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SmartWT: An open IoT sensor, datalogger and GPRS data transmission device for monitoring water levels in rice fields, with application to AWD irrigation

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ABSTRACT

Water management is a time-consuming aspect of rice cultivation, particularly when the Alternate Wetting and Drying (AWD) irrigation technique is adopted. This technique requires the ponding water level to be monitored daily to determine the optimal time for flooding the paddy. This study proposes SmartWT, a remote monitoring system for continuously monitoring ponding water levels in flooded rice fields. Based on open-source architecture, the system uses an Arduino Nano in conjunction with a General Packet Radio Service (GPRS) board to acquire and transmit data for remote communication purposes. Distance is measured by an ultrasonic sensor installed on a Water Tube (WT) inserted into the soil, perforated below the soil surface. The entire system has been optimised for this operating environment and features a waterproof sensor and container. The device has been designed to operate using minimal power; it runs on batteries alone, with an approximate lifespan of three months when transmitting every two hours. Several laboratory and field tests have been carried out to verify the sensor's accuracy and investigate the influence of pipe diameter and environmental temperature. Field tests have demonstrated that the sensor can withstand the extremely challenging conditions found in rice paddies, conditions that are too difficult for most instruments to handle. The accuracy error is typically less than 1 cm, which is a reasonable tolerance for ponding water level management. If accurate readings are needed, an accuracy error of a few millimetres can be achieved by adding a temperature sensor to the device.

1. Introduction

Rice (Oryza sativa L.) is the third most widely produced cereal in the world after wheat and maize, with 776 million tonnes harvested in 2022 (Food and Agricolture Organization of the United Nations, 2022). Rice cultivation often involves the continuous flooding of the crop from sowing to harvest, which leads to the use of large amounts of water, the production of climate-altering gases (GHGs), as well as the presence of arsenic (Ar) in the grain (Rahman et al., 2024; Gharsallah et al., 2023; Carrijo et al., 2017; Lampayan et al., 2015).

Italy is the leading rice producer in Europe (Food and Agricolture Organization of the United Nations, 2022), but the cultivation of this cereal in the last two decades is facing several problems, including water scarcity. This is partly due to the introduction of dry seeding techniques, which prevent groundwater resources from being properly replenished at the start of the agricultural season and delay the peak of the irrigation demand in June, exacerbating the competition for water with other crops, such as maize (Gilardi et al., 2023). However, it is primarily a consequence of climate change, which is leading to less precipitation in the Alps, especially in autumn and winter, and higher temperatures (Crespi et al., 2021; Ranzi et al., 2021). Additionally, increasingly stringent limits on the presence of heavy metals in cereal grains are being introduced, and the European Union is enforcing policies to reduce emissions of climate-altering gases.

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The AWD is a promising irrigation strategy that can address many of these issues, at least to some extent. The AWD technique is a well-established method in Asia and has already been tested in rice fields across various countries for 20–30 years; in Italy it has been implemented in experimental fields since 2019 (Rahman et al., 2024; Vuciterna et al., 2024; Gharsallah et al., 2023; Gilardi et al., 2023; Lampayan et al., 2015;) It is based on intermittent flooding, allowing continuous alternation of aerobic and anaerobic soil conditions and it can be applied starting from the tillering phase onwards, whether after water seeding or dry seeding. Each intermittent irrigation event comprises: 1) a flooding phase that stops when the ponding water level in the field reaches a given height (usually 8–12 cm); 2) a waterlogging phase in which the water remains in the field and its level drops due to infiltration and evapotranspiration; 3) an aerobic phase in which the field surface is allowed to dry; and 4) a new flooding performed when a certain soil moisture threshold is reached in the rooted soil (Rahman et al., 2024; Gharsallah et al., 2023; Carrijo et al., 2017). The literature suggests different types of thresholds, which vary in severity and in the way soil water status is measured. The water content of the rooted soil can be monitored using soil water status sensors (e.g., soil moisture or soil water potential sensors) or a field WT. The WT is a simple, inexpensive device consisting of a perforated tube inserted vertically into the rooted soil. Once the ponding water has completely infiltrated, it allows the monitoring of the water level below the soil surface, also known as the ‘perched groundwater level’. In the WT method, the threshold for a new AWD flooding is not set according to a soil moisture value, but to a water level in the WT, which is assumed to be a proxy for the soil moisture content of the rooted zone. Consequently, when the water level in the tube reaches a certain depth below the soil surface, a new flooding event occurs (Gharsallah et al., 2023). Bouman et al. (2007) and Carrijo et al. (2017) point out as a general rule that an AWD re-flooding threshold of 15 cm below the soil surface results in no yield loss. Obviously, applying the WT method requires farmers to install a WT in each field and to check the water level daily during the drying periods throughout the AWD season.

