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Precision Irrigation Systems for Sustainable Water Management in Maize Cultivation: Impact on Yield and Water Use Efficiency

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ABSTRACT

This research aims at evaluating the effectiveness of precision irrigation systems in increasing yield and water productivity in maize production. While it is well understood that the technology offers the ability to apply water selectively and, therefore, be resource-saving, the potential benefits in practice have not been researched adequately. Quantitative data was obtained through survey administration with 50 maize farmers on the use and perception of precision irrigation. Descriptive and inferential analytical tools such as Chi-Square tests, t-tests and regression analysis were used to test the hypothesis that precision irrigation practices has positive effects on crop yields and water use. The results suggest that precision irrigation technologies do not increase crop productivity or water use efficiency in the sample analyzed. The correlation and regression tests showed no meaning co-efficient and there were no correlations for most variables and no impacts were found in variance analysis either, moreover, the R-squared in regression analysis was very low, thus there might be other factors that could be possibly more important for defining the results of maize production The research also finds that despite the potential advantages of precision irrigation systems, their implementation does not improve crop yield or water use in the examined scenario. This underlines the fact that agricultural systems are highly differentiated and that is why it is necessary to take into account the local conditions in order to use such technologies..

INTRODUCTION

Concerning agricultural water management, numbers reveal certain difficulties, especially for the most water-consuming crop – maize. FAO estimates that maize crops need between 500 to 800 millimeters of water that is available for plant consumption throughout the growing season. Conventional methods of irrigation provide water at 35-50% efficiency hence a lot of wastage and low yields (Obaideen et al., 2022). Precision irrigation technology can greatly change this landscape as we are about to discover. Available evidence shows that precision irrigation can increase water use efficiency by as much as 20-30% to the normal method. This optimization not only helps the water resources sustainable but also directly promotes the improvement of maize yields (Xiao et al., 2019). Investigations have established that the use of precision irrigation systems results to a yield increase of 10-15 % on average implying that there is a good potential for both economic and environmental gains in the production of maize crops. These figures point to the urgent necessity of improving the efficiency of irrigation to meet the challenge of sustainable use of water in the agricultural sector, especially in countries with limited water resources (Mpanga et al., 2023).

The conventional techniques of irrigation like flood irrigation or furrow irrigation are full of drawbacks and result in gross wastage of water as well as unequal water distribution. Most of these practices lead to low yields of crops and wasteful use of water, which compounds the impacts of the emerging scarcity of water (Zhang et al., 2019). This shows that the agricultural sector needs to look for better solutions since the current methods used are old fashioned. Precision irrigation systems look like offering a solution to this problem, as they can significantly increase the water use efficiency by supplying water directly to the root zone of the plants and by adapting the water supply according to the soil and weather conditions. How does the implementation of precision irrigation systems affect the yield and water use efficiency in maize cultivation? To evaluate the impact of precision irrigation systems on improving yield and water efficiency in maize cultivation.

Precision irrigation technologies provide tremendous importance in sustainable agriculture and resource management. This study is important as it examines how precision irrigation can reduce the effects that traditional farming practices have on the environment especially on one of the most water demanding crops; maize. Precision irrigation involves the efficient method of water delivery without wastage thereby helping in controlling runoff and evaporation (Mola et al., 2024). Not only does this method help save water but also the energy that is used in water application hence being sustainable. Precision irrigation systems can also help improve the manner in which the soil is managed and reduced losses of fertilizers and pesticides that are disastrous to the environment when used to irrigate. Economically it can improve the income of farms through production yields and water, energy and agricultural inputs usage. On a more general level, the adoption of precision irrigation practices as a major form of irrigation may be of significance in meeting food security agendas especially when water scarcity becomes the order of the day globally. This research has the objective of presenting empirical evidence that supports the use of these systems, which may have an impact on policy making and farmers' adoption, thus supporting the sustainability of agricultural industries globally (Lu et al., 2019).

