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Research Article

Precision Irrigation Scheduling Based on Wireless Soil Moisture Sensors to Improve Water Use Efficiency and Yield for Winter Wheat in Sub-Saharan Africa

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In Sub-Saharan Africa, where most irrigation systems are manually operated, water allocation and irrigation scheduling are often based on uniform application irrespective of crop needs and growth stages, which results in nonoptimal water use. Recently, a lot of research has been carried out to improve irrigation water use efficiency through automation by employing wireless sensor-based monitoring systems. Further to the improvement of water use efficiency and yield, while reducing costs, a field trial was carried out at a farm in Harare, Zimbabwe, during the 2016, 2017, and 2018 winter seasons to test whether a new approach to the automated irrigation systems, one based on IoT and wirelessly connected soil sensors (called hereafter as WCSS), improves water use efficiency without reducing yield. WCSS method was compared with three widely used conventional irrigation methods, that is, manual scheduling, tensiometer-based scheduling, and weather-based scheduling. Impacts on water savings and yield of winter wheat crops under drip irrigation were evaluated. WCSS saved up to 25% more water compared to typical fixed irrigation schedule rates used by wheat growers during the winter season.

1. Introduction

Globally, the demand for freshwater resources has been increasing, largely driven by a growing population, industrial expansion, and agricultural production [1]. When considered temporally and spatially, there are large variations in the availability of fresh water across different regions of the world. In Sub-Saharan Africa, it has been observed that the average rainfall received in semiarid zones has been on the decline in the last two decades. This is largely attributed to the upsurge in drought years as a result of climate change and global warming [2].

The inclement weather conditions characterizing the Sub-Saharan Africa region necessitated investments in irrigated agriculture [3–5]. Given that the bulk of existing irrigation systems in small-scale farming is traditional flood, water canals, and sprinkler systems, high rates of water loss have been experienced. For instance, a study of Mutorahuku irrigation scheme showed that approximately 8m^3/hr of water was lost due to damaged canals [6]. This is further exacerbated by the observation that irrigators assume that the water requirement of each plant across a field is the same and ignore differences in crop water requirements due to spatial factors, which include plant genetics, soil type, and topography [7–9], resulting in a blanket application of water. Such anecdotes give credence to the need to improve water use efficiency in smallholder irrigation systems [10, 11]. Furthermore, efficient water management strategies become necessary to improve agricultural productivity to meet food demands for a growing population.

Precision agriculture is often identified as a solution to the myriads of inefficiencies related to water, fertilizer, and herbicide use [12, 13]. Irrigation scheduling, in particular, affords farmers the opportunity to use scarce water resources in an optimal manner [14, 15]. Over the years, numerous irrigation scheduling techniques have been developed, ranging from satellite-based/arial, soil-based [16–19], and microwave-based sensors to those based on evapotranspiration [20, 21]. However, most of these approaches are implemented in the developed country context, with limited literature for developing countries.

Several authors [22–24] also focused on control systems, which are based on the prediction of soil moisture content and atmospheric conditions, but without much attention to developing intelligent agriculture systems that are less costly and efficient in terms of water and energy use.

This paper focuses on wireless-based sensor systems for commercial irrigated wheat production at the University of Zimbabwe Farm. Wireless sensor systems and real-time soil moisture data for irrigation control are a potential solution to the optimization of water application. Typically, this is achieved by remotely accessing in-field soil water conditions and site specifically controlling irrigation applicators [25–27]. Previous studies have demonstrated that optimal sensor placement in the field can be achieved through dividing the field into management zones using Electromagnetic (EM) mapping [28]. EM mapping allows for the simultaneous collection of geo-referenced apparent soil electrical conductivity and accurate elevation data that can be interpolated to yield a relationship between soil and field elevation, which reflects on the water storage and movement. The aims of this paper are twofold: (i) to determine the effect of the wireless-based sensor technology or wireless sensor networks (WSNs) in irrigated wheat on water use efficiency and (ii) to compare the yield of wheat crop between a control system using the conventional irrigation system and the proposed new treatment (wireless sensor technology).

WSNs comprise systems with radio frequency (RF) transceivers, sensing devices, controllers, and power sources [29]. Advances in wireless sensor technology have brought about the development of multifunctional sensor nodes that are affordable and use less power. Sensor nodes in a network are capable of performing some data processing and the gathering of sensory information that can be communicated with other connected nodes in the given network. Many types of sensors are available, including those that can sense physical properties such as temperature, humidity, pressure, moisture content, or radiation. These allow monitoring of different environments and are capable of networking with other sensor systems for the purposes of exchanging data with external users [30, 31].

