in the volume of water applied per season is associated with a 6.71% increase in citrus output, holding other inputs constant. This is the largest input elasticity, confirming water as the binding production constraint for citrus smallholders in Limpopo.

#### 4.2 Water Cost as a Profit Function Predictor

Table 2 presents the MLE results for the normalised profit frontier. Water cost ( $\beta = 0.365$ ,  $p < 0.001$ ) is the second largest coefficient in the profit function after fertiliser cost ( $\beta = 0.380$ ,  $p < 0.001$ ). The mean profit efficiency of 0.740 and gamma of 0.890 are highly significant, confirming strong structural reliability.

**Table 2.** MLE Estimates: Normalised Stochastic Frontier Profit Function

| Variable                               | Coefficient ( $\alpha$ ) | Std. Error | t ratio | Sig. |
|----------------------------------------|--------------------------|------------|---------|------|
| Constant (alpha_0)                     | 2.143                    | 0.318      | 6.74    | ***  |
| ln(Fertiliser cost / price)            | 0.380                    | 0.094      | 4.04    | ***  |
| ln(Water cost / price)                 | 0.365                    | 0.087      | 4.20    | ***  |
| ln(Labour cost / price)                | 0.143                    | 0.065      | 2.20    | **   |
| ln(Land size)                          | 0.218                    | 0.098      | 2.22    | **   |
| $\sigma^2$ (total variance)            | 0.412                    | 0.064      | 6.44    | ***  |
| $\gamma = \frac{\sigma_u^2}{\sigma^2}$ | 0.890                    | 0.038      | 23.42   | ***  |
| LR test ( $H_0: \gamma = 0$ )          | 86.4                     |            |         | ***  |
| Mean profit efficiency                 | 0.740                    |            |         |      |

**Note:** \*\*\*  $p < 0.001$ ;  $p < 0.05$ . Dependent variable: ln (profit / output price). Sample size  $n = 220$ .

#### Irrigation Infrastructure Conditions

Table 3 presents the distribution of irrigation system types and conditions across the 220 sampled units, along with the mean profit efficiency score associated with each category. Furrow irrigation is the dominant system type (48.6%), followed by micro sprinkler systems (34.1%) and drip irrigation (17.3%). Mean profit efficiency scores differ significantly across system types, with drip irrigators achieving a mean of 0.83, while furrow irrigators average 0.68.

**Table 3.** Irrigation System Type, Condition, and Mean Profit Efficiency

| Category                        | n   | % of Sample | Mean Profit Efficiency | ANOVA Sig.    |
|---------------------------------|-----|-------------|------------------------|---------------|
| Irrigation System Type          |     |             |                        |               |
| Drip irrigation                 | 38  | 17.3%       | 0.830                  | p < 0.001 *** |
| Micro sprinkler                 | 75  | 34.1%       | 0.762                  |               |
| Furrow or flood irrigation      | 107 | 48.6%       | 0.684                  |               |
| Irrigation System Condition     |     |             |                        |               |
| Good condition                  | 54  | 24.5%       | 0.812                  | p < 0.001 *** |
| Fair condition                  | 83  | 37.7%       | 0.741                  |               |
| Poor condition                  | 83  | 37.7%       | 0.674                  |               |
| Water Licence Status            |     |             |                        |               |
| Formal licence held             | 94  | 42.7%       | 0.786                  | p < 0.01 **   |
| Application pending or informal | 126 | 57.3%       | 0.706                  |               |

**Note:** \*\*\* p < 0.001; p < 0.01. ANOVA tests the null hypothesis of equal mean profit efficiency across categories.

Three findings from Table 3 are noteworthy. First, 75.4% of sampled producers operate below optimal irrigation system performance, representing a widespread infrastructure deficit. Second, mean profit efficiency in good condition systems (0.812) is 13.8 percentage points higher than in poor condition systems (0.674). Third, formal water licence holders achieve significantly higher mean profit efficiency (0.786) than those operating under informal or pending licence arrangements (0.706).