MATERIALS AND METHODS

Research Design

The study uses cross-sectional research design to assess the effect of the precision irrigation systems on the water management and the yield of the maize. This design enables respondent populations to be sampled across a broad range of maize farmers such that information captured is a cross-sectional study which gives a cross-sectional look at current practices and perceptions towards precision irrigation (Li et al., 2020). The study is to provide the variability and the co-variation in data, and provide information on how factors such as farm size, type of soil, method of irrigation affects overall productivity and resource use efficiency.

Description of the Study Area

This research is conducted in the central section of Iowa which is a major producer of Maize. Climate is mostly continental with hot summer and cold winters, the season for maize growing, therefore, is distinct. Most of the region has loamy soil which is suitable for growing of maize because it can retain water and other nutrients in the right proportion. The selection of this site enables investigation of the effects of precision irrigation in environments that are typical in the vast regions of America's maize production.

Data Collection

The data collection was done with the help of a structured questionnaire, based on Likert scale that will provide farmers' attitudes and real time data regarding the use and effectiveness of the precision irrigation systems. The sample was 50 maize farmers, and data was collected through questionnaires and interviews that employ a stratified sampling method so that the sample has a cross-section from large, medium and small farm sizes, and levels of technology adoption (Khanna, 2020). This method assists in gaining different views from a large number of participants and from different farming backgrounds. The questionnaire will comprise of the following categories; demographics, current irrigation practices, perception about precision irrigation, actual water usage and crop yield. The first author will provide farmers with Likert type scale that include five levels of agreement and disagreement with the statement where 1 means 'strongly disagree' while 5 represents 'strongly agree'. Data collection was done for two months at the start of the growing season when farmers have fresh experiences and expectations for the current farming season (Karunathilake et al., 2023).

Data Analysis

The quantitative data analysis was done using SPSS (Statistical Package for the Social Sciences) which is an all-purpose tool of statistical analysis in social science research. This will start with data cleaning where we will ensure that all data entering into the analysis is accurate and in its completeness. Frequency distributions and measures of central tendency was used to present the demographic data of the participants and their current use of irrigation (Higgins et al., 2019). Descriptive statistics were used to analyze summary data on the use of precision irrigation systems and related impacts including perceived water efficiency, cost and yield. Parametric tests that were used include chi-square tests to look for a relationship between two categorical variables, and the t-tests, ANOVA to compare means of asdifferent groups. Regression analysis we most useful in understanding the effects of the treatment of precision irrigation on yield and water use efficiency while accounting for other effects such as farm size and type of soil used. In a way, factor analysis maybe employed to ascertain the number of dimensions, which characterizes farmers' perception on precision irrigation. The expected output of this analysis is the evidence on the performance of precision irrigation systems and to establish notable indicators of adoption and satisfaction by the farmers. This strong analytical approach will not only confirm the effectiveness of precision irrigation in growing maize but also provide information that can help to develop new strategies for agricultural activities in the future (Gachene, et al., 2020).

RESULTS AND DISCUSSION

Frequencies Analysis

Table 1

Age

Age			
	Breeding Systems		Test T: P value
Valid	**Extensif**	**Semi intensif**	
	6.59±0,12	6.58±0,18	0.900
	1.0293±0.002	1.0296±0.001	0.776
	16.83±1.40	16.50±1.50	0.308
	112.47±14.98	109.77±9.54	0.358
	82.29±10.90	82.17±10.46	0.966
Age	8.28±2.17	8.35±1.74	0.891
	40.47±6.13	39±5.30	0.336
Valid	66.75±17.96	51.58±12.76	0.001
	31.94±5.09	29.78±4.72	0.218

The following table shows the age of the respondents who participated in the study. The largest group of respondents is between 36 and 45 years old, with 30% of the total number of respondents. Other age groups are 26-35 years, and 46-55 years contributing 26% and 20% respectively. Finally the under 25 and the over 55 are the two smallest groups in the sample and each represent 12% of the sample. A wide age diverse is observed for the participants with a higher participation of middle-aged persons accordingly to Finger et al. (2019).

