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Research Article

A Prototype That Improves the Interpretation of Soil Moisture by Using the BGT-SEC Z2 Sensor

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Abstract

The amount of water required to irrigate, is essential in agricultural planning. In Mexico the water required for irrigation is generally not estimated when it is carried out despite several estimation methods being available (direct and indirect). However, some methods can be very expensive, requiring preparation time to use them or time to obtain the results. One of the methods involves using sensors based on relative permittivity. This method have been widely used in agriculture because they show the percentage of water contained in the substrate. However, this value helps the producer know the soil moisture status of their crop in percentage units but does not tell them how much water needs to be added to each plant in liters. Knowing this value could help reduce water losses due to infiltration, thereby increasing the crop area. Therefore, it was developed a device capable of recommending the amount of water in v/v (volume of water/volume of soil) required to irrigate a crop. The prototype device was based on the BGT-SEC Z2™ sensor and the ATMEGA 2560™ microcontroller. The obtained device was calibrated and a specific model was developed for two types of soil: sandy (with an RMSE of 0.0107) and loamy (with an RMSE of 0.00556). With factory calibration, a RMSE value of 0.0339 was found for the loamy soil and 0.0278 for the sandy soil. In addition, the sensor was tested on strawberry plants with pots covered with and without plastic mulch (using loamy soil). The results on the strawberry plants, indicated that water consumption was best explained by the specific calibration equation for loamy soil covered with plastic mulch (67.8 mL RMSE) and without plastic mulch (82.8 mL RMSE). Finally, it was found that at least two measurements are required to obtain soil moisture average in plastic mulch strawberry pots and 6 measurements in pots without plastic mulch. With the above, it is concluded that the device developed in this study performed adequately during experiments and the sensor worked continuously without failing.

Keywords

Water Volumetric Content, Sample Size, Acceptable Error, Sensor Accuracy

1. Introduction

Soil moisture is an essential parameter for understanding the interactions and feedbacks between the atmosphere and the Earth's surface through energy and water cycles. Knowledge of the spatiotemporal distribution of soil moisture has long been a challenge [1].

The experimental and accurate determination of soil moisture is a matter of great importance in different scientific fields, such as agronomy, soil physics, geology, hydraulics, and soil mechanics [2].

It is worth mentioning that there are current technologies to

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measure soil moisture, such as sensors based on the principle of dielectric characterization of the soil and water and use conversion relationships. These sensors require appropriate calibration for precise measurements [3].

On the other hand, it is possible to make a data acquisition card calculate in real-time, the irrigation needed in terms of water volume required per given volume of soil (v/v), however, conventional measuring devices do not provide this value.

Due to the above, it was proposed to develop and evaluate a device capable of calculating the amount of water that should be used for irrigation in a crop, based on the measurement of moisture with a BGT-SEC Z2™ sensor, to help producers apply the irrigation supply in the right quantity and at the right time, to avoid wasting water resources.

2. Materials and Methods

To develop the project in this study, the BGT-SEC Z2™ sensor was used. With this sensor, a datalogger was created to process the sensor data. The sensor was calibrated with two soils, and finally a test was carried out on strawberry (*Fragaria* spp.) crops to determine its performance and obtain the sample size to measure the average soil moisture.

To do the above, the soil moisture sensors available on the market were analyzed. It was decided to use the BGT-SEC Z2™ sensor (based on dielectric permittivity), by the company Bejing Guoxinhuyan Techonology Co., Ldt, due to its price and the variables it measures (soil moisture, soil temperature and electrical conductivity).

2.1. Design and Development of the Datalogger

A datalogger for the sensor that displays water quantity indications (in liters) was searched for on the market, however, no device was found. Because of this, a datalogger was designed based on a precise open source Arduino-Mega 2560™ microcontroller board. In addition, integrated circuits were used such as: the DS1302TM RTC™ module (which provides a real-time clock), Neo-6m™ GPS module (to obtain the location of the sampling site), Gy-906™ module (MLX90614™ temperature sensor with accuracy ± 0.2 C), MLMSD™ module (to store variable measurements) and, a 3.5-inch TFT LCD touch screen (to display information). The container containing all the ICs was printed on a Creality Ender 3 V2™ 3D printer. These electronic modules were used, because they have been used in some agricultural research before [4-6]. To communicate with the BGT-SEC Z2™ sensor, the Arduino™ 2560 receives a data stream that includes three raw measurements, space-delimited and terminated by the return character [7].

