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The Impact of Innovative Irrigation System Use on Crop Yield Among Smallholder Farmers in Mbombela Local Municipality, South Africa

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Abstract

Smallholder farmers play a pivotal role in food production and rural development in South Africa. However, their productivity is often constrained by reliance on rainfed agriculture and the underutilisation of innovative technologies such as irrigation systems. This study assessed the impact of innovative irrigation system (IIS) use on crop yield among smallholder crop farmers (SCFs) in Mbombela Local Municipality. Focusing on vegetables and agronomic crop producers. Primary data was collected from 308 SCFs using a structured questionnaire through descriptive and cross-sectional survey design. A Probit regression model was used to estimate the probability of using an IIS, while Propensity Score Matching (PSM) estimated the average treatment effect on the treated (ATT) in terms of yield. The results reveal that age group (p = 0.080), main source of off-farm income (p = 0.042), and high input costs (p = 0.006) significantly determined IIS use. Impact analysis confirms that users of IISs achieved higher yields than non-users. The study concludes that innovative irrigation technologies can significantly improve smallholder productivity. It recommends that policymakers and government bodies prioritise scaling up access to IIS, introduce subsidies or low-interest financing schemes to alleviate the IIS usage costs, and strengthen extension services to provide targeted training on irrigation scheduling, system maintenance, and water-use efficiency.

Keywords: innovative irrigation system; crop yield; crop farmers

Academic Editor: Claudio Bellia

Received: 25 June 2025
Revised: 2 August 2025
Accepted: 12 August 2025
Published: 16 August 2025

Citation: Monamodi, P.; Ndoro, J.T.; Matiwane, M.B. The Impact of Innovative Irrigation System Use on Crop Yield Among Smallholder Farmers in Mbombela Local Municipality, South Africa. *Agriculture* **2025**, *15*, 1755. https://doi.org/10.3390/agriculture15161755

1. Introduction

Smallholder farming plays a critical role in food production, rural development, and livelihood support across many developing countries, including South Africa (SA) [1]. According to Ogundipe et al. [2], smallholder farming remains central to poverty reduction, food security enhancement, and rural employment creation. Furthermore, smallholder farmers contribute significantly to agricultural output, particularly in rural areas where farming remains the main source of income [3–5]. It is estimated that smallholder farmers produce more than 80% of the food consumed in developing countries [6,7].

Recognising the importance of smallholder agriculture for rural development and food security, South Africa's National Development Plan (NDP) Vision 2030 identifies smallholder farming as a key driver of rural transformation. The NDP highlights its potential to positively impact the livelihoods of over 370,000 people living in communal areas [8]. This vision is further supported by the South African government's commitment to the sector, evidenced by the allocation of more than ZAR 2 billion in recent years towards targeted agricultural development programmes. This positions smallholder farmers at the centre of efforts to achieve sustainable food and nutrition security [9]. As noted by the Food and Agriculture Organisation (FAO) [10], the success of the 2030 Agenda for Sustainable Development is closely linked to the smallholder farming sector, particularly in relations to Sustainable Development Goals (SDGs) 1 and 2, which aim to eradicate poverty and hunger while ensuring sustainable food security.

Despite these contributions of smallholder farming and policy-level support, many smallholder farmers in SA continue to face low crop productivity. This is largely due to persistent challenges such as erratic rainfall, limited access to modern agricultural technologies, and inadequate production resources [11–14]. In Sub-Saharan Africa, agriculture is predominantly smallholder-based and largely rainfed, which places household and national food security at significant risk, especially during periods of drought [15].

Among the proposed solutions to these challenges, innovative irrigation systems (IISs) are increasingly recognised as vital technologies for improving water-use efficiency and crop productivity in developing countries. This is particularly relevant for economies that remain strongly agro-based and aim to meet both food security and development goals [16,17]. For example, research by Burney et al. [18], Fereres and Connor [19], and Postel et al. [20] has demonstrated that drip irrigation systems significantly improve water-use efficiency and crop productivity compared to conventional irrigation methods.

However, the utilisation of such systems remains relatively low in rural areas due to technological, socio-economic, and structural barriers [2,21,22]. In this study, IISs refer to modern water delivery methods such as drip irrigation, which delivers water directly to the root zone, and sprinkler irrigation, which disperses water over crops. These systems are designed to enhance water-use efficiency, boost crop yields, and promote sustainable agricultural production. This is in contrast to traditional irrigation methods such as flood irrigation, where water covers the entire field, or furrow irrigation, which channels water between crop rows. Many smallholders still rely on these conventional methods or entirely on rainfed agriculture [23–25]. Traditional irrigation often involves simple river diversion techniques used to grow subsistence crops [26].

While irrigation technologies can improve productivity, they also pose potential environmental risks, such as water depletion and soil salinisation, if not properly managed. A notable example is the Aral Sea ecological disaster, where large-scale unsustainable irrigation led to severe shrinkage of this water body in Central Asia [27]. Although the advantages of irrigation systems, particularly in terms of water-use efficiency and improved household welfare, are well documented, there remains limited empirical evidence on their direct impact on crop yields [28–30].