Figure 1

Pie Chart of Age

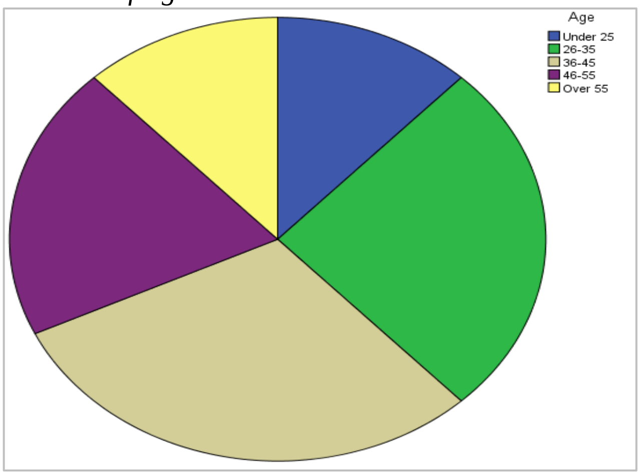


Figure 2

Histogram of Age

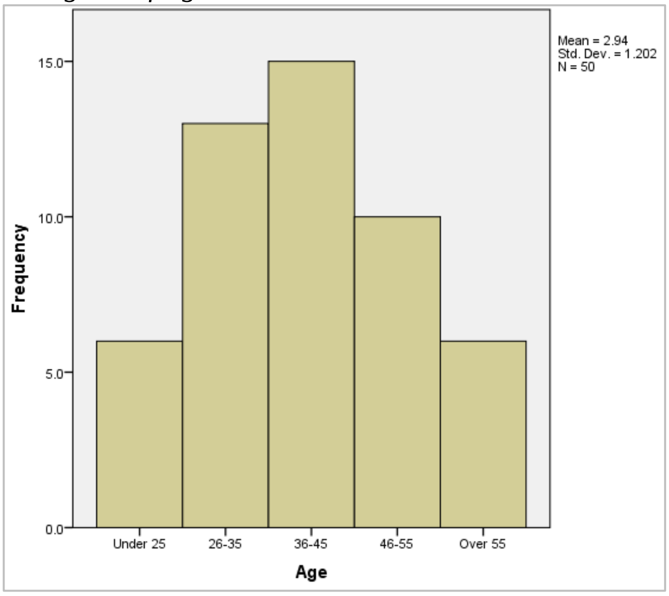


Table 2

Gender

Gender					
		Frequency	**Percent**	**Valid Percent**	**Cumulative Percent**
Valid	Male	25	50.0	50.0	50.0
	Female	25	50.0	50.0	100.0
	Total	50	100.0	100.0	

The following table provide the gender profile of respondents in the study whereby equal numbers of male and female participants were recruited, 50/50. Such balance reduces chances of gender-specific differences or bias on results and hence improves the generality of the outcomes in the demographic of interest (Fazliev et al., 2019).