2.2. BGT-SEC Z2™ Sensor Calibration

If an ellipsoidal cylinder is drawn around the sensor with the experimentally measured dimensions, the total volume of influence of the 10HS™ is approximately 1160 cm^3 [8]. On the other hand, if an ellipsoidal cylinder is drawn around the sensor with dimensions measured experimentally, the total volume of influence of the Teros10™ is approximately 430 cm^3 [9]. Due to the above, to calibrate the BGT-SEC Z2™ sensor and avoid an error due to a lack of soil, a volume of soil greater than the influence volume required by the 10HS™ sensor, was obtained. These soil samples were collected from sandy soil (Sandy-Puebla) in Zacapoaxtla, Puebla, Mexico, at the WGS84 coordinates (19.841637,-97.593339) and loamy soil (Loamy-Colpos) in the "Colegio de Postgraduados" at the WGS84 coordinates (19.841637,-97.593339). Soil texture classes were determined according to the USDA method [10].

Subsequently, the Sandy-Puebla soil was left to dry in sunlight (spread over 2.5 m^2) for three days and then placed inside a 20-liter container, with an internal radius of 13.5 cm and a height of 35.5 cm. The container was completely filled with sand and the moisture was measured with the BGT-SEC Z2™ sensor (12 measurements were done for each level at random places in the container) when the amounts of water added were at the following levels: 0 Lt, 0.91 Lt (0.0455 v/v), 1.815 Lt (0.09075 v/v), 2.895 Lt (0.14475 v/v), 4.265 Lt (0.21325 v/v), 5.41 Lt (0.2705 v/v), 7.84 Lt (0.392 v/v). The moisture of each level was calculated (m^3 of water/m^3 of soil), by taking 20 liters as the soil volume and considering 0.026 m^3/m^3 as the initial soil moisture, which was the initial value measured by using the BGT-SEC Z2™ sensor factory-calibration. The Ɛa values of each measurement were obtained as indicated in the sensor manual [7], and related to the soil moisture of their respective level to estimate the parameters of the cubic regression equation.

To calibrate the Loamy-Colpos soil, the same procedure was followed as with the sand, using specific amounts of added water: 0 Lt, 1.175 Lt, 2.315 Lt, 3.205 Lt, 4.49 Lt and, 5.930 Lt.

2.3. Sample Size in Loamy-Colpos and Sandy-Puebla Soil

To determine the number of repetitions to measure in the Sandy-Puebla and Loamy-Colpos soil, a simple random sampling was carried out to determine the minimum number of samples that should be taken to obtain an average value of soil moisture with 95% confidence, based on the method of Lohr [11]. The population size was assumed to be N = 100,000 and a sample size was calculated for each soil moisture condition. The value N = 100,000 was used because a sample of size 100 from a population of 100,000 units has almost the same precision as a sample of size 100 from a population of 100 million units [11]. The sample sizes were calculated taking into account the margin of error values of 0.0075, 0.01, 0.02, 0.03 and 0.04. Sampling was carried out for each soil moisture level and for each type of soil (Sandy-Puebla and Loamy-Colpos). It is worth mentioning that this soil was mixed very well and was allowed to rest for 30 minutes before measuring to allow the water to disperse within the soil.

2.4. Sample Size in the Strawberry-Soil

To evaluate soil moisture in the strawberry crop, strawberry plants of 1.5 years of age on average (with different plant cover conditions) were used, which were inside pots with an estimated soil volume (Strawberry-Soil) of 2723.21 cm^3 (0.002273 m^3). The soil was watered at some points in the pot and allowed to rest for 1 hour before measuring (to allow the distribution of water in the soil), however, the water was not distributed homogeneously, causing the sensor to detect variations in moisture. Therefore, a simple random sampling was carried out in the pots (with strawberries) to determine the sample size (to estimate moisture). Moisture was measured (more than 10 measurements) in 6 pots covered with plastic mulch (black plastic on the bottom and white plastic on top) and in 6 pots without plastic mulch, in loamy soil [10].