WSNs are used for gathering the information needed by intelligent systems, smart cities, industrial applications, or smart healthcare just to mention a few [32, 33]. WSNs support deployment of networks while covering communication needs with flexibility in time and space without the requirement for a fixed infrastructure [34]. Currently, there are several wireless technologies that are available on the market. These are ZigBee, Wi-Fi, or Bluetooth, which enable easier deployment compared to wired ones, thus avoiding any need to wire building structures, and thus decrease the costs and drawbacks normally associated with the setup phase. The wide possibilities provided by WSNs actually allow developing a wide range of applications that include energy cost control, ability to monitor environmental data, security and control of access environments, among others [35]. In this regard, sensing actually makes it possible to obtain information about the users and their environment. This allows offering users customized online services with respect to the state of their environment.

Another advantage of using wireless transmission is the considerable reduction and simplified wiring over and above, saving the cost of the wires. Wireless sensors also allow users to collect data from otherwise impractical sensor applications such as keeping a check on hazardous, unwired, or remote locations. Wireless sensor technology contributes extensive installation pliability for sensors and an improved network robustness [36, 37]. Furthermore, an added advantage of using wireless sensor technology is the transportability of the sensors, as they can be moved around in vehicles to monitor the environment "on-the-go." In addition, wireless sensor technology lessens the maintenance difficulties and costs incurred. Transmission of signals in digital form ensures that the noise pickup is minimum, and this becomes a less serious problem. Consequently, wireless sensors have been deployed in agriculture to aid with site-specific application of irrigation to crops in the field.

2. Materials and Methods

In this section, we present the design of wirelessly connected soil sensors for automated irrigation control. Subsequently, we present the field testing of the sensor in comparison with other known sensors and methods of irrigation scheduling.

2.1. Experimental Design and Setup. Field experiments were conducted on winter wheat at a Research and Development station of the University of Zimbabwe, situated at a farm on the north of Harare city during the 2016, 2017, and 2018 winter seasons. The topography is mainly a plain field with less than 8 per cent in-field elevation differences that result in ponding of lower elevation areas. Soils are mostly clay loam, and these are influenced by the variability of a fluctuating water table both in space and time. Although electrical conductivity (EM) surveys were not carried out to quantify soil variability largely based on soil texture and moisture content, an equally versatile method of grid sampling was used to divide the field into management zones [38]. After spatial data analysis, the soil and land surface were partitioned into 3 classes (zones) using the k-means clustering algorithm. In order to carry out the investigation of irrigation scheduling, a field capacity (FC) index was adopted corresponding to specific irrigation thresholds. Irrigation scheduling occurred when root zone soil moisture was depleted by the crop with the specific thresholds initially set.

A plot design with 0.25-hectare field under drip irrigation was developed and implemented to test whether a new wireless-based irrigation system performed better than conventional irrigation methods in terms of water use efficiency and yield. It was hypothesized that, compared to conventional methods, this automated system could send continuous soil moisture data to a base station programmed to open and close valves when irrigation was necessary, and significant water use savings would be achieved without compromising yield. To test this hypothesis, seven irrigation treatments were set up on the plot as shown in Table 1, with each treatment having three replicates. The seven types of irrigation treatments for drip irrigation presented in the table show the type of sensor and irrigation set points used in this research.

The treatments were applied to wheat plants belonging to a local variety of wheat (SC Nduna). This variety was chosen because a local commercial seed company (Seed Co. Zimbabwe) recommended it based on its superior performance in terms of yield.

2.2. Wirelessly Connected Soil Sensor System. The architecture used to implement the wirelessly connected soil sensor-based system is shown in Figure 1. The system had a low cost, locally designed (Munyaradzi M. and Masocha M., University of Zimbabwe, Deed of Assignment 2020) soil moisture sensor, which gave a reliable performance for the application under consideration.

The automated system implemented used an ATmega328P microcontroller. The data read by the sensors would be relayed to wireless sensor nodes deployed in the plot before being routed to a base station controller housed in a pump house some 130m away from the nearest node. The base station controller carried out the local processing and analysis needed to predict crop water requirements before operating relays that control the opening of electronic valves allowing water to flow to the field. Processed information from the base station is transferred to a Web or mobile device via a GSM/GPRS module. The hardware settings are elaborated in the following section.

2.3. Hardware Settings. The WCSS system employs some sensors for gathering data from the environment and in turn transfers it to sensor nodes for further transmission to a local base station. A GSM module SIM808 was used to transfer the values to a mobile/Web server. A data SIM card was inserted in it to enable real-time data transportation. A resistance sensor was used for soil moisture measurement, while for air moisture, an AM2302 DHT22 (temperature/humidity) sensor was used. Their details are described as follows.

2.3.1. Wireless Sensor Nodes. The wireless sensor nodes used in this study operated on license-free radio frequency (2.4 GHz) with mesh networking capability to assure redundancy of the communication path with the base station in the event of another node's failure. These wireless sensor nodes comprised the sensors, a microcontroller, RF module, and a solar power source with a battery that could operate without sunlight for up to three weeks. Figure 2 shows a solar powered sensor node in the wheat field.