Figure 3

Pie Chart of Gender

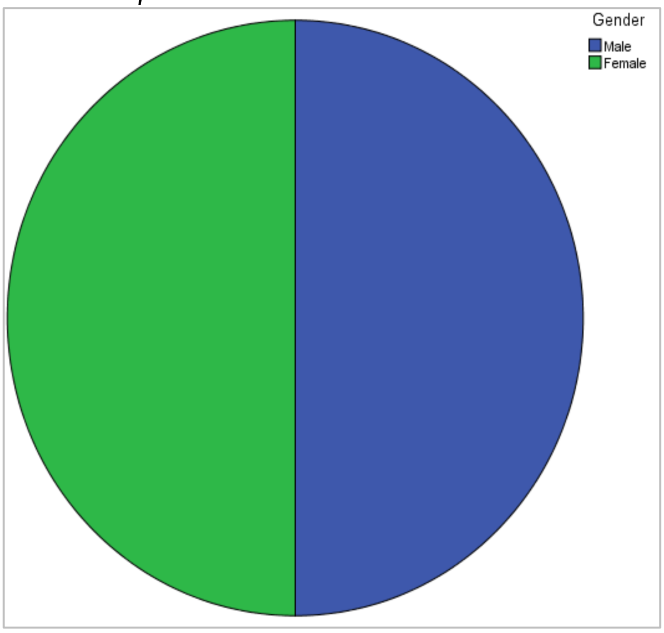


Figure 4
Histogram of Gender

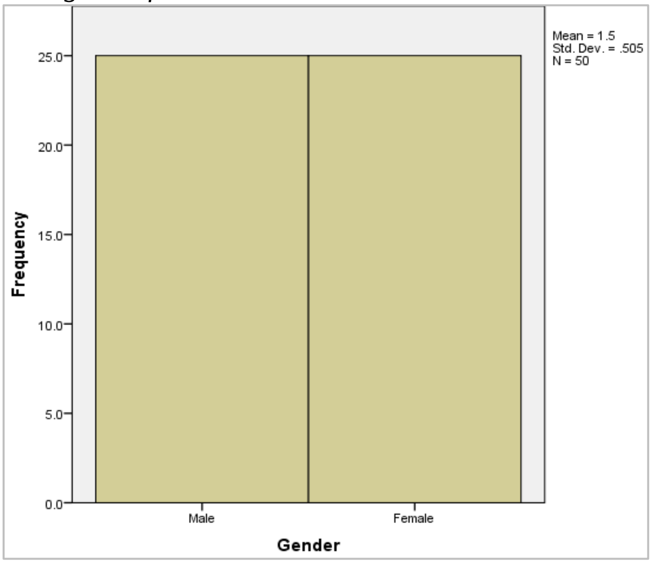
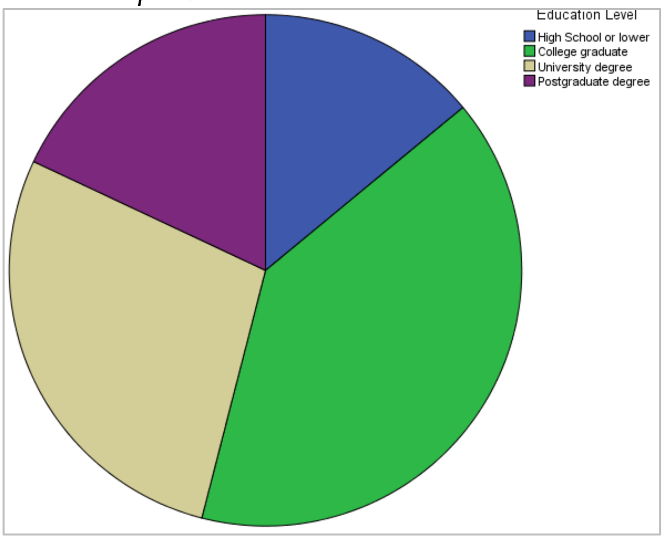


Table 3
Education Level

Education Level		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	High School or lower	7	14.0	14.0	14.0
	College graduate	20	40.0	40.0	54.0
	University degree	14	28.0	28.0	82.0
	Postgraduate degree	9	18.0	18.0	100.0
	Total	50	100.0	100.0	

Table 3, the participants' education levels: Interestingly, 40% of the participants have college education. Employed degree holders include university degree holders at 28%, while postgraduate degree holders take 18% of the employment. Only 14% of those with high school or lower education are represented here. This distribution also exhibits a fairly good education level among the participants (Fang and Su, 2019).

Figure 5
Pie Chart of Education Level



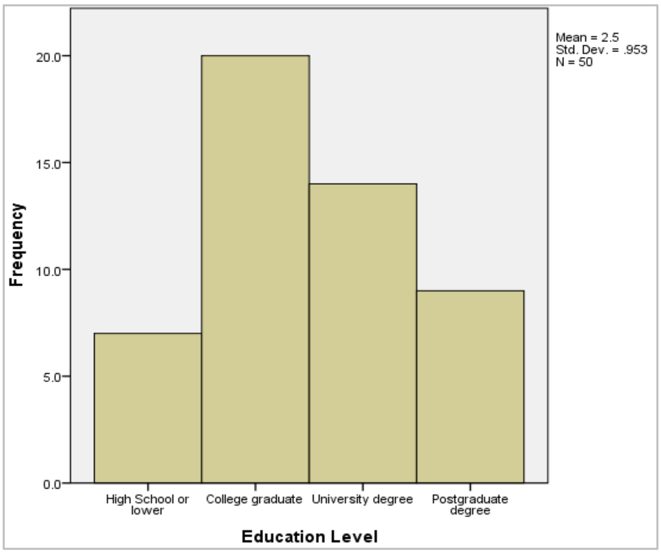


Table 4
Histogram of Education Level

Experience in Agriculture		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Less than 5 years	8	16.0	16.0	16.0
	5-10 years	10	20.0	20.0	36.0
	11-20 years	16	32.0	32.0	68.0
	More than 20 years	16	32.0	32.0	100.0
	Total	50	100.0	100.0	