2.5. Test in Strawberry Cultivation (*Fragaria* spp.)

The moisture of the Strawberry-Soil (two measurements with the BGT-SEC Z2™ sensor) and the weight (using a B-Zeero™ digital scale, 40 Kg) were measured in each pot (0.002273 m^3 of soil), at the same time (1:00 p.m. central Mexico time), under two conditions: 6 plants with plastic mulch (black plastic on the bottom and white plastic on top) and 6 plants without plastic mulch.

The measurements were carried out, during the months of July and August (MM/DD): 07/18, 07/19 (irrigation), 07/20, 07/21 (irrigation), 07/24, 25 /07, 07/26 (irrigation), 07/28 (irrigation), 07/31, 08/01 (irrigation), 08/02 and, 08/03. Moisture and weight were measured before irrigation and 1 hour after irrigation (so that the water had time to disperse in the substrate).

Subsequently, the weight losses (water consumption) recorded with the scale (observed values, transformed to mL and a water density equal to 1 was assumed), were compared with the water consumption detected by the BGT-SEC Z2™ sensor (estimated values) at the same time interval. The specific calibration equations in loamy soil, the factory calibration equation, and the regression equation found with Excel-Solver™ were used. Negative water consumption occurred when the irrigation was carried out (when moisture increased).

2.6. Calibration-Equation Found with Excel-Solver™

The root mean square error (RMSE) was calculated as the difference between water consumption measured (with the scale) and water consumption estimated (with the sensor) in the Strawberry-Soil. When calibrating the sensor, a cubic model was adjusted, and the model coefficients were estimated with the following restrictions ("changing variables"): The coefficient of the cubic variable was set to be greater than -0.001 and less than 0.001; the square term must be greater than -0.1 and less than 0.1; the first order term must be greater than -1 and less than 1; the constant must be greater than -100 and less than 100. Additionally, the lowest measurement found by the sensor was set to be greater than 0.02 and less than 1. The GRG Nonlinear method was used to perform the optimization.

2.7. Comparison Among Strawberry-Soil Means

Soil moisture values for each date were obtained for the following treatments: without plastic mulch and with plastic mulch measured with the sensor and; without plastic mulch and with plastic mulch measured with the scale in each strawberry pot. Data greater than 0 were taken into account, because data less than zero represent irrigation. In addition, water consumption data for 1 full day were used. To carry out the comparison, the R-STATISTICS™ program version 4.2.2 was used. The shapiro.test command was used to perform the Shapiro-Wilk normality test [12], based on the research of Royston [13]. The bartlett.test command was used to perform Bartlett's test of homogeneity of variances [12], based on Bartlett test [14]. To perform the Tukey test, the HSD.test command included in the agricolae library was used [15].

3. Results

3.1. Design and Development of the Datalogger

The resulting prototype has three menus as an initial result: the first menu displays the measured variables, the second menu displays the substrate soil moisture data, and the last menu gives the option to update date and time (Figure 1).

The variables that the device can measure are: air temperature (℃), soil temperature (℃), object temperature (℃), soil electrical conductivity (ds), soil moisture (v/v), latitude, longitude and altitude (masl).

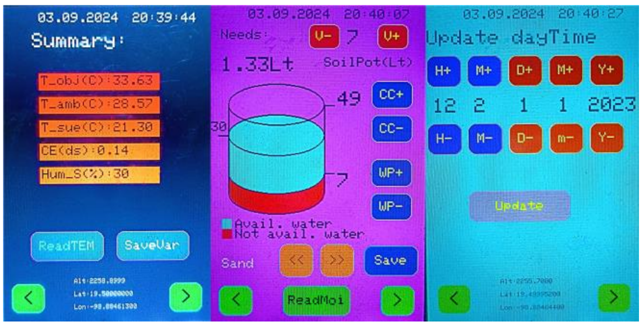


Figure 1. Variable summary menu (left), soil moisture summary menu (center), and date and time menu (right).