2.3.2. Base Station Controller. The Base Station controlled the electronic valves through which the different treatments were irrigated. Figure 3 shows a wireless base station in the control room. Raspberry pi3 was used to connect to sensor nodes through ZigBee protocol and to users through the Internet or GSM/GPRS module. Mobile interface and Web interface provided remote monitoring of the treatments. An XBee module was configured as coordinator within the Raspberry Pi and connected to the XBee module via a USB cable. The Raspberry Pi's MySQL database received data sent by the sensor nodes in the field for local processing. For this irrigation method, two values were programmed to open at 415 millivolts (mV) and 450 mV, respectively. The two treatment levels are hereafter referred to as WCSS_{415} and WCSS_{450}.

2.3.3. Locally Built Soil Moisture Sensor. For the detection of soil moisture content, we used a locally built resistance moisture sensor. Figure 4 shows the soil moisture sensor. The purpose of using the resistance moisture sensor was due to its low cost nature, and comparable accuracy to other existing expensive soil moisture sensors. This sensor was used for real-time monitoring of soil moisture content in our experimental setup. The output voltages of the sensors varied according to the amount of water in the soil. If there was high moisture content in the soil, the output voltage would decrease, but if there was soil moisture depletion, the output voltage would increase. The soil moisture sensor output signal was analog in nature, and a conversion to digital was done by the microcontroller. The processed output was then used to control the water application through electronic valves. Soil moisture sensors were attached to the wireless sensor nodes to measure soil moisture at a depth of between 20 mm and 30 mm. Soil moisture measurement was important in order to obtain information with regard to the exact amount of water required to irrigate the wheat crop.

2.3.4. AM2302 DHT22 Sensor. The DHT22 sensor is a common temperature-humidity sensor used to determine temperature and humidity in the air (Figure 5). The DHT22 sensors are made up of two parts: a humidity sensor and a temperature sensor. The DHT22 sensor is a low-cost device, which is good for 0–100% humidity readings (2–5% accuracy) and good for −40 to 80°C temperature readings of ±0.5°C accuracy. The DHT22 sensor consumes a maximum of 2.5 mA while requesting data and has a body size of approximately $15.1\,\mathrm{mm} \times 25\,\mathrm{m} \times 7.7\,\mathrm{mm}$, of which 4 pins

Table 1: Irrigation treatments for drip irrigation showing type of sensor and irrigation set-points used for this research.

Irrigation method	Treatments	Sensor	Irrigation set points (thresholds)
Drip	T_{FP}	Fixed based on observation. (farmer practice used as control)	Field capacity
Drip	T10	Tensiometer	10 kPa
Drip	T25	Tensiometer	25 kPa
Drip	$ETc_{0.75}$	Weather data	$ETc^{*}1.00$
Drip	$ETc_{1.0}$	Weather data	$ETc^{*}0.75$
Drip	$WCSS_{415}$	WCSS (dielectric probe)	415 mV–25 kPa
Drip	$WCSS_{450}$	WCSS (dielectric probe)	450 mV–15 kPa

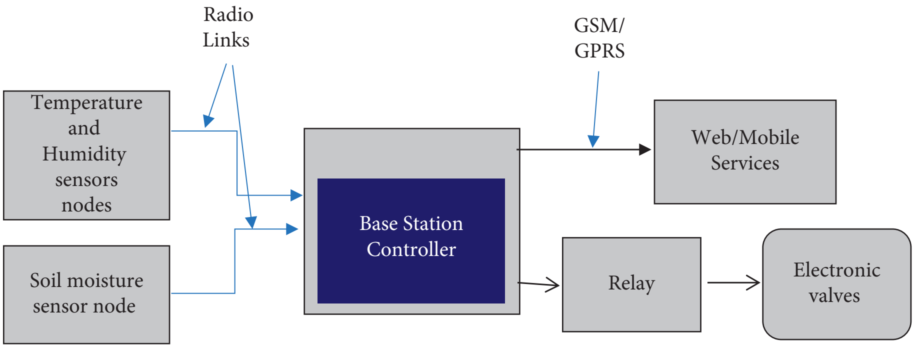

Figure 1: Architecture of the automatic irrigation system.

Figure 2: Winter wheat under drip irrigation and one of the sensor nodes designed.