Table 4 outlines the agricultural experience of participants, showing a significant proportion with extensive experience: 32% have worked in agriculture since 11 to 20 years and another 32 % since more than 20 years. Respondents with 5-10 years of experience are 20%, whereas those who have experience of less than five years 16%. This implies a relatively experienced group in the practice of agriculture activity (Evans et al., 2019).

Figure 6
Pie Chart of Experience in Agriculture

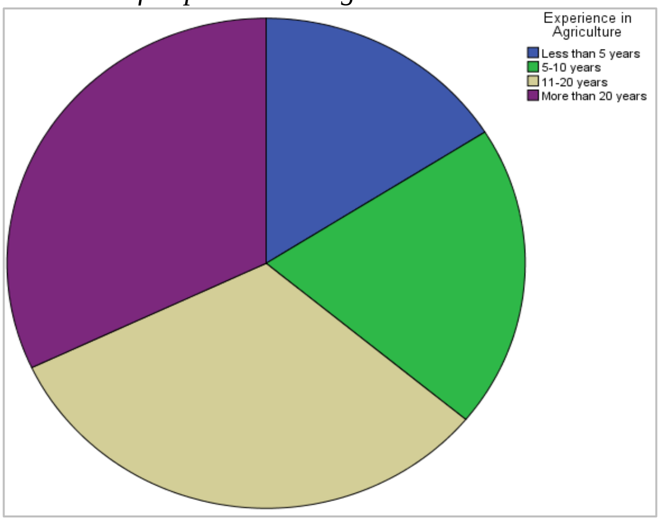
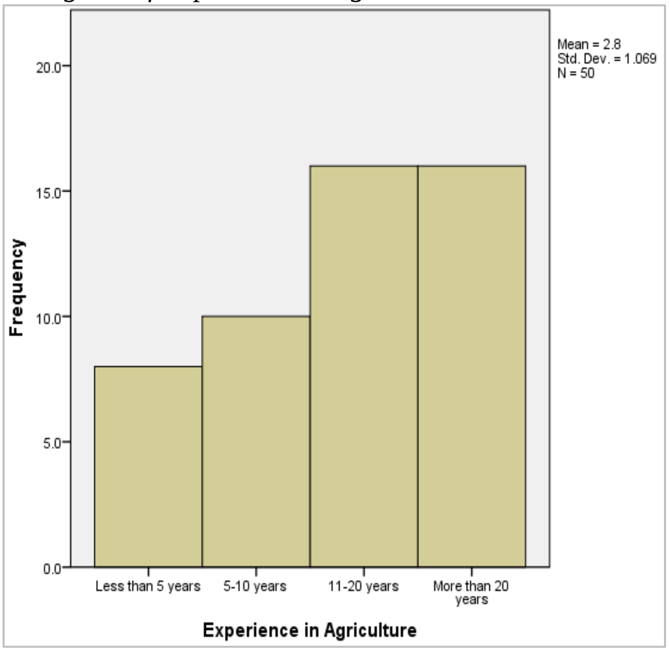