3.2. Sensor Specific Calibration for Loamy-Colpos and Sandy-Puebla Soils

The estimated Sandy-Puebla soil calibration curve obtained a RMSE value of 0.0107 v/v, and the coefficients are described in equation (1).

$$WVC = 1.82369X10^{-5}\varepsilon_a^3 - 0.00137208\varepsilon_a^2 + 0.0415136\varepsilon_a - 0.0709040 \quad (1)$$

And for the Loamy-Colpos soil the RMSE found was 0.00556 v/v and the coefficients are described in equation (2).

$$WVC = 5.02444X10^{-5}\varepsilon_a^3 - 0.00304235\varepsilon_a^2 + 0.06530588\varepsilon_a - 0.163747022 \quad (2)$$

Where WVC is the volumetric water content (v/v), and Ɛa is the value obtained by the sensor divided by 50.

In addition, the RMSE was calculated with the factory-calibration equation [7], for soil moisture and a value of 0.0278 v/v was found for the Sandy-Puebla soil and 0.0339 v/v for the Loamy-Colpos soil.

3.3. Sample Size for the Sandy-Soil and the Loamy-Soil

It was found that the Sandy-Soil and the Loamy-Soil must be measured once to obtain the true value of the average soil moisture with 95% confidence and a measurement error of 0.02 v/v (Figure 2) when the researcher performs the calibration of a homogeneously moistened substrate as indicated in the methodology of this study.

3.4. Sample Size for the Strawberry-Soil

With respect to the soil in the strawberry pots (Strawberry-Soil), it was found that to obtain the soil moisture value with 95% confidence, the Strawberry-Soil must be measured with at least two repetitions (Figure 2) when covered with plastic mulch, with an error of 0.02 v/v. On the other hand, when there is no plastic mulch covering the pot, up to 6 repetitions should be measured (Figure 2). However, when carrying out more measurements in the pot, the roots may be damaged, due to the metal tips of the BGT-SEC Z2™ sensor. Due to the above, to carry out the experiment under the same conditions, two measurements were made when measuring the soil moisture in the strawberry pots.

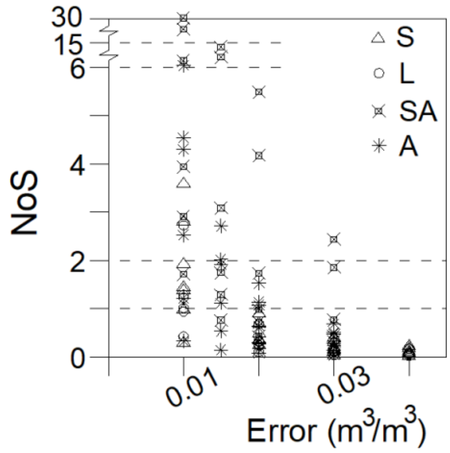


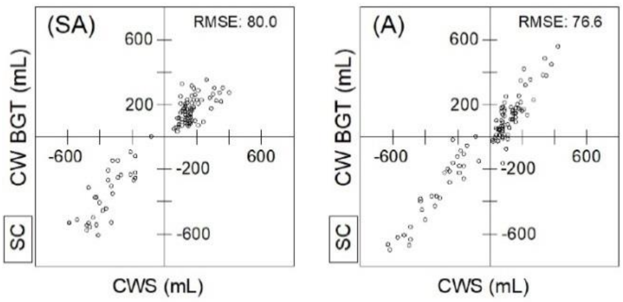
Figure 2. *Sample size required, (NoS) to obtain a soil moisture mean value with an acceptable error (Error, m^3/m^3), with 95% confidence for the Sandy-Puebla soil (S), for the Loamy-Colpos soil (L) calibrated with homogeneous soil moisture and, for the sample size required in the soil of the pots of the strawberry crop studied without plastic mulch (SA) and with plastic mulch (A) with its variable soil moisture found in the field.*

3.5. Strawberry-Soil Experiment

RMSE values were calculated by comparing water consumption and irrigation obtained with the scale versus those obtained with the sensor in the Strawberry-Soil (Figure 3).