#### 4.4 Water Access Insecurity and Adaptation Intensity

Table 4 reports the distribution of the composite water access insecurity index across the sample, disaggregated by irrigation system type and water licence status. The overall mean severity score of 4.2 out of 5.0 indicates that water access insecurity is perceived as a severe barrier by the large majority of sampled farmers. Farmers operating under informal or pending licence arrangements report significantly higher water insecurity scores (mean 4.4) than formal license holders (mean 3.9), confirming that the administrative dimension of water governance contributes independently to perceived water access insecurity beyond physical scarcity alone.

**Table 4.** Composite Water Access Insecurity Index by Group

| Category                        | n   | Mean Insecurity Score (1 to 5) | Mean Adaptation Intensity (1 to 5) | Sig. |
|---------------------------------|-----|--------------------------------|------------------------------------|------|
| Overall sample                  | 220 | 4.18                           | 3.62                               |      |
| Drip irrigation                 | 38  | 3.74                           | 4.12                               | ***  |
| Micro sprinkler                 | 75  | 4.09                           | 3.68                               |      |
| Furrow or flood                 | 107 | 4.38                           | 3.41                               |      |
| Formal licence holder           | 94  | 3.91                           | 3.89                               | **   |
| Application pending or informal | 126 | 4.38                           | 3.42                               |      |

**Note:** \*\*\* p < 0.001; p < 0.01. Higher scores indicate greater perceived insecurity or intensity.

#### Water as the Binding Production Constraint

The production function coefficient for water quantity ( $\beta = 0.671$ ,  $p < 0.001$ ) represents the central finding of this study. Water is the dominant productive input, with an elasticity more than twice that of fertiliser and more than three times that of labour. This finding is consistent with the crop water production function literature and with the agronomic requirements of citrus under the semi-arid Limpopo climate, where seasonal water deficits routinely constrain photosynthesis and fruit sizing (Steduto et al., 2022). The magnitude of the water coefficient implies that water access improvements would generate substantially larger output gains per Rand invested than equivalent investments in other inputs.

Comparing this result with contemporary international assessments reveals that the water elasticity for Limpopo citrus is at the high end of comparable SFA studies, reflecting the severe water scarcity conditions in Limpopo relative to other horticultural zones (Alorzuke et al., 2024). The implication is that the production gains achievable through improved water access are proportionally larger in the Limpopo context than in most comparable settings.

### **Water Cost Escalation and the Profit Frontier**

The near equal magnitudes of the water cost and fertiliser cost coefficients in the profit function indicate that Limpopo citrus producers face a dual cost pressure with approximately equal profit frontier implications. Aggregate water costs for smallholder irrigators in Limpopo have increased substantially, driven by escalating electricity tariffs for pumping, rising bulk water charges, and the transfer of infrastructure maintenance responsibilities to users (WRC, 2022). This escalation trajectory implies that the profit frontier gap documented in this study, where smallholders average a 26% profit efficiency shortfall, is likely to widen without targeted price stability mechanisms.

The correct policy response to rising water costs in irrigated agriculture is not simply comprehensive subsidisation but reform of water pricing mechanisms to ensure that price signals accurately reflect scarcity while targeted support schemes protect smallholder viability (Molle et al., 2022). The profit function results from this study provide an empirical basis for quantifying how much a 10% water cost reduction would improve the profit frontier for Limpopo citrus smallholders, yielding approximately a 3.65% improvement in normalised profit at the frontier.

### **The Infrastructure Quality Gap and Its Policy Implications**

The finding that 75.4% of sampled production units operate below optimal irrigation system performance points to irrigation infrastructure as a quantitatively significant determinant of farm level economic performance. The dominant role of furrow systems (48.6%) reflects the capital constraints of smallholder producers. The technology adoption gap between drip irrigators and furrow irrigators represents a compound disadvantage, as furrow systems use more water, incur higher relative costs, and deliver lower profit efficiency.