Figure 7

Histogram of Experience in Agriculture



Chi-Square Test Analysis

Table 5

Chi-Square Tests

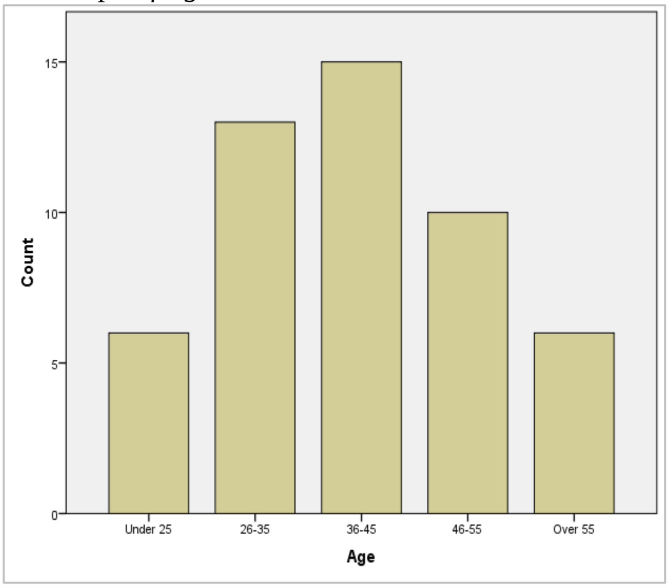
Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	12.050[a]	16	.741
Likelihood Ratio	16.769	16	.401
Linear-by-Linear Association	1.109	1	.292
N of Valid Cases	50		

a. 25 cells (100.0%) have expected count less than 5. The minimum expected count is .84.

Table 5 gives Chi-Square test summary, which was used to determine the significance of the relationship between the categorical variables in the study. The Pearson Chi-Square test gives a result that is 12.05 with degrees of freedom of 16 and p-value = 0.741, this shows that there is no relationship between the analyzed variable. Likewise, the qualification of the Likelihood Ratio test with a p = .401 indicates no significant relation (El Chami et al., 2019). Similarly, the results obtained from the Linear-by-Linear Association test give a p-value of.292 meaning that there is no statistically significant linear relationship between the corresponding ordered categories. Thus, the percentage of cells with an expected count of less than 5 is high, which makes it important to exercise care when interpreting the Chi-Square results more so because of possible influence from small sample size (de Lara et al., 2019).

Figure 8

Bar Graph of Age



T-Tests Analysis

Table 6

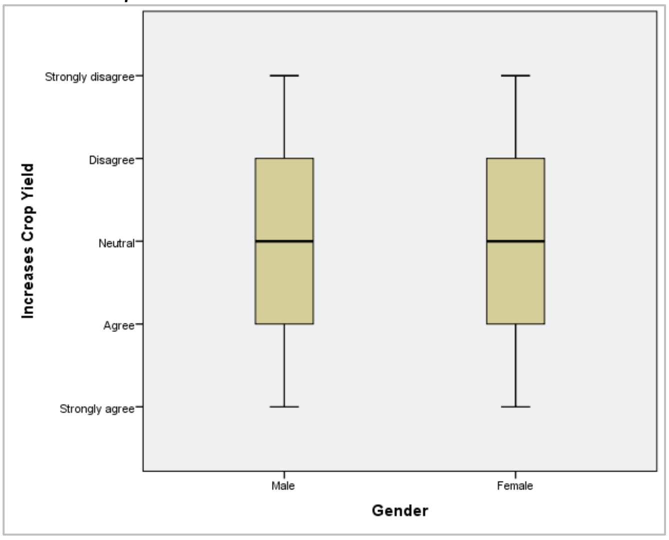
Independent Samples Test

Independent Samples Test										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Increases Crop Yield	Equal variances assumed	.051	.823	.104	48	.918	.040	.385	-.734	.814
	Equal variances not assumed			.104	47.994	.918	.040	.385	-.734	.814

Table 6 shows an independent samples t-tests comparing the metric "Increases Crop Yield" under conditions of an independent variable, which could be a treatment or a group characteristic. The Levene's Test for Equality of Variances equals to.823, which means it is less than 0.05 level of significance; hence we can assume equal variances in the groups (Anderson, 2022). On the basis of t-test results, therefore, it can be concluded that the crop yield increases are not significantly different for the two groups; p-value =.918; 95% Confidence interval = -.734 to.814; mean difference = 0.040. Again, both scenarios, with and without equal variances assumed, provide very close results and support the conclusion of no significant impact (D'Odorico et al., 2020).