3.6. RMSE Optimization for the Straberry-Soil with Excel-Solver™

Optimization with Excel-Solver™ yielded a RMSE value of 76.6 mL for the strawberry pots with plastic mulch and 80.0 mL for the strawberry pots without plastic mulch, when plotting the water consumption observed with the scale versus the water consumption estimated with the sensor using the calibration equations: factory-calibration, specific-calibration for Loamy-Colpos soil and, Excel-Solver™ calibration (Figure 3).



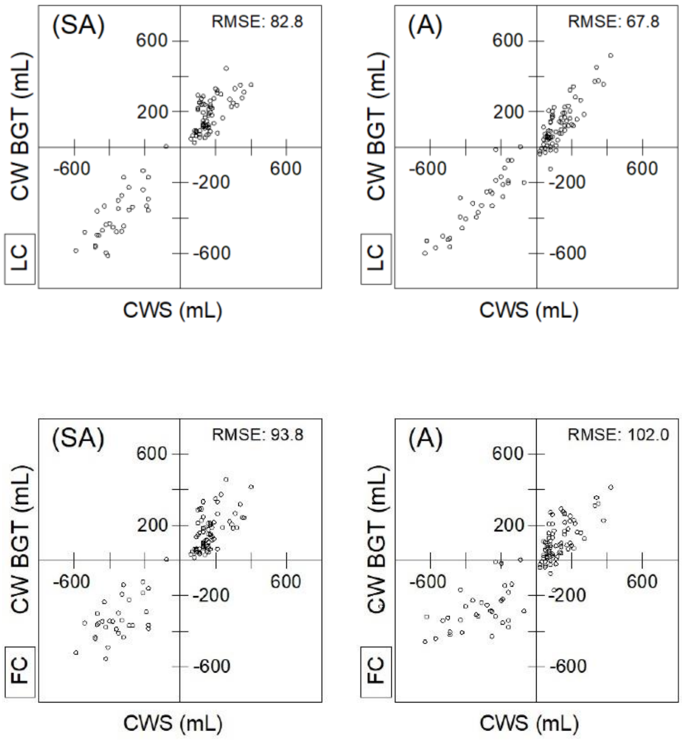


Figure 3. Water consumption obtained using the digital scale (CWS) compared to water consumption obtained using the sensor BGT-SEC Z2 (CW BGT), by using the three models: factory-calibration (FC), Loamy-Colpos calibration (LC) and Excel-Solver calibration (SC), and under two conditions: plots covered with plastic mulch (A) and without plastic mulch (SA).

3.7. Comparison of Means Among the Four Treatments in the Strawberry-Soil

The water consumption measured: with the sensor without plastic mulch, with the sensor with plastic mulch, with the scale without plastic mulch and, with the scale with plastic mulch for the Strawberry-Soil, gave a p-value of 0.0007189 for the Shapiro-Wilk test. This result indicated that there is no normality for the residuals.

The data were transformed by using the square root method derived from the Box-Cox methodology in the MASS library and the boxcox command in R Statistics™. Then the Shapiro-Wilk test was performed again, and a p-value of 0.496 was obtained, indicating normality in the residuals. The next test, Bartlett's test [14], was performed, which yielded a p value of 2.548e-05. This indicated that there was no homogeneity of variances.

When visually comparing the data using the box and axis plot (Figure 4), it was observed that the treatment with soil moisture measured using the scale and without plastic mulch presented a variance that could be causing the null hypothesis to be rejected.

Due to this, the values of the treatment measured with the scale and without plastic mulch were omitted and data were transformed again by using the square root method derived from the Box-Cox methodology in the MASS library and the boxcox command in R Statistics™. Then, the Shapiro-Wilk and Bartlett tests were performed again, obtaining p-values of 0.2036 and 0.09 respectively. This ensured the normality of the residuals and the homogeneity of variances.