Most previous studies in West Africa, as well as in North-West Ethiopia, have focused on small-scale irrigation's contributions to household food security [31,32]. However, there are no empirical studies that specifically investigate the impact of IIS use on the crop yields of smallholder crop farmers (SCFs) in Mbombela Local Municipality, South Africa. Existing research, such as that by Singels et al. [33] and Jiba et al. [34], has largely focused on commercial crops like sugarcane or broader irrigation schemes and their impacts on livelihoods, rather than the specific effects of modern irrigation technologies on yield outcomes.

This study therefore aimed to investigate the impact of innovative irrigation systems (IISs) on crop yields among smallholder crop farmers in Mbombela Local Municipality. It was hypothesised that the use of IISs significantly increases crop yields for these farmers. Specifically, the study examined how drip and sprinkler irrigation systems affect the productivity of selected vegetable and agronomic crops cultivated by smallholder farmers in the area. The findings are intended to inform policymakers, extension services, and agribusiness stakeholders who seek to promote irrigation technologies and enhance agricultural productivity in resource-constrained contexts.

This paper is organised into five sections. Following this introduction, Section 2 outlines the methodology, including a description of the study area, research design and sampling approach, data collection and analysis methods, and ethical considerations. Section 3 presents and discusses the results, focusing on the socio-economic characteristics of the farmers, the types and use of IISs, and the impact of these systems on crop yields. Section 4 provides the conclusions and recommendations, while Section 5 discusses the broader implications and proposes directions for future research.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted in 16 villages within the Mbombela Local Municipality, located in Mpumalanga Province (MP), South Africa. Mbombela forms part of the Ehlanzeni District Municipality and serves as the capital city of Mpumalanga [35]. Geographically, the municipality is located in the north-eastern part of South Africa within the Lowveld sub-region, with approximate coordinates of 25.4° south and 30.9° east. It covers a total area of approximately 7152 km^2 [36]. The climate in Mbombela is classified as subtropical, characterised by hot, wet summers and mild, dry winters, with average annual rainfall ranging between 600 mm and 1000 mm [37].

According to Statistics South Africa [5], Mbombela has a population of approximately 818,925, the majority of whom are Black African (94.6%). IsiSwati is the most widely spoken language in the municipality. The area is predominantly rural, and agriculture remains the primary livelihood strategy for most households [38].

Smallholder farmers in the rural parts of the municipality primarily cultivate vegetables and other agronomic crops for both household consumption and income generation [39]. However, most of these farmers rely heavily on rainfed agriculture, which makes them highly vulnerable to climatic variability, particularly prolonged droughts and erratic rainfall patterns [40–42].

The main water sources in the area include rivers, boreholes, and communal reservoirs; however, access to these resources varies across villages. These agro-ecological conditions have a direct impact on the viability and effectiveness of irrigation technologies in the region [37]. Although the agricultural sector in Mbombela has experienced a gradual decline, the municipality still holds substantial potential for agricultural growth—particularly through the adoption of innovative farming practices aimed at addressing challenges such as limited arable land and climate change [43] (Figure 1).

2.2. Research Design and Sampling Procedure

This study employed a quantitative research approach, using a descriptive and cross-sectional design. Quantitative research allows for the collection of discrete numerical data, making it well-suited for the analysis of measurable variables [44]. According to Bauer et al. [45], quantitative methods are used to investigate social or human-related problems by testing hypotheses through the statistical analysis of variables.

The target population comprised smallholder crop farmers (SCFs) registered with the Department of Agriculture, Rural Development, Land and Environmental Affairs (DARDLEA) in Mbombela. A list of 1343 registered SCFs was obtained from the department, with the assistance of an extension officer, and served as the sampling frame. While this ensured access to active SCFs, it may have introduced selection bias, as it excluded unregistered smallholder farmers, thus potentially limiting the generalisability of the study's findings.