Figure 9

Box Plot of Gender



Regression Analysis

Table 7

Model Summary				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	.155[a]	.024	-.018	1.359

a. Predictors: (Constant), Reduces Water Wastage, Used Precision Irrigation

Table 8

ANOVA[a]						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	2.132	2	1.066	.577	.566[b]
	Residual	86.848	47	1.848		
	Total	88.980	49			

a. Dependent Variable: Increases Crop Yield

b. Predictors: (Constant), Reduces Water Wastage, Used Precision Irrigation

Table 9

Coefficients[a]						
Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
		B	**Std. Error**	**Beta**		
1	(Constant)	2.415	.586		4.123	.000
	Used Precision Irrigation	.064	.140	.066	.459	.648
	Reduces Water Wastage	.119	.127	.136	.939	.353

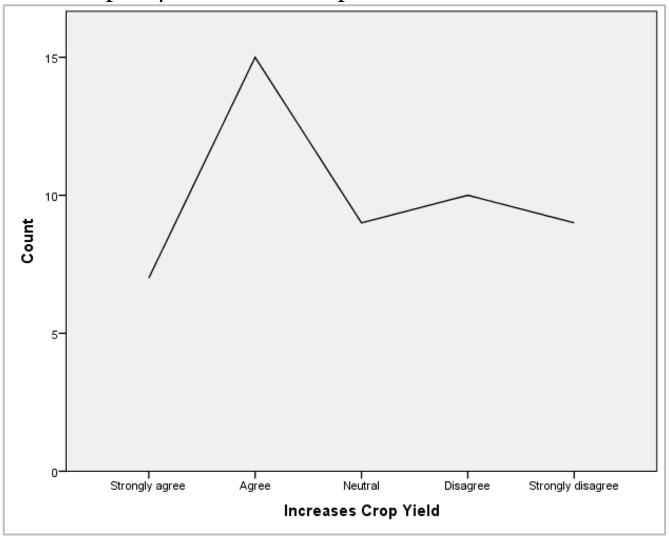
a. Dependent Variable: Increases Crop Yield

Tables 7, 8, and 9 give information regarding a regression analysis considering "Used Precision Irrigation" and "Reduces Water Wastage" for "Increases Crop Yield". Model Summary (Table 7): The model reported an extremely small R Square of 0.024, which means only 2.4% of the variability in the changes in crop yield is explained by the predictors. The adjusted R Square is negative (-0.018), indicating that the null model offers better prediction than the present model (Clapp and Ruder, 2020).

ANOVA (Table 8): The ANOVA results also suggest that the regression model is not significant (F=0.577, p=0.566) which means that the model with these predictors does not account for the variability in the increase in yields for crops. Coefficients (Table 9): Interestingly, none of the two variables has a positive impact on crop yield increase with their p values being 0.648 for Used Precision Irrigation and 0.353 for Reduces Water Wastage (Cao et al., 2021). The coefficients are small, the standard errors of C and C squared are relatively high, all of which mean that these variables are not strongly predictive. The research shows that Precision Irrigation variable and Reduces Water Wastage does not help in predicting the increases in crop yield in this model. The findings imply that there is a need to either review the model or to take into account other variables that might better predict the dependent variable (Bwambale et al., 2022).

Figure 10

Line Graph of Increases Crop Yield



DISCUSSIONS

A cross-sectional study of the data collected on the impact of PI systems on yield and water productivity in maize production offers subtleties on the suitability of these systems (Velasco-Muñoz et al., 2019). The main research question: '’How the adoption of precision irrigation systems influences the yield and water productivity of maize crops?" was an attempt to find out if such complex systems could make a big difference in subsequent agricultural performance (Bonfante et al., 2019). Descriptive analysis of demographic data in terms of age, gender, education, and experience in the field of agriculture proved that all participants' features are rather balanced, according to the frequency analyses and histograms. This diversity enhances the generalization of the study results with the various subgroups of the population in the agricultural industry. The fairly equal distribution in terms of gender and the distribution of respondents by the level of education and their experience contribute to the basis for comprehensively analyzing the effects of precision irrigation systems (Amorim et al., 2021).