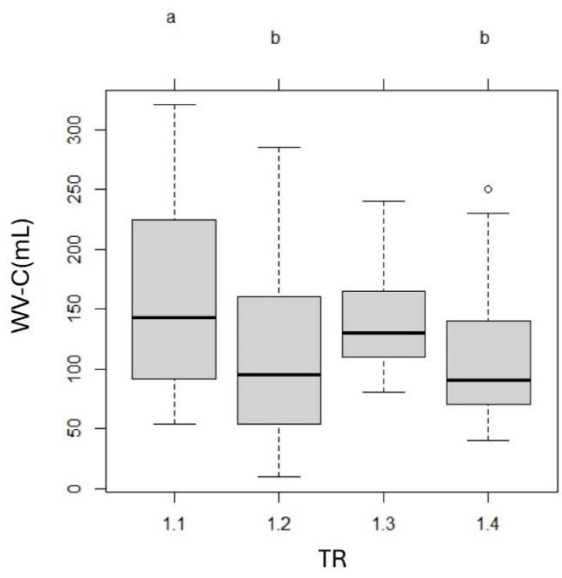


Figure 4. Tukey test results (letters above) for water consumption (WV-C) and treatments (TR): measured with the sensor (without plastic mulch "1.1" and with plastic mulch "1.2") and, measured with a scale (without plastic mulch "1.3" and with plastic mulch "1.4"), in the Strawberry-Soil.

Subsequently, the analysis of variance test was carried out with the data used for the previous tests and it was found that at least one treatment is significantly different.

The Tukey test was carried out according to the agricolae library [15], and it was found that the treatment of water consumption measured with the sensor without plastic mulch had a significant difference from the other two treatments, while the water consumption treatments with the sensor and plastic mulch, and with the scale and plastic mulch had no significant difference between them.

4. Discussion

As shown in Figure 4, the Strawberry-Soil treatment measured with the sensor and without plastic mulch presented high dispersion, while the treatment measured with the sensor and with plastic mulch showed less dispersion (Bartlett's test value of 2.548e-05).

This coincides with the study by Martínez-Saldaña *et al.* [16], who found that with plastic mulch there is greater uniformity of water distribution, both vertically and horizontally, as well as a longer wetting length in the horizontal direction compared to soils without plastic mulch.

In this regard, in this study it was also found that the substrate in pots covered with plastic mulch, showed better moisture distribution since the soil moisture sensor obtained values closer to the average moisture of the substrate. In contrast, in pots not covered with plastic mulch, the sensor had greater dispersion when determining moisture values.

It is worth mentioning that in this study two repetitions of soil moisture measurement were carried out for each pot to obtain the average soil moisture value in both treatments with and without plastic mulch.

However, the number of repetitions may vary depending on the substrate or treatment. In their study, Tenelanda-Patiño *et al.* [17] used three repetitions to capture the spatial variability of soil moisture and reported averages of those three measurements. On the other hand, in the study of Abanto-Rodríguez *et al.* [18], performed four repetitions to determine the soil moisture of a Geric Xanthic Ferralsol soil. Furthermore, there is currently no method that specifies the number of repetitions needed to determine average soil moisture. Therefore, each substrate must be analyzed with a different number of repetitions to obtain soil moisture values with 95% confidence and an acceptable error margin.

In this study it was found that two repetitions are enough to obtain the average soil moisture in the strawberry pots with 95% confidence and an error of 0.02 v/v in the Strawberry-Soil covered with plastic mulch (Figure 2). There are points in Figure 2 that exceed two repetitions, these values correspond to pots without plastic mulch, which aligns with results found by Martínez-Saldaña *et al.* [16], on better water distribution in soils protected with plastic mulch. Additionally, it is necessary to highlight that when calibrating the sensor, the loamy (Loamy-Colpos) and sandy soils (Sandy-Puebla) were carefully mixed with water to achieve maximum moisture homogeneity. Thus, only one measurement is required to obtain soil moisture with an error of 0.02 v/v and 95% confidence.