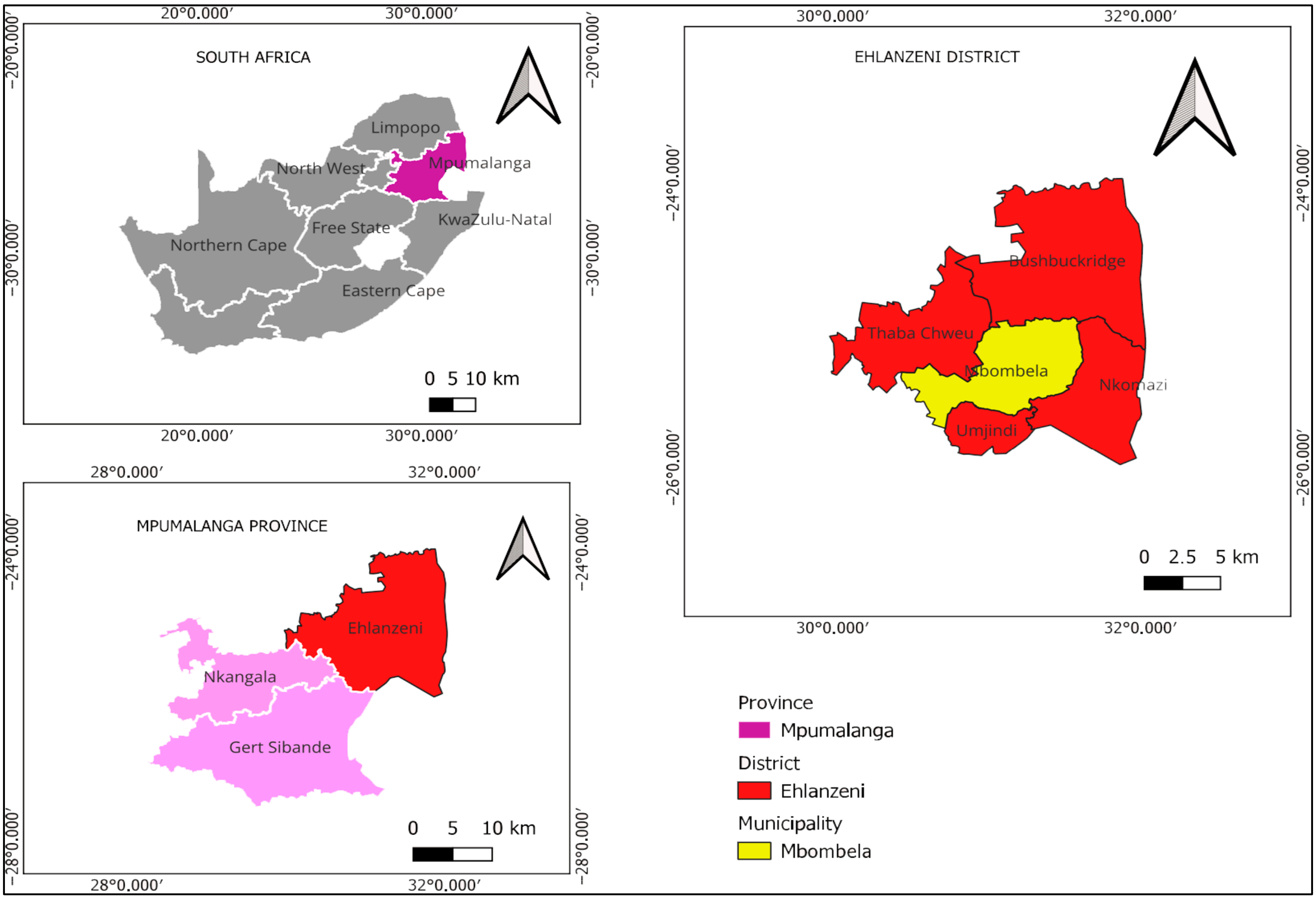

Figure 1. Location of Mbombela Local Municipality within Mpumalanga Province, north-eastern South Africa; author's own compilation using QGIS (2025).

To determine the appropriate sample size, Slovin's formula was used at a 5% margin of error and 95% confidence level:

$$n = \frac{N}{(1 + Ne^2)}$$

where n is the sample size, N is the population size (1343), and e is the margin of error, which is 5% divided by 100%, giving 0.05.

$$n = \frac{1343}{\left(1 + 1343\ (0.05)^2\right)} = 308$$

As a result, a total sample of 308 smallholder crop farmers was drawn, consisting of 130 users of innovative irrigation systems (IISs) and 178 non-users.

A systematic sampling technique was employed to select participants from the list. Each SCF in the sampling frame was assigned a unique number. Following the approach outlined by Mostafa and Ahmad [46], the sampling interval (K) was calculated as follows:

$$K = \frac{population\ size\ (N)}{sample\ size\ (n)} = \frac{1343}{308} = 4$$

According to Makwana et al. [47], the researcher must randomly select a starting point between 1 and K. In this case, a random number between 1 and 4 was drawn, and the number 3 was selected. Therefore, the third SCF on the list was chosen as the first respondent, and every fourth SCF thereafter was selected until a total of 308 participants had been reached.

2.3. Data Collection

This study utilised both primary and secondary data sources. Primary data were collected between August and September 2024 in Mbombela Local Municipality, Mpumalanga Province, using a structured and pre-tested questionnaire comprising closed-ended questions. The questionnaire was administered through face-to-face interviews conducted by trained enumerators who were proficient in the local language to ensure accurate interpretation and communication.

A pilot study was conducted prior to the main survey to refine the questionnaire in terms of clarity, relevance, and time efficiency. Data collection was supervised by the researcher to ensure quality control and to promptly address any challenges encountered in the field.

The questionnaire gathered both descriptive data on the socio-economic characteristics of the smallholder crop farmers (SCFs) and cross-sectional data on their use of innovative irrigation systems (IISs) and crop yields during the 2023/2024 cropping season.

Secondary data were sourced from departmental reports, government publications, academic books, peer-reviewed journal articles, and other reputable scholarly sources.

2.4. Data Analysis

Data collected through the questionnaire were first coded and entered into Microsoft Excel before analysis. Both descriptive and inferential statistics were applied using the Statistical Package for the Social Sciences (SPSS) version 29.0 and STATA version 14.0.