It should be noted that measuring the water level inside the WT is particularly uncomfortable and, since farmers typically manage dozens of fields, this makes applying the WT method very labour-intensive. Therefore, automating the WT measurements could greatly reduce labour requirements and increase measurement frequency and regularity.

If on the one hand, the device must be extremely reliable and robust to work in the extreme environment of the paddy field (water, humidity, animals, spiders, insects, etc.), on the other, very high-quality precision measurements of the water level are not that useful. Indeed, there is a margin of uncertainty of a few centimetres in defining the ground surface level in rice fields due to small-scale roughness caused by differences in ground elevation due to the presence of rice root systems, erosion and deposition processes caused by water flow, and small laser levelling errors.

Although some commercial devices are available to monitor the ponded water levels in rice fields, many of them are not specifically designed for use inside WTs. Furthermore, they are all too expensive to be installed in every field on a farm.

For these reasons, the authors developed a relatively inexpensive device based on open-source technologies, which have been shown to be crucial for the realisation of the Internet of Things (IoT) vision. Indeed, IoT applications in agriculture include mainly tools suitable for monitoring key agro-meteorological and soil water status variables on a field scale (e.g., Djalilov et al., 2023; Kirar, 2023; de Moura Campos et al., 2021; Sapsal et al., 2021; Vani et al., 2021; Pasika and Gandla, 2020; Thakare and Bhagat, 2018; Masseroni et al., 2016; Di Prima, 2015). These field devices must fulfil certain key criteria, which were taken into consideration during the development of our novel system:

i. robustness and reliability, to enable continuous data collection regardless of external conditions (e.g., weather, presence of insects);
ii. measurement accuracy sufficient to monitor the processes, but not so high as to cause unnecessary cost increases;
iii. ease of installation, as indicated by Nayyar and Puri (2017) and Miskam et al. (2009), to prevent the installation of the sensors from becoming too labour-intensive;
iv. low cost, to be compatible with the farmers’ needs for widespread monitoring of many paddies;
v. ease of access to and consultation of the monitored information to overcome the barriers faced by rice farmers who are often unfamiliar with electronic devices and reduce the time needed daily for the data collection.

The aim of this paper is to present a device called SmartWT, which is an Arduino-based IoT system that enables continuous water level monitoring in a WT throughout the rice growing season. SmartWT reduces the effort required by farmers to correctly implement the AWD rice irrigation strategy, thereby increasing the Water Productivity (WP) while reducing greenhouse gas emissions and the arsenic content in rice grains. This paper also describes the laboratory tests carried out to assess the device’s accuracy, the influence of adding a thermometer on the measurement error, and, finally, it illustrates the device’s behaviour during a full cropping season field trial, demonstrating its robustness, reliability and accuracy in a rice field environment. In conclusion, this paper presents the features and construction characteristics of the SmartWT device, demonstrates the device’s suitability for the practical needs of farmers, illustrates the tests that were carried out during its development, and explains the limitations that emerged and how they were addressed.

2. Materials and methods

2.1. System design

The core of the SmartWT system is an Arduino Nano, equipped with an ATMEGA328P processor (Microchip Technology) with 32 kB of memory and a 5 V power supply. It communicates serially with the Shield Internet GPRS SIM900 (Simcom), which contains a SIM card for internet connection and a waterproof ultrasonic sensor, JSN-SR20 (Manorshi), also powered by 5 V.