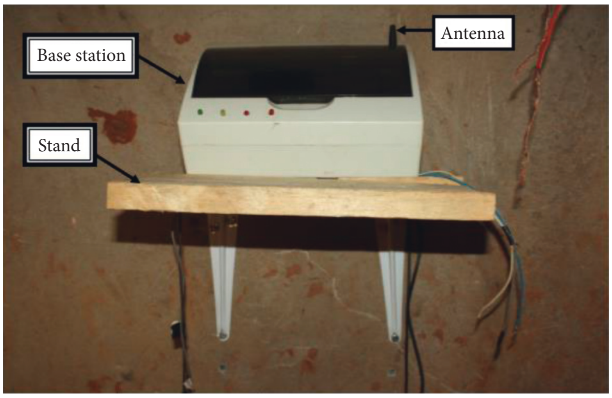

Figure 3: Base station controller housed in the control room.

Figure 4: The soil moisture sensor used in this research.

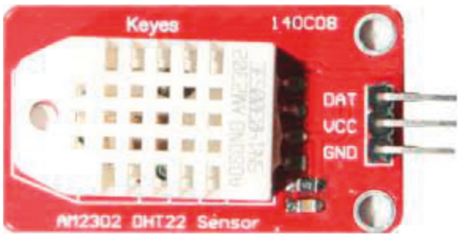

Figure 5: AM2302 DHT-22 temperature humidity sensor module used in the research.

have 0.1 mm spacing between them. These variables were measured at 15-minute intervals and relayed to the base station. The humidity sensor measured the humidity and air temperature. Humidity and temperature play crucial roles in the growth of plants. Low temperatures cause a reduction in the absorption and movement of water in plants, while low humidity causes increased transpiration rate, which results in plants using more water.

2.4. Manual Human Scheduling (T_{FP}). For typical farmer practice (T_{FP}), a field is irrigated 12 hours per week as follows: 4 hours every Monday, 4 hours every Thursday, and 4 hours every Saturday starting at 1000 hours. At each irrigation event, one liter of water is applied over an hour from each emitter. There were 82 standard emitters spaced 30 cm apart in a line. In this experiment, there were seven treatments, and each had three replications.

2.5. Tensiometer Irrigation Treatment (T_{10} and T_{25}). In this field experiment, two tensiometer treatments were used for automated irrigation. Irrigation was triggered at two suction thresholds, that is, 10 kPa and 25 kPa. Thus, this treatment had two levels, hereafter referred to as T_{10} and T_{25} corresponding to the two suction thresholds. The total amount of water used per drip line for T_{10} and T_{25} was 13776 liters and 14108 liters, respectively, for the 2016 season, followed by 14672 liters and 14289 liters, respectively, for the 2017 season, and finally 13967 liters and 14178 liters, respectively, for the 2018 season.

2.6. Evapotranspiration (ETc) Irrigation Treatment ($ETc_{0.75}$ and $ETc_{1.0}$). The crop water requirement is also called crop evapotranspiration and is usually represented as ETc. Evapotranspiration combines evaporation of water from the ground surface or wet surfaces of plants and transpiration of water through the stomata of leaves. The water requirement can be supplied by stored soil water, precipitation, and irrigation. Irrigation is required when ETc (crop water demand) exceeds the supply of water from soil water and precipitation. As ETc varies with plant development stage and weather conditions, both the amount and timing of irrigation are important. Estimates of ETc can be included in a simple water balance (accounting) method of irrigation scheduling to estimate the required amount and timing of irrigation for crops. This method can be used if initial soil water content in the root zone, ETc, precipitation, and the available water capacity of the soil are known.

The weather-based drip irrigation method (Figure 6) also comprised two treatment levels. For this method, an automatic weather station was installed at a site located about 300 m from the experimental field. The relays were set to trigger and open the valves at two thresholds, that is, crop evapotranspiration (ETc = 0.75), here called $ETc_{0.75}$, and (ETc = 1.0), here called $ETc_{1.0}$. These treatments are referred to as $ETc_{0.7}$and $ETc_{1.0}$. In a season, the total amount of water applied per drip line for (ETc = 0.75) and (ETc = 1.0) was 15350 liters and 13985 liters, respectively, for the 2016 season, followed by 16531 liters and 13450 liters, respectively, for the 2017 season, and 15190 liters and 14896 liters, respectively, for the 2018 season.

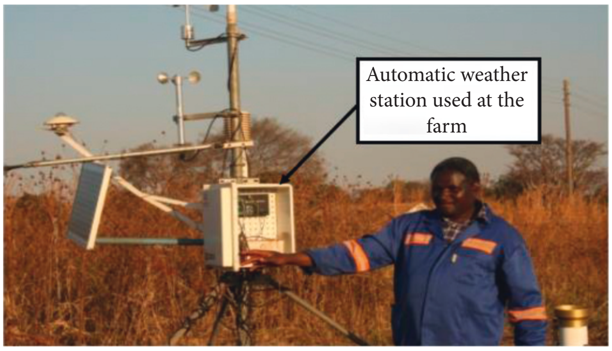

Figure 6: Automatic weather station that generated weather data.