2.4.1. Descriptive Statistics

To achieve the study objectives, descriptive statistics including frequencies and percentages were used to analyse the socio-economic characteristics of the smallholder crop farmers (SCFs), as well as their use of and access to different types of innovative irrigation systems (IISs) in the study area.

2.4.2. Propensity Score Matching (PSM)

To assess the causal impact of IIS use on crop yield among SCFs during the 2023/2024 cropping season, Propensity Score Matching (PSM), as proposed by Rosenbaum and Rubin [48], was employed. PSM addresses the selection bias inherent in observational studies by matching treated (users) and control (non-users) groups with similar propensity scores, thereby reducing the influence of confounding variables [49].

Since the decision to adopt IISs is not random, but rather influenced by farmer-specific and structural characteristics, it introduces a self-selection process that may bias the comparison of crop yields between users and non-users.

Rosenbaum and Rubin [48] define PSM as a method for estimating treatment effects by comparing two groups (treated and control) that are similar in all observed covariates. In this study, the treated group consisted of SCFs using IIS, while the control group comprised those not using IIS. The procedure involved two key steps: estimating the probability of treatment (propensity score) using regression analysis and assessing the treatment effect on the outcome variable (crop yield) [50].

The propensity score represents the probability that a given SCF would adopt an IIS, conditional on a set of observed covariates. It is defined mathematically as

$$e(xi),\ (i = 1\ldots,N) \tag{1}$$

$$e(xi) = Pr(zi = 1|xi) \tag{2}$$

$$Pr(Zi, \ldots, X1, \ldots Xn) = \sum eNi = 1\{Xi\}\ Zi\{1 - e\{X\}\}\ 1 - Zi \tag{3}$$

where $zi = 1$ represents treatment; $zi = 0$ represents control; and xi represents the vector of observed covariates for the ith subject.

A Probit regression model was used to estimate the propensity scores, as it is appropriate for binary dependent variables [46,47]. In this case, the binary dependent variable was IIS use (1 = yes, 0 = no). The independent variables included a range of socio-economic characteristics and structural constraints, as summarised in Table 1.

Table 1. A description of the independent variables included in the model.

Variables	Description	Variable Type	Expected Sign
Age group	Age category of farmer	Categorical	+/−
Level of education	Highest qualification attained	Categorical	+
Main source of off-farm income	Income from non-farming activities	Categorical	+/−
Farm size (hectares)	Size of land cultivated	Continuous	+
Years of farming experience	Number of years spent farming	Continuous	+
Cooperative membership	1 = yes, 0 if otherwise	Categorical	+
Insufficient water supply	1 = insufficient water supply perceived as constraint, 0 if otherwise	Categorical	+
High production input costs	1 = high input costs perceived as constraint, 0 if otherwise	Categorical	−
Lack of reliable power	1 = lack of power perceived as constraint, 0 if otherwise	Categorical	+
Lack of access to market	1 = limited access to market perceived as constraint, 0 if otherwise	Categorical	+

PSM allows for the estimation of the average treatment effect on the treated (ATT), which reflects the change in crop yield attributable to IIS use. Only matched observations were retained for the final estimation of treatment effects, thereby improving causal inference and reducing bias. The estimated treatment effect is calculated as

$$\Delta = Y1 - Y0 \tag{4}$$

where $Y1$ = observed outcome (crop yield) for treated SCFs (IIS users) and $Y0$ = observed outcome (crop yield) for control SCFs (non-users).

To estimate the ATT, three PSM methods were employed:

(a) Kernel-based matching: This matches each treated observation with a weighted average of all control observations within the common support region [51].
(b) Nearest neighbour matching: This pairs each treated unit with the control unit that has the closest propensity score [52].
(c) Radius matching: This matches treated units with control units that fall within a specified calliper (range) of propensity scores [53].

The use of multiple matching techniques helps compare results and check the robustness of the results. Consistent findings across methods indicate reliability in estimating the treatment effect of IIS use on crop yields. For each method, the statistical significance of the average treatment effect on the treated (ATT) was evaluated using the t-statistic, from which a p-value was derived. The hypothesis testing implicitly examined the null hypothesis (H_0)

that IIS use has no effect on crop yields among smallholder farmers. Therefore, a *p*-value less than 0.05 was considered statistically significant, leading to the rejection of the null hypothesis. A statistically significant positive ATT estimate indicated that the use of IISs significantly increased crop yields among smallholder crop farmers.

2.5. Ethical Consideration

Ethical clearance for this study was obtained from the University of Mpumalanga's Faculty of Agriculture and Natural Sciences Research and Innovation Committee, under the reference number UMP/Monamodi/201995670/MAGR/2024. The research adhered to strict ethical standards throughout its implementation.

Prior to participation, all respondents were fully informed about the purpose of the study and provided informed consent. No physical or psychological harm was inflicted on any participants, and their well-being was prioritised by both the trained enumerators and the researcher.