The entire system is powered at 5 V by a Recom R-78E5.0-0.5 voltage regulator (Recom), with the 12 V input voltage supplied by two 6 V lead-acid batteries connected in series. One of the batteries separately powers a TPL5110 (Adafruit) timer module separately. This ultra-low power timer has a standby consumption of 50 nA and a triggering interval that can be set from 100 ms to 7200 s. It acts as a switch controlling a MOSFET, on the power supply line of the Arduino board, significantly reducing power consumption and thus extending the battery life. When the timer activates the Arduino, the other components (e.g., the ultrasonic sensor) are used to take the measurements, which are sent to the server (the estimated time for this process is 75 s). Once the transmission process is complete, the power supply to the board is switched off, except for the timer.

The entire system is housed in a waterproof box measuring 180 x 120 mm. A 3D-printed ultrasonic sensor housing is located at the bottom of the box and also serves as a mounting system for the WT. All components have been selected to keep the system cost-effective. Fig. 1 shows a scheme of the hardware.

2.2. Software

The system relies on a custom developed open-source firmware, written using the Arduino IDE, and responsible for data acquisition, preprocessing, and GPRS transmission.

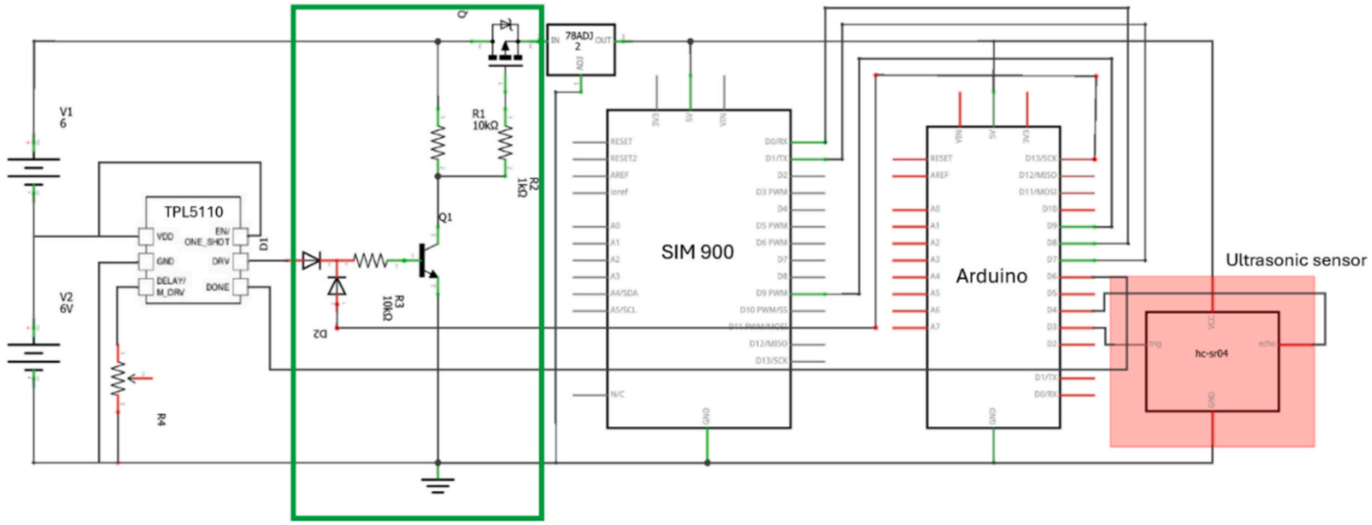

Fig. 1. Hardware electrical scheme; the waterproof sensor is marked in red. A MOSFET is part of the switch on the circuit that powers the system (green line), controlled in turn by the timer. The V2 battery powers the TPL5110; the second battery V1 is used in series with the V2 battery only when the Arduino is switched on.