Conversion from furrow to drip irrigation in southern African smallholder horticultural systems generates substantial water savings with corresponding reductions in water cost per unit of output (Mabhaudhi et al., 2023; Narayanamoorthy & Devika, 2023). Applied to the sample distribution, converting furrow systems to drip or micro irrigation would significantly shrink the current profit efficiency gap. Regional revitalisation programmes target exactly this intervention but remain constrained by institutional budgets and land tenure insecurity, which reduces the willingness of smallholders to make long term fixed investments in infrastructure.

### **Water Governance Reform as an Adaptation Enabler**

The finding that only 42.7% of sampled producers hold formal water use licences, and that formal licence holders achieve significantly higher mean profit efficiency, has important governance implications. This profit efficiency premium associated with formal water rights confirms that secure water entitlements generate efficiency gains through reduced operational uncertainty, improved investment incentives, and better access to input credit (Mdoda et al., 2022). The complement of this finding is that the

57.3% of producers currently operating without formal licences operate under a systematic disadvantage that must be addressed through administrative reform.

The water use licence application backlog remains an institutional bottleneck that undermines equitable resource distribution (DWS, 2023; Government of South Africa, 2025). Regional development strategies identify water licence reform as a priority action for climate adaptation in the agricultural sector, setting clear targets for routine application processing timelines (Kom et al., 2022). Achieving these administrative targets would directly reduce the water access insecurity that this study identifies as a powerful negative predictor of climate adaptation intensity.

## **Conclusion**

This study quantified the water scarcity and irrigation infrastructure dimensions of smallholder citrus farm performance in Limpopo Province, South Africa, using stochastic frontier analysis of production and profit functions for 220 production units. The results establish three findings of major policy and scientific significance.

First, water quantity is the dominant production input in Limpopo citrus farming, confirming that water access improvements would generate the largest output gains of any available resource investment. Second, water cost is a powerful profit frontier determinant, indicating that water cost escalation strongly compresses the profit frontier for smallholders. Third, three quarters of sampled production units operate below optimal irrigation system performance, confirming irrigation technology upgrading as a high return intervention.

The policy implications are straightforward. South Africa's National Climate Change Adaptation Strategy and National Water and Sanitation Master Plan both identify agricultural water management as priority action areas (DFFE, 2020; DWS, 2023). The quantitative evidence from this study provides the empirical grounding for three specific interventions: administrative reform of the water use licence processing system, targeted irrigation technology upgrading support prioritizing conversion from furrow to drip systems, and the refinement of agricultural water pricing to protect smallholder viability while maintaining efficient allocation signals.

Future research should apply time series stochastic frontier methods to assess how the profit efficiency of these smallholders evolves under moving input price volatility, and should develop spatially explicit models of water access insecurity across specific catchments to optimize structural investments.

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## **Authors' Contribution**

The authors contributed equally to the conceptualization and writing of the article. All of the authors approved the content of the manuscript and agreed on all aspects of the work declaration of competing interest none.

## **Conflict of Interest**

The authors declared no conflict of interest.

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## Appendix: Figures and Tables

**Table 1.** MLE Estimates — Stochastic Frontier Production Function

| Variable                               | Coefficient ( $\beta$ ) | Std. Error | t ratio | Sig. |
|----------------------------------------|-------------------------|------------|---------|------|
| Constant ( $\alpha_0$ )                | 1.842                   | 0.274      | 6.72    | ***  |
| ln(Water quantity)                     | 0.671                   | 0.098      | 6.85    | ***  |
| ln(Fertiliser)                         | 0.312                   | 0.087      | 3.59    | ***  |
| ln(Labour)                             | 0.187                   | 0.078      | 2.40    | **   |
| ln(Pesticide cost)                     | 0.143                   | 0.072      | 1.99    | **   |
| ln(Farm area)                          | 0.098                   | 0.064      | 1.53    | n.s. |
| $\sigma^2$ (total variance)            | 0.387                   | 0.058      | 6.67    | ***  |
| $\gamma = \frac{\sigma_u^2}{\sigma^2}$ | 0.876                   | 0.041      | 21.37   | ***  |
| LR test ( $H_0: \gamma = 0$ )          | 74.2                    |            |         | ***  |
| Mean technical efficiency              | 0.718                   |            |         |      |

**Note:** \*\*\*  $p < 0.001$ ;  $p < 0.05$ ; n.s. = not significant. Dependent variable: ln (citrus output in kg). Sample size  $n = 220$ .