2.7. Seeding and Fertilizer Application Rates. The crop was planted at a seed rate of 150 kgs/ha. There were three replicates for each of the treatments. Drilling method was used for planting at a rate of 2.2 kg of seed per each treatment with three replicates in rows 25m long. An interrow spacing of 0.30 m was used. Preplant dry fertilizer (compound D) was broadcasted at a 1860 kg/ha to each row of the treatments together with the seed. Figure 7 illustrates the rows that were 25m long. Irrigation was supplied with drip lines (T-TAPE TS × 508-12-450, T-systems International, Calif with 0.015-m internal diameter, 0.30 m emitter spacing, 1.0-L/h emitter discharge at 69 kPa, and 0.002-m thickness) approximately 0.50 m apart on either side of the wheat row. Planting was done between the 7th and 9th of July for all three seasons 2016, 2017, and 2018. A uniform amount of water was applied to both tensiometer treatments in the first two weeks of planting. Thereafter, irrigation occurred according to the threshold levels set on the tensiometers. After five weeks, urea fertilizer was broadcasted to each row of the two treatments at a rate of 1720 kg per hectare. Water application was terminated two weeks before harvesting the wheat crop.

2.8. Field Installation and Test on Wheat Crop. The drip irrigation field test and winter wheat crop layout are given in Figure 7.

3. Results

3.1. Plant Height. Figure 8 shows the achieved average plant height (cm) for all treatments in the three seasons for drip irrigation. $WCSS_{450}$ and $WCSS_{415}$ treatment had the highest plant heights at 76.7 cm and 75.56 cm, respectively. The $ET_{C1.0}$ had the lowest average plant height at 71.73 cm over the three seasons. This shows that our Wirelessly Connected Soil Sensor (WCSS) design had the largest average plant height over the three seasons. It is, however, important to note that the average plant height for all treatments was very close, and none of the treatments caused stunted growth.

3.1.1. Irrigation Water Use Efficiency and Amount of Water per kg of Yield. There was no rainfall during all three wheat growing seasons, and as a result, rainfall was not considered

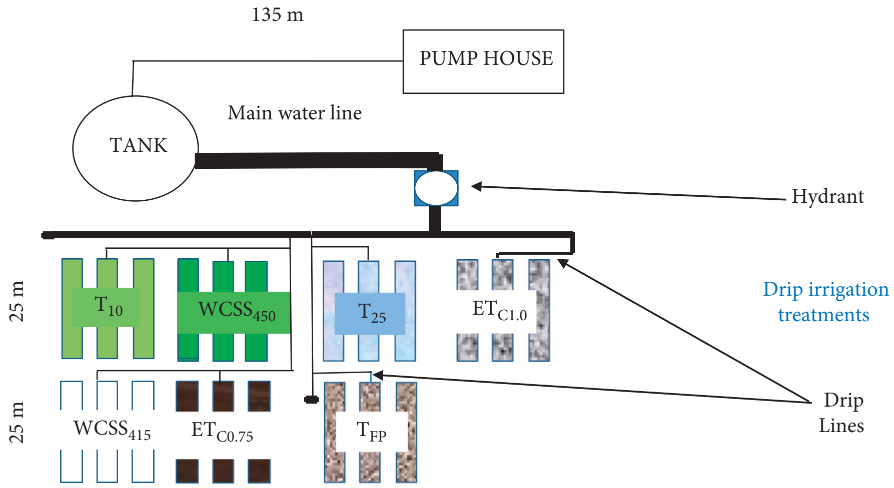

FIGURE 7: Drip irrigation field test and winter wheat crop layout.

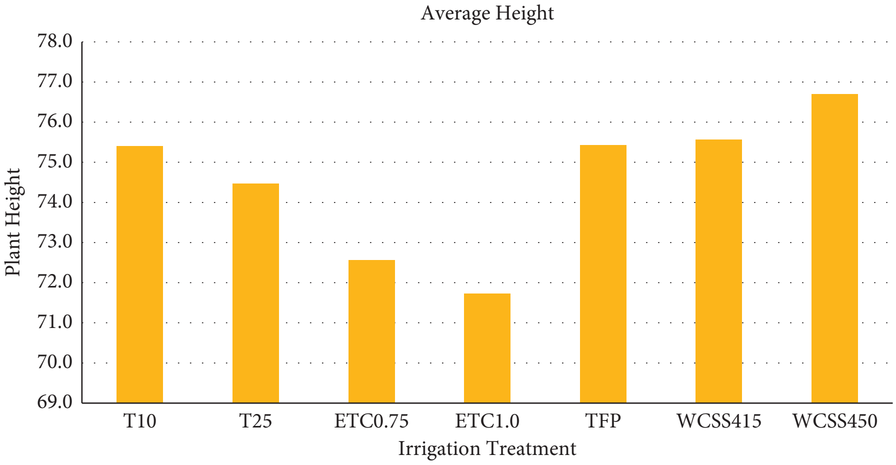

FIGURE 8: Plant height (cm) for winter wheat crop for the 2016, 2017, and 2018 seasons.