Moreover, participants' confidentiality and anonymity were guaranteed. All data collected were used solely for academic purposes and securely stored to ensure compliance with ethical research practices.

3. Results and Discussion

3.1. Socio-Economic Charasteristics of Smallholder Crop Farmers (SCFs)

Table 2 presents a summary of the socio-economic characteristics of the SCFs in the study area. These characteristics were analysed to provide contextual insights into factors influencing the productivity of SCFs and their likelihood of adopting innovative irrigation systems (IISs). Only variables included in the regression analysis for estimating the probability of IIS adoption are discussed.

The results show that the majority (46.4%) of SCFs were aged 60 years and above, followed by those aged 35–59 (30.2%), while only 23.4% fell within the youth category (18–34 years). This suggests that smallholder crop farming in the study area is primarily undertaken by older individuals. This finding is consistent with Agholor et al. [54], who noted that older individuals dominate farming in Mbombela. Dzanku et al. [55] similarly observed that elderly farmers make up the majority of smallholder farmers across Sub-Saharan Africa. Geza et al. [56] also pointed out that many young people perceive agriculture as having limited potential to improve their living standards. However, these findings contrast with studies conducted in Nkomazi, Mpumalanga, where Zondo and Ndoro [57] found that the majority of farmers were aged 20–39. Similarly, Nyawo et al. [58] reported that 76.5% of smallholder farmers in north-eastern South Africa were under the age of 40.

In terms of education, 26.3% of the respondents had no formal education, while 23.7% had completed secondary school and 18.8% had a primary-level education. A smaller proportion had completed matric (16.9%), ABET (6.5%), or obtained post-secondary qualifications such as a higher certificate (3.6%), diploma (2.6%), or degree (1.6%). These findings indicate that nearly half of the respondents had some level of secondary or post-secondary education. This aligns with findings by Muhammad et al. [59], who noted that 55% of surveyed farmers had completed primary school, 12.5% secondary school, and 7.5% tertiary education, while 25% had not completed any formal education. Similarly, Ndhlovu and Masika [60] and Chimonyo et al. [61] observed that over 90% of Zimbabwean farmers had at least a secondary-level education. However, in other regions, such as parts of Tanzania, Ethiopia, and rural South Africa, educational attainment among smallholder farmers remains significantly lower [62,63].

Table 2. Socio-economic characteristics of respondents.

Variables	Frequency	Percentage
Age group (years)		
18–34	72	23.4%
35–59	93	30.2%
60 and above	143	46.4%
Level of education		
No formal education	81	26.3%
Primary	58	18.8%
Secondary	73	23.7%
Matriculated	52	16.9%
ABET	20	6.5%
Higher certificate	11	3.6%
Diploma	8	2.6%
Degree	5	1.6%
Main source of off-farm income		
None	49	15.9%
Salary	6	1.9%
Old age pension	97	31.5%
Child support grant	93	30.2%
Social relief grant	61	19.8%
Remittance	2	0.6%
Years of farming experience		
≤5 years	78	25.3%
6–10 years	108	35.1
11–20 years	94	30.5%
≥21 years	28	9.1%
Farm size		
≤5 ha	246	79.9%
6–10 ha	58	18.8%
11–20 ha	4	1.3%
Cooperative membership		
Yes	92	29.9%
No	216	70.1%

With regard to off-farm income source, the majority of SCFs relied on social grants, particularly old age pensions (31.5%) and child support grants (30.2%). A further 19.8% received social relief grants, while only 15.9% reported having no off-farm income. Very few respondents earned a salary (1.9%) or received remittances (0.6%). These findings reflect a high dependency on government social protection mechanisms, supporting the observation by Pienaar and Traub [1] that social grants are critical income sources for smallholder farmers. Such grants provide an essential safety net, helping farmers buffer against losses in agricultural income caused by climate variability and other risks [64,65]. In contrast, Raza et al. [66] reported that 79.3% of rural communities in Pakistan rely directly on agriculture as their primary income source, with limited dependence on government assistance.

In terms of farming experience, 35.1% of the respondents had 6–10 years of experience, followed by 30.5% with 11–20 years, and 25.3% with 5 years or less. Only 9.1% had more than 21 years of farming experience. This suggests that about 60% of SCFs had 10 years or less of farming experience. These findings are comparable to those of Effiong et al. [67], who found that most smallholder farmers in Nigeria had between 6 and 10 years of experience. However, these results contrast with Ramadan et al. [68], who reported that 41.5% of farmers had 11–20 years of experience and 31.9% had over 20 years. Similarly, Yawson [69] observed that 78% of surveyed farmers had 10 or more years of experience. According to Mektel and Mohammed [70], farming experience is a crucial factor in agricultural research, as it shapes farmers' behaviour and decision-making processes. Farmers with more farming experience are better equipped to make informed decisions, suggesting a more established and seasoned farming community [71,72].