In the Tukey test (Figure 4), it was found that there is a significant difference between treatments without plastic mulch compared to those with plastic mulch (measured with the sensor). Visually observed in the diagrams (Figure 4), the treatment with higher water consumption, is the one without plastic mulch. This coincides with the research of Martínez-Saldaña *et al.* [16], who found that plastic mulch significantly reduced direct water evaporation in their study. This also aligns with Inzunza-Ibarra *et al.* [19], who found that in terms of water use efficiency, crops grown with plastic mulch are more efficient than those without mulch. For their part López-López *et al.* [20], found that irrigation sheets can be reduced by using plastic mulch in irrigation scheduling. In this section, authors are advised to provide a thorough analysis of the results and make comparisons with relevant literature, not a short summary or conclusion. Any future research directions could also be stated in the discussion.

5. Conclusions

When water is mixed with the soil as indicated in this study, a single measurement can be made to obtain the average soil moisture with 95% confidence and an error of 0.02 v/v. To measure soil moisture in loamy soil covered with plastic mulch, at least two measurements are needed to obtain the soil moisture value with the same confidence and acceptable error. However, if plastic mulch is not available, up to six soil moisture measurements per pot must be made with the sensor to obtain the true average value with the same confidence and acceptable error.

In addition to the above, it should be noted that BGT-SEC Z2^{TM} soil moisture sensors perform well in the indicated substrates (after calibration), because measurements were made in the exact same place in a pot without changing position and the soil moisture value did not change. However, in soil without plastic mulch, changing the position of the sensor results in different measurements because the real soil moisture varies along the surface or depth. This change in real soil moisture requires more measurements to be done in soil without plastic mulch.

Derived from the study, it was also found that soils with plastic mulch will have lower water consumption than soils without mulch.

With the above, it is concluded that the device developed in this study performed adequately to obtain precise values in real time, on the quantities of water to be irrigated in units of v/v and liters.

Abbreviations

RMSQ	Root Mean Square Error
DD	Day
MM	Month
TM	Trademark
GRG	Generalized Reduced Gradient
WGS84	World Geodetic System 1984
LCD	Liquid Cristal Display
TFT	Thin-Film Transistor
HSD	Honestly Significant Difference
v/v	Water Volume (m^3) / Soil Volume (m^3)

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Author Contributions

Abel Quevedo-Nolasco: Conceptualization, Supervision, Methodology

Graciano-Javier Aguado-Rodríguez: Data curation, Investigation, Writing – review & editing

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Abel Quevedo-Nolasco is an Agronomist, Specialist in irrigation (1988), graduated from the Autonomous University of Chapingo. Master of Science in Agrometeorology (1994) with honorable mention, and Doctor of Science in Edaphology (2005), by the Postgraduate College. He made update curses at the University of Tottori, Japan and the United States Forest Service. He has participated in the training of undergraduate, master's and doctoral students. He has been a professor of the Bachelor's degree in Hydrology at the Metropolitan Autonomous University - UAM. He is currently a Research Professor of the Postgraduate Program in Hydrosciences, has published scientific articles, co-authored two books, co-translator and compiler. He is a Member of the National System of Researchers (Level 1: 2015-2018, 2021-2025). Coordinator of the first meeting on "Innovation in Water, Agriculture and Environment (2013)". He was Coordinator of the Postgraduate Program in Hydrosciences (2015-2016).

Graciano-Javier Aguado-Rodriguez is an Irrigation Engineer from the Autonomous University of Chapingo and Doctor of Science in Hydrosciences from the Postgraduate College. He has an honorable mention in his undergraduate thesis and congratulations for his academic career in his doctoral thesis. He has worked at the Polytechnic University of Francisco I. Madero for eight years, teaching subjects in Agrotechnology Engineering and in the Master of Science in Sustainable Agrotechnological Development. He is a Member of the National System of Researchers (Level 1: 2021-2024). He has conducted irrigation research primarily designing prototypes that control irrigation systems. In addition, he has worked with image analysis to detect problems due to diseases in fruits.

Research Field

Abel Quevedo-Nolasco: Agrometeorology, Agroclimatology, Irrigation, Software Design, Hydrology.

Graciano-Javier Aguado-Rodríguez: Irrigation, Software Design, Water Balance in Plants, 3D Printing, Sensor Reading.