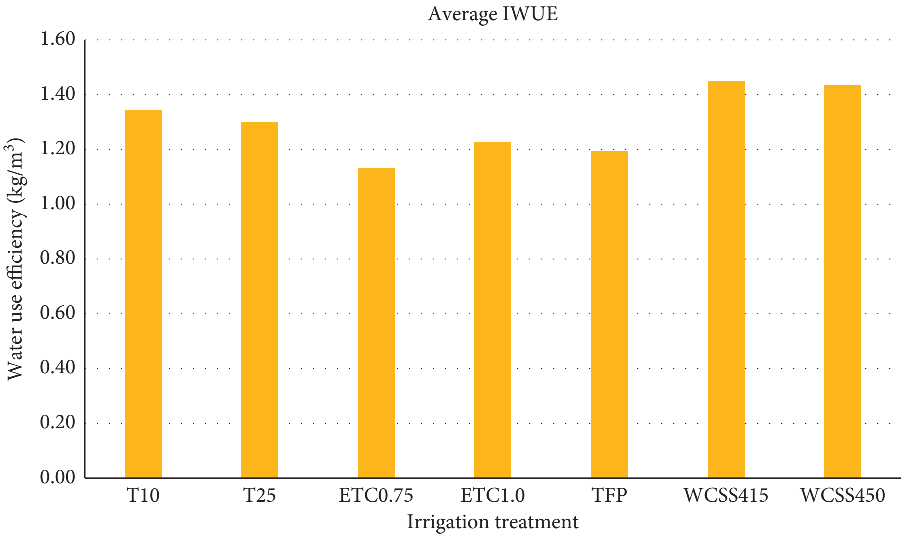

FIGURE 9: Average water use efficiency (kg/m^3) during 2016, 2017, and 2018 seasons.

as a parameter in any of the calculations. Figure 9 shows a plot of the amount of water used to produce a kilogram of yield versus the various treatments for the 2016, 2017, and 2018 seasons.

The WCSS415 treatment was associated with the least amount of water (1.54 kg/m^3, 1.41 kg/m^3, and 1.4 kg/m^3) in the three years 2016, 2017, and 2018, respectively. This translates to an average water use efficiency of 1.45 kg/m^3. It was closely followed by the WCSS$_{450}$ treatment, which had 1.436 kg/m^3. The ETC$_{0.75}$ treatment had the least water use efficiency at 1.133 kg/m^3, which was even lower than the farmer practice or control (TF$_P$) at 1.19 kg/m^3. All other automation treatments had higher water use efficiency when compared with the control.

These results were further confirmed by one-way analysis of variance (ANOVA). When compared to farmer practice (T$_{FP}$), both wireless connected soil moisture sensors (WCSS$_{415}$ and WCSS$_{450}$) were more efficient in terms of water use ($p < 0.005$). Similarly, WCSS$_{415}$ and WCSS$_{450}$ were more efficient when compared with ETc0.75 ETc$_{1.00}$ ($p < 0.005$). The mean for WCSS$_{415}$ versus tensiometer at 25kpa (T$_{25}$) was statistically different ($p = 0.016$), while WCSS450 against T$_{25}$ was also statistically different ($p = 0.041$). This indicates that WCSS system performed better than all other treatments in terms of water use efficiency. Both WCSS$_{415}$ and WCSS$_{450}$ versus T$_{10}$ showed that there were no statistical differences in the average values with p values of 0.209 and 0.306, respectively. This implies that the tensiometer at 10 kPa performed well in terms of water use efficiency.

3.2. Yield. Figure 10 indicates that high yields were obtained from all treatments with no significant difference to traditional farmer practice for all three seasons. Average yields for winter wheat in Zimbabwe range between 1 ton/ha and 7 tons/ha (Farm Management Handbook, V1-43), with the yields for all treatments falling within the expected range.

The WCSS$_{415}$ and WCSS$_{450}$treatments' average yields at 3.26 tons/ha and 3.24 ton/ha were slightly higher than the yields for other treatments for the three seasons.

An ANOVA test was also used to test for differences in observed average yields. The comparison of WCSS$_{415}$ and WCSS$_{450}$ versus farmer practice (T$_{FP}$) showed no statistical difference in the mean yield for both WCSS treatments with p values of 0.916 and 0.979, respectively. This result was at variance with our *a priori* expectation with respect to yield. This could have been as a result of system breakdowns that occurred in the WCSS treatments during the experimental seasons. Nonetheless, the WCSS system still performed better than T$_{FP}$ in terms of IWUE.