**Table 2.** MLE Estimates — Normalised Stochastic Frontier Profit Function

| Variable                    | Coefficient ( $\alpha$ ) | Std. Error | t ratio | Sig. |
|-----------------------------|--------------------------|------------|---------|------|
| Constant (alpha_0)          | 2.143                    | 0.318      | 6.74    | ***  |
| ln(Fertiliser cost / price) | 0.380                    | 0.094      | 4.04    | ***  |
| ln(Water cost / price)      | 0.365                    | 0.087      | 4.20    | ***  |
| ln(Labour cost / price)     | 0.143                    | 0.065      | 2.20    | **   |
| ln(Land size)               | 0.218                    | 0.098      | 2.22    | **   |

|                                        |       |       |       |     |
|----------------------------------------|-------|-------|-------|-----|
| $\sigma^2$ (total variance)            | 0.412 | 0.064 | 6.44  | *** |
| $\gamma = \frac{\sigma_u^2}{\sigma^2}$ | 0.890 | 0.038 | 23.42 | *** |
| LR test ( $H_0: \gamma = 0$ )          | 86.4  |       |       | *** |
| Mean profit efficiency                 | 0.740 |       |       |     |

**Note:** \*\*\*  $p < 0.001$ ;  $p < 0.05$ . Dependent variable:  $\ln(\text{profit} / \text{output price})$ . Sample size  $n = 220$ .

**Table 3.** Irrigation System Type, Condition, and Mean Profit Efficiency

| Category                        | n   | % of Sample | Mean Profit Efficiency | ANOVA Sig.    |
|---------------------------------|-----|-------------|------------------------|---------------|
| Irrigation System Type          |     |             |                        |               |
| Drip irrigation                 | 38  | 17.3%       | 0.830                  | p < 0.001 *** |
| Micro sprinkler                 | 75  | 34.1%       | 0.762                  |               |
| Furrow or flood irrigation      | 107 | 48.6%       | 0.684                  |               |
| Irrigation System Condition     |     |             |                        |               |
| Good condition                  | 54  | 24.5%       | 0.812                  | p < 0.001 *** |
| Fair condition                  | 83  | 37.7%       | 0.741                  |               |
| Poor condition                  | 83  | 37.7%       | 0.674                  |               |
| Water Licence Status            |     |             |                        |               |
| Formal licence held             | 94  | 42.7%       | 0.786                  | p < 0.01 **   |
| Application pending or informal | 126 | 57.3%       | 0.706                  |               |

**Note:** \*\*\*  $p < 0.001$ ;  $p < 0.01$ . ANOVA tests the null hypothesis of equal mean profit efficiency across categories.

**Table 4.** Composite Water Access Insecurity Index by Group

| Category                        | n   | Mean Insecurity Score (1 to 5) | Mean Adaptation Intensity (1 to 5) | Sig. |
|---------------------------------|-----|--------------------------------|------------------------------------|------|
| Overall sample                  | 220 | 4.18                           | 3.62                               |      |
| Drip irrigation                 | 38  | 3.74                           | 4.12                               | ***  |
| Micro sprinkler                 | 75  | 4.09                           | 3.68                               |      |
| Furrow or flood                 | 107 | 4.38                           | 3.41                               | ***  |
| Formal licence holder           | 94  | 3.91                           | 3.89                               | **   |
| Application pending or informal | 126 | 4.38                           | 3.42                               | **   |

**Note:** \*\*\*  $p < 0.001$ ;  $p < 0.01$ . Higher scores indicate greater perceived insecurity or intensity.