Regarding farm size, 79.9% of respondents cultivated 5 hectares or less of land, qualifying them as smallholders. Only 18.8% had between 6 and 10 hectares, and a mere 1.3% had land holdings of 11–20 hectares. This is consistent with the general profile of smallholder farmers in Sub-Saharan Africa, who often operate on less than 2 hectares of land [73,74]. A survey data conducted by CGAP [75] in Mozambique, Tanzania, and Pakistan reported that most small-scale farmers operated farms between 1 and 2 hectares, with only 20% managing farms larger than 3 hectares.

Lastly, cooperative membership was low, with 70.1% of farmers not affiliated with any cooperative and only 29.9% indicating membership. This low participation rate may limit access to input supply, credit, markets, and technical support, which are often accessed through farmer organisations. Msimango and Oladele [76] and Mbanza and Thamaga-Chitja [77], similarly reported low levels of cooperative participation. One possible reason may be the perception that cooperatives fail to deliver meaningful support in terms of credit, mechanisation, and extension services [78,79]. However, these findings are contrary to those from Nigeria, where Chikaire et al. [80], Onyeneke [81], and Mbah et al. [82] reported high levels of cooperative membership among smallholder farmers.

3.2. Innovative Irrigation System Usage and Types Among Smallholder Crop Farmers

Table 3 presents the distribution of smallholder crop farmers (SCFs) based on their use of innovative irrigation systems (IISs) and the specific types of systems utilised during the last cropping season (2023/2024).

Table 3. Innovative irrigation system usage and types used.

Variable	Frequency	Percentage
Use of innovative irrigation system		
Using IIS	130	42.2%
Not using IIS	178	57.8%
Type of innovative irrigation system used		
None	178	57.8%
Drip only	20	6.5%
Sprinkler only	67	21.8%
Both drip and sprinkler	43	14.0%

Note: Farmers who reported using an innovative irrigation system (IIS) could select more than one type of system. Percentages are based on the total sample (n = 308).

The results show that out of the 308 SCFs surveyed, the majority (57.8%) reported not using any form of IIS during the 2023/2024 cropping season, while 42.2% indicated that they had used such systems. This indicates that despite the well-documented benefits of irrigation technologies for enhancing crop productivity, adoption and utilisation remain limited among smallholder farmers in the study area. A similar trend was observed in Ethiopia by [70].

In terms of the specific types of IIS used, 57.8% of farmers indicated they did not use either drip or sprinkler systems. Among the 130 farmers who used IISs, sprinkler irrigation was the most commonly reported type (21.8%), followed by the combined use of both drip and sprinkler systems (14.0%), while drip irrigation alone was the least used (6.5%). This distribution suggests that most SCFs in the study area still rely heavily on rainfed agriculture or traditional irrigation practices. However, among those adopting innovative methods, sprinkler irrigation appears to be the preferred option. This finding is consistent with the work of Mkuna and Wale [17], who reported that sprinkler systems tend to be more accessible and affordable for smallholder farmers in KwaZulu-Natal, particularly within communal and resource-constrained farming settings.

3.3. Impact of Innovative Irrigation Systems Use on Crop Yields

3.3.1. Factors Influencing the Use of IISs

A Probit regression model was employed to examine the factors influencing smallholder crop farmers' (SCFs') decisions to adopt innovative irrigation systems (IISs). The results are presented in Table 4. In addition to socio-economic variables, selected structural constraints were included to better understand their influence on IIS adoption. The model was statistically significant at the 5% level (Prob > Chi^2 = 0.0382), indicating a good overall fit [83]. Furthermore, the model correctly predicted approximately 61% of the observations, demonstrating moderate predictive accuracy based on Receiver Operating Characteristic–Area Under the Curve (ROC–AUC) criteria [84].

Numerous studies have investigated the factors influencing farmers' adoption of agricultural technologies [85–87]. In this study, the age group of farmers was positively associated with IIS use and statistically significant at the 10% level. This suggests that older farmers are more likely to adopt IISs, potentially due to greater experience and a stronger understanding of irrigation's benefits. The marginal effect indicates that a one-unit increase in the age group raises the likelihood of using IISs by approximately 9.5%. This is consistent with findings by Daniel [88], Salome and Rotimi [89], and Jiba et al. [34], who found that age positively influences technology implementation. However, contrasting evidence from Algeria [86] suggests that older farmers may be less inclined to adopt new technologies due to conservatism and risk aversion, while younger farmers are more innovative. Similarly, Mattee and Gebreyes [90] in Ethiopia found that younger farmers tend to be more receptive to innovation, indicating that adoption behaviour may be context-specific.

Off-farm income was positively and significantly associated with IIS use at the 5% level, suggesting that farmers with additional income streams are more capable of investing in irrigation technologies. The marginal effect (0.186) implies that having an off-farm income increases the probability of using IISs by 18.6%. This align with Yatribi [91], who observed that farmers with non-agricultural income are 18.23% more likely to adopt irrigation technologies. Similarly, Jambo et al. [32] found that, in Ethiopia, non-farm income plays a critical role in facilitating irrigation technology usage.