Further analysis indicated that WCSS$_{415}$ and WCSS$_{450}$were similar to T_{10} in terms of average yield with p values of 0.523 and 0.714, respectively. A possible explanation to this is related to the intermittent breakdowns that occurred in WCSS treatments between seasons when the experiment was being carried out. In addition, Qualia birds were also always a menace some weeks before wheat harvest at the end of each season, thus reducing the yield. Comparison of both WCSS$_{415}$ and WCSS$_{450}$ versus evapotranspiration treatments (ETc0.75 ETc$_{1.00)}$ yielded $p \leq 0.001$, meaning that the means were statistically different. WCSS$_{415}$ versus T$_{25}$ also showed averages that were statistically different with p-value of 0.012, while WCSS$_{450}$ against T$_{25}$ gave a statistical difference with p-value of 0.028. This shows that WCSS system performed better than all these other treatments in terms of yield.

4. Discussion

The main objective of this research was to assess the performance of wireless sensor connected systems (WCSS), viz-a-vis other methods, that includes traditional farmer practice, in terms of IWUE, yield, and plant height. The analysis should be understood in a national context where the country requires about 400,000 tons of wheat with the current production level of approximately 180,000 tons per year [39]. Furthermore, the country has been increasingly faced with erratic rainfall patterns due to climate change. Therefore, the need to increase input efficiency in cropping systems is a critical component in increasing national agricultural throughput.

Study findings showed that wirelessly connected sensor systems (WCSS) performed better than other irrigation scheduling methods used locally in terms of water use efficiency. Average IWUE indices associated with WCSS$_{415}$ and WCSS$_{450}$were 17% higher than TFP. Comparable results have been found in Sub-Saharan Africa. For example, a study in Ethiopia indicated that the use of wireless sensors in maize-based systems achieved significant gains compared to methods anchored on evapotranspiration. IWUE values achieved are comparable to those that have been obtained in other parts of the globe [40]. It has been reported that, generally, wheat IWUE ranges between 0.40 and 1.83 kg/m^3 globally when considering yield. For example, irrigation water use efficiency values of 0.70–1.51 kg/m^3 were reported in North China Plain [41, 42]. High IWUE values are quite important for farmers and other irrigation agencies in areas that have water scarcity. It could be argued that WCSS resulted in precise water availability in the root zone and thus a positive effect on crop growth. By providing the water needed by the crop based on temporal and geographical scales, the WCSS system produced higher yields than the farmer practice (T$_{FP}$).

One of the major factors to consider is the economic implication of the type of irrigation used by the farmer. As reported in the results section, the average irrigation water use efficiency (IWUE) for the wireless connected sensor systems (WCSS) treatment was higher than that of other treatments. On average, WCSS saved up to 25% water compared to typical fixed irrigation schedule rates used by wheat growers during the winter growing season [43]. This implies that wheat farmers can save about 0.15 USD per kg or 450 USD to produce about 3 tons of wheat per hectare. Results on IWUE also showed that high values could be realized either by saving water using WCSS drip irrigation system or simply improving yield through optimized utilization of water. The cost saving associated with the use of

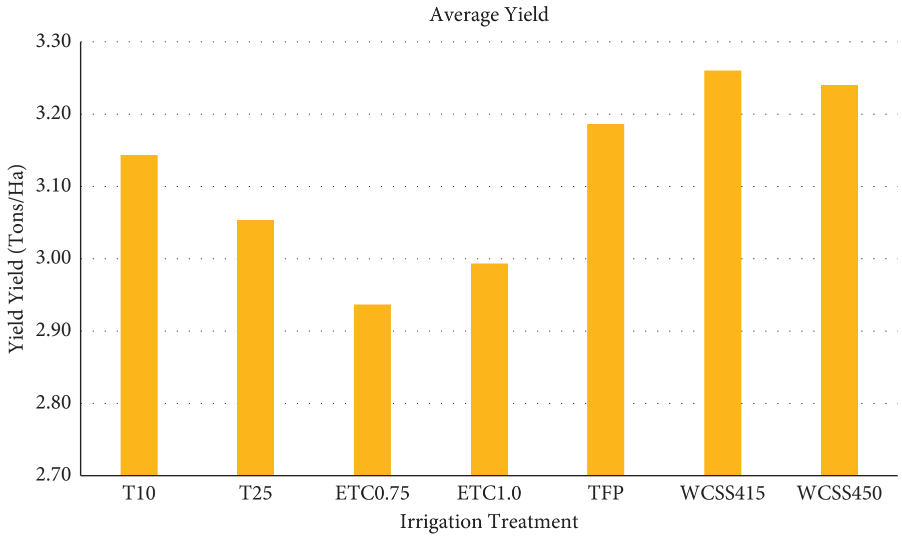

Figure 10: Yield (Ton/Ha) *vs.* treatments for 2016, 2017, and 2018 season.