Data storage, processing, and visualisation are managed by edge functions in Supabase (Supabase, 2024). The user interface is designed as a chat-based service that relies on the Telegram Bot API. Different commands can be used to obtain the real-time level in the field, set a notification threshold, and create personalized graphs. ThinkSpeak (Mathworks, 2024) can also be used for data illustration in case a more traditional plotting interface is preferred. The code is publicly available at [https://github.com/Tech-A-P/water_level_sensor].

2.3. Water level sensor

The chosen sensor is a waterproof ultrasonic distance meter (JSN-SR20 produced by Manorshi), which is equipped with two ultrasonic cones (one emitter and one receiver). Combined with the 60° angle of wave emission, this gives the sensor a very small blind spot (3 cm), compared to single cone sensors. Specifically, the emitter cone emits an ultrasonic wave that is reflected by any obstacle in its path and returns to the receiver cone of the sensor. The microcontroller measures the time elapsed between transmission and reception, and by knowing the speed of sound, it calculates the distance.

The accuracy of the device decreases with distance to the obstacle; due to the way it works. Temperature can also affect the measured distance by affecting the air density and, consequently, the speed of sound according to (Huang and Young, 2009).

Preliminary tests on the sensor show that it has a very good accuracy in measuring the distance from solid objects when using factory settings (tests not shown here). However, some distortion was observed when the sensor was used to measure the distance to a water surface, as in field applications. Careful investigations (Section 3.1) led to guidelines for obtaining reliable and accurate measurements of the ponding water level in paddy fields.

2.4. Laboratory tests

The accuracy of the newly developed SmartWT sensor was experimentally evaluated. Tests were also performed to assess the sensor's linearity, as preliminary field measurements (not shown) revealed inconsistencies that suggested possible non-linear behaviour. The experimental setup depicted in Fig. 2 was used to perform the linearity and accuracy tests.

A cylindrical test chamber (35 cm in diameter and 120 cm high, sealed at the bottom) was placed vertical and used as a controlled-level water tank. The test tube, inside which the sensor measures the water level, was installed inside the chamber and the SmartWT was fixed on its top, with its emitter and receiver cones (2.6 cm in length) inserted into the pipe, as shown in Fig. 2. A temperature sensor (DS18B20 from Dallas Semiconductor, with a temperatures range of −55 to +125 °C and an accuracy of 0.5 °C between −10 °C and +55 °C) was positioned into the tube.

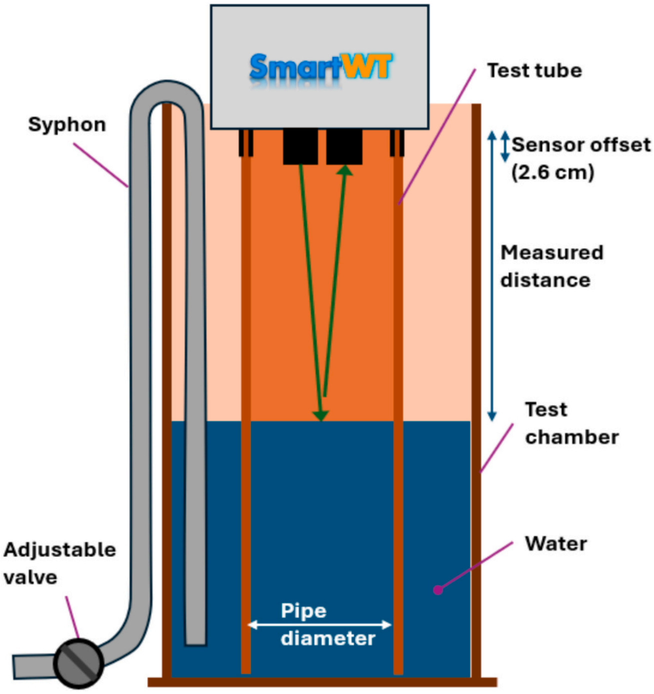

Fig. 2. Experimental setup used for the linearity and accuracy tests.