Interestingly, high production input costs were also positively and significantly associated with IIS use at the 1% level. This contradicts the work of Hards and Du Plessis [92] and Mkuna and Wale [17], who reported high input costs as a barrier to innovation. In the present study, the positive association likely reflects the financial capacity of betterresourced farmers who can afford both high input costs and irrigation investments. This suggests that the main barrier to IIS adoption among non-users in Mbombela Local Municipality may not be cost, but rather entrenched practices and attitudes toward traditional methods.

Table 4. Factors determining the use of innovative irrigation systems.

Variables	Coefficient	*p*-Value	Marginal Effect
Socio-Economic Characteristics			
Age group (years)	0.254	0.080 *	0.095
Level of education	0.044	0.434	0.016
Main source of off-farm income	0.498	0.042 **	0.186
Years of farming experience	−0.035	0.716	−0.013
Farm size	0.133	0.449	0.041
Cooperative membership	0.200	0.251	0.075
Structural Constraints			
Insufficient water supply	−0.030	0.516	−0.012
High production input costs	0.415	0.006 ***	0.155
Lack of access to reliable power	0.011	0.944	0.004
Lack of access to market	−0.064	0.675	−0.024
Constant	−2.278	0.001	

Number of observations: 308
Log likelihood: −200.85988
LR chi^2 (10): 17.75
Prob > Chi^2: 0.0382
Pseudo R^2: 0.4203
Percentage correctly predicted: 60.90%

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

3.3.2. Estimated Impact of Innovative Irrigation System on Crop Yields

The impact of IIS use on crop yields was estimated using the Propensity Score Matching (PSM) technique. Table 5 presents the average treatment effect on the treated (ATT) under different matching methods for selected crops grown during the 2023/2024 cropping season. Yield was measured in tonnes per hectare.

Although SCFs cultivated a variety of crops, the analysis focused on three vegetables (tomatoes, cabbage, and chillies) and one agronomic crop (maize). These were selected based on their frequency of cultivation among respondents and the availability of sufficient treatment and control observations to ensure reliable statistical comparisons.

For contextual clarity, SCFs in the study area typically quantify yields as follows: (a) one ton of tomatoes or chilies is equivalent to 143 crates (7 kg per crate), (b) one ton of cabbage is equal to approximately 500 heads (2 kg per head), (c) one ton of maize is estimated based on a standard pickup truck (Bakie) load.

The results show a consistent, statistically significant, and positive impact of IIS use on crop yields across all four crops. SCFs who used IISs reported notably higher yields compared to their counterparts who relied on traditional methods. Specifically, the ATT was 7.273 tonnes/ha for tomatoes, 8.851 tonnes/ha for cabbage, 3.196 tonnes/ha for chillies, and 2.471 tonnes/ha for maize. These finding corroborate other studies in North Asia, East Africa, Swaziland, and China, which demonstrate a positive relationship between irrigation and crop productivity [30,93–95]. Furthermore, evidence from Sub-Saharan

Africa indicates that irrigated agriculture improves food security, reduces vulnerability to rainfall variability, and enhances resilience among smallholder farmers [18–20]. Similarly, Badr et al. [96] noted that, in Algeria, efficient water supply systems, such as drip irrigation, significantly increase crop yield potential.

Table 5. Estimated average treatment effect (ATT) on yield.

Types of Crops Cultivated	Matching Method	Treated (ton/ha)	Control (ton/ha)	ATT (ton/ha)	t-Statistics
Vegetables					
Tomato	Kernel	18.273	11	7.273 **	51.64
	Nearest neighbours	19.074	11	8.074 **	14.49
	Radius	19.074	11	8.074 **	14.49
Cabbage	Kernel	33	24.149	8.851 **	4.10
	Nearest neighbours	33	24.437	8.563 **	3.35
	Radius	32.855	24.149	8.706 **	5.79
Chillies	Kernel	8.965	5.769	3.196 **	8.41
	Nearest neighbours	8.965	5.877	3.088 **	7.77
	Radius	8.965	5.833	3.132 **	11.69
Agronomic					
Maize	Kernel	7.190	4.710	2.471 **	2.86
	Nearest neighbour	7.190	4.757	2.433 **	2.68
	Radius	7.190	4.25	2.940 **	3.77

Note: ** indicates statistical significance at the 5% level ($p < 0.05$).

Moreover, the results from the PSM analysis show consistently positive and statistically significant average treatment effects on the treated (ATTs) across all three matching methods. This provides strong evidence to reject the null hypothesis that innovative irrigation system (IIS) use has no impact on crop yields. The results consistently demonstrate that the use of IIS significantly increased crop yields among smallholder crop farmers in Mbombela Local Municipality, confirming the alternative hypothesis of this study.

4. Conclusions and Recommendations

This study reaffirms the pivotal role of irrigation as a catalyst for enhancing smallholder productivity, sustaining rural livelihoods, and promoting sustainable agricultural development in resource-constrained environments. Specifically, the research assessed the impact of innovative irrigation system (IIS) usage on crop yields among smallholder farmers in Mbombela Local Municipality, South Africa. By applying Propensity Score Matching (PSM) and statistical analysis, the study provides compelling evidence of the positive relationship between IIS utilisation and improved crop productivity.