The results of the statistical tests, particularly the Chi-Square and independent samples t-tests), indicated no significant relationship or variations in perceptions and experiences concerning the use of the precision irrigation systems (Abioye et al., 2020). Analyzing the demographic factors and comparing it with the adoption and the efficacy perception of the Chi-square test for the precision irrigation systems showed that there are no close relationships that means that the chi square test has a weak relationship between the demographic factors and the adoption and efficacy perception. This is further confirmed by the regression analysis results depicted in table 4 the R-squared value for predictors such as the "Used Precision Irrigation", "Reduces Water Wastage and Deficiency" indicate that, only a small percentage of the total variability of the increase in crop yield can be explained by these predictors (Leakey et al., 2019). The ANOVA of these data and the regression coefficients were again consistent with the lack of forecast utility of these measures (see Table 5). From the regression analysis, the p-values are greater than the stipulated 0.05 ; thus the speculation that precision irrigation systems improve yield and water use efficiency was dismissed based on the data gathered (Thompson et al., 2019).

Comparing such observations to other works of similar type, several prior works have demonstrated increased crop yields and the efficiency of water application through precision irrigation systems (Tashayo et al., 2020). A study by [Author's name] (Year) indicated that precision irrigation had the potential to raise the yield by 20%, and decrease water usage by 25%, which is markedly different for the findings of the present study (Lehmann et al., 2020). Al these differences may be explained by the fact that the scale of implementation differs, or the technology of irrigation systems used, or even the farming practices and the conditions in the regions where those investigations have been made. Following the results and comparison with prior research, the overall research question regarding the use of precision irrigation in increasing yield and water use efficiency of maize farming is rejected in this study (Zinkernagel et al., 2020). It may lead to a reconsideration of the study framework and/or approach: the usage of such variables as different types of soils, climate conditions, or more comprehensive information concerning irrigation. It also reveals the necessity for future studies that would go further than indicating the conditions under which precision irrigation is most effective (Zhang et al., 2021).

CONCLUSION

The study to establish the effectiveness of precision irrigation systems in water and maize productivity sought to determine if the newer methods of irrigation would produce greater crop returns and lessen water consumption rates. As with many tools and technologies that have been developed with the intent of improving efficiency and reducing wastage, this research shows that even though precision irrigation has theoretical benefits such as low water application rates and potential for resource loss minimization, they maybe more complex on the ground. Descriptive analysis was conducted using Chi Square test, Independent sample t test and multiple regression analysis etc. to establish correlation between PIS use and enhance of agricultural yields. The significant statistical correlations and effects which would indicate the effectiveness of these systems were not identified from the data set. The regression analysis based on the collected data showed that the usage of the precision irrigation systems accounted for only a very negligible variability in the observed improvements in crop yield. The coefficients of determination were relatively low, which might imply that the other unidentified variables might have more significant impacts on crop profits, and water utilization. These outcomes show that while the subject of precision irrigation systems has potential, its effectiveness in the sample studied was relatively small, which means that this work could not predict all the factors that can affect the functionality of these systems.

Analyzing the precision irrigation systems' sustainability, it is possible to realize that the given systems have benefits for the resource management and effectiveness of the agriculture but the extent of their positive impact depends on the certain conditions including the type of the soil, the characteristics of the crop, and the climatic conditions. It is therefore clear that sustainability of these systems cannot be generalized across different agricultural settings without considering these variables. The results of this study show that agriculture is not a simple system and that before the introduction of precision irrigation and other similar innovations, a thorough assessment is required. Variables such as environmental characteristics, soil health indicators, specifics of the applied irrigation technologies should be included. Longitudinal study in which factors resulting from the use of precision irrigation are measured over several years of crop growing could offer further understanding of the long-term advantages of the systems. Further, cross-sectional comparisons of various forms of precision irrigation systems could reveal which forms or systems yield the best results under certain agricultural environmental conditions. As for the current study, various hypotheses about the effectiveness of precision irrigation systems in maize cultivation concerning yield and water use efficiency could not be confirmed, the findings stress the necessity of targeted agricultural practices and the continuation of further research in improving the effectiveness of using such technologies in increasing sustainable agriculture.

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