WCSS is likely to increase the probability of long-term adoption by commercial wheat farmers in the country.

There were small differences in yield between the treatment and control across the three seasons. In this regard, $WCSS_{415}$ and $WCSS_{450}$ had 2.14% and 15% higher wheat yield than the T_{FP}. A number of previous wireless sensor-based studies have achieved varying levels of yield increases depending on the context. In their analysis conducted in Texas, onion yields were 93% higher for the drip irrigation system compared to the flood irrigation system [44]. It was observed that the earlier ensured that water availability had been synchronized with the underlying crop water needs. In our study, there were external factors that could have resulted in low wheat yield difference across treatments. Qualia birds were a constant menace in the early stages of grain filling and could also have a contribution in reducing harvestable yield. The differences in yield among all treatments could also be attributed to yield decrease with crop stress, especially in the initial stages when it becomes difficult for plant roots to extract adequate soil water from considerable depth, thus restricting its water uptake capability [45]. The result is that plant growth and yield are affected.

In wheat production, plant height is an important parameter that affects grain potential and other characteristics including spike length [46–52]. Findings from this research revealed that $WCSS_{450}$ had the highest plant height, while $ET_{C1.0}$ had the average lowest plant height at 71.73 cm over the three seasons. Although no significant differences were observed in terms of plant height across treatments, this parameter has been shown to have a positive effect on wheat grain yield [53]. Moreover, wheat residues can also be used for other purposes such as cattle feed and bedding for livestock. This enhances the linkages between the crop and livestock sectors on the farm [54, 55].

The main aim of this research was to design a low cost, wirelessly connected, automated controller with soil moisture sensors for irrigation scheduling. The researchers designed and constructed a reliable low cost intelligent controller that is affordable by low-income farmers. The results of this research are similar to those of [56–58] who concluded that information-based irrigation scheduling is inevitable for tightening the spatial-temporal variability of the field in the advent of global warming. The control system developed was made from cheap off-shelf components found abundantly in local laboratory stores and electronic retail shops with the potential to provide maximum water use efficiency by monitoring soil moisture at optimum levels. This is in sync with [59–61] among others, who found a 50% reduction in water use in tomato plants using soil water-based automatic irrigation system in comparison to daily manually irrigated treatments.

5. Conclusion

Traditional irrigation schemes found in Sub-Saharan Africa generally have a fixed supply of water irrespective of crops, their stage of growth, and underlying soil conditions. In this study, an experiment was carried out to evaluate the performance of a new wirelessly connected sensor system, for drip irrigation scheduling, and its effects on plant height, irrigation water use efficiency, and yield of winter wheat compared to other irrigation scheduling methods that are normally used by farmers in the region. The results obtained show that irrigation scheduling methods had notable effects on growth and the yield of winter wheat. The newly designed automatic irrigation controller treatments, $WCSS_{415}$ and $WCSS_{450}$, respectively, used much less water compared to other irrigation treatments employed in this research. WCSS saved up to 25% water on average, while maintaining yields compared to typical fixed irrigation schedule rates used by wheat growers during the winter season. Considering the necessity for water saving and to achieve sustainable food production, it becomes prudent for irrigation managers to move from rigid irrigation delivery schedules to more flexible delivery systems that are more efficient. WCSS irrigation scheduling also gave higher wheat average yield compared with other irrigation scheduling methods (+8%, +15%, and +29% for typical fixed farmer practice, tensiometer, and weather-based treatments, respectively). A similar improvement was noticed for irrigation water use efficiency (+25%, +12%, and +30%, respectively). This innovation is appropriate for both small-scale and large-scale commercial wheat growers as it can be manufactured using locally available materials such as scrap metal. Given the intermittent power cuts in the country, the WCSS sensors should ideally use a stable and green source of energy such as solar power. In addition, farmers must have a basic understanding of how to use such an ICT based irrigation. It therefore becomes important to provide appropriate training schedules for wheat farmers to increase ICT literacy.

5.1. Future Work. In this study, we have been able to implement wireless technologies and Internet of Things (IoT) for efficient irrigation of a wheat crop in Sub-Saharan Africa. As for future work, research work must continue with more field trials in order to prove that precision irrigation can provide greater benefits than conventional irrigation scheduling. The combination of wireless sensor technologies (IoT), Artificial Intelligence, and Cloud Computing should provide a precision irrigation system with robust and low-cost sensing capabilities, identification of sensing locations, data gathering, and efficient transfer for storage and processing. In addition, more research work has to focus on an improved optimization model in order to further reduce the water usage.

Data Availability

The data are not archived but can be availed upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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