The findings indicate that smallholder farmers who adopted IIS recorded significantly higher crop yields than their counterparts who did not. Notable yield increases were observed for tomatoes (7.273 tons/ha), cabbage (8.851 tons/ha), chillies (3.196 tons/ha), and maize (2.471 tons/ha), with statistically significant differences across all three matching methods (Kernel, Nearest neighbour, Radius). These results strongly underscore the positive impact of IISs on crop performance. The study highlights that IISs can play a crucial role in reducing the vulnerabilities of rainfed agriculture, especially in areas experiencing erratic rainfall, thus contributing to more stable and improved agricultural output.

These findings reinforce the importance of water management as a key pillar of productivity in smallholder farming systems. The demonstrated benefits of IISs support their strategic promotion as part of broader efforts to strengthen food security, enhance rural incomes, and build resilience to climate variability. In the context of increasing climate risks and water scarcity, investment in IISs presents a viable pathway towards sustainable agricultural transformation.

To optimise the benefits of IISs, it is critical that smallholder farmers have reliable access to suitable irrigation technologies, technical training, and financial support mechanisms. Based on the study's results, it is recommended that policymakers prioritise the expansion of programmes that facilitate widespread and equitable access to IISs, particularly those that have shown the strongest effects on productivity across diverse crops. Government departments and development agencies should explore the introduction of subsidies, grant schemes, or low-interest financing options to reduce the financial barriers to IIS adoption. Furthermore, offering targeted training on irrigation scheduling, system maintenance, and water-use efficiency could significantly enhance the effectiveness and sustainability of these technologies.

Investment in water infrastructure, such as the development and maintenance of smallholder-accessible dams, boreholes, and irrigation channels, remains crucial for enabling broader uptake of irrigation technologies. Strong collaboration between policymakers, agricultural extension services, research institutions, and agribusiness actors is essential in order to provide institutional support, build farmer capacity, and ensure inclusive access to productivity-enhancing innovations.

5. Implications for Future Research

This study was conducted exclusively with smallholder crop farmers registered with the Department of Agriculture, Rural Development, Land and Environmental Affairs (DARDLEA) in Mbombela Local Municipality. The exclusion of unregistered farmers introduces sampling bias and limits the generalisability of findings beyond this specific group and geographic area. Additionally, focusing solely on Mbombela restricts the applicability of results to broader district or provincial contexts. Future research should consider expanding the geographic scope beyond Mbombela, and including unregistered farmers will enhance representativeness and reduce sampling bias.

The research concentrated specifically on the use of innovative drip and sprinkler irrigation systems to improve crop yield, without considering other conventional or traditional irrigation methods. Future studies could compare the efficiency and impact of both irrigation methods. Given that this study employed a cross-sectional design, it was not possible to assess the long-term sustainability and continued effectiveness of these irrigation systems. Future research should consider adopting a longitudinal design to track farmers and crop yields across multiple production seasons. This would offer valuable insights into the persistence of yield gains, continued system use, and the long-term environmental and economic sustainability of IISs. Additionally, the reliance on self-reported yield data may introduce reporting bias. Future studies should complement farmer-reported data with objective measurements where feasible.

Certain variables were excluded from regression analyses due to perfect prediction, which may affect the robustness of the findings. Penalised Probit (ridge/lassos) can be used to address it. Furthermore, reliance solely on quantitative data constrained a deeper understanding of socio-economic and institutional factors influencing the use of innovative irrigation systems. These limitations highlight the need for mixed-methods research. Integrating qualitative approaches such as interviews and focus groups could offer deeper insights into farmers' evolving perceptions, usage challenges, and adaptations related to IISs. Furthermore, future studies should investigate practical strategies to overcome barriers to sustained IIS use. These include financial, technical, and institutional constraints that may hinder uptake. Identifying and evaluating such strategies would be essential for enhancing the scalability, effectiveness, and long-term impact of IISs among smallholder crop farmers.

Author Contributions: Conceptualisation, P.M., J.T.N. and M.B.M.; Writing—Original Draft, P.M.; Reviewing and Editing. J.T.N. and M.B.M.; Supervision, J.T.N. and M.B.M.; Funding Acquisition, J.T.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the CSIR-DSI Inter-Bursary Support Programme (IBS) and by the National Research Foundation-Thuthuka Grant (TTK210419595905-138309).

Institutional Review Board Statement: The study was reviewed and approved by the Faculty Research and Innovation Ethics Committee of the University of Mpumalanga. Protocol reference number: UMP/Monamodi/201995670/MAGR/2024. Ethical approval was granted prior to data collection. Participants were informed about the purpose of the research, their rights, and the voluntary nature of participation. Both verbal and written informed consent were obtained from all participants.

Data Availability Statement: Data will be provided upon request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge the institutional support provided by the University of Mpumalanga for approving the research and granting ethical clearance. Sincere appreciation is extended to the Department of Agriculture, Rural Development, Land and Environmental Affairs for granting permission to conduct the study, and to their extension officers for assisting with farmer coordination. The authors are also deeply grateful to the smallholder crop farmers who participated in this study; their insights and experiences were vital to the success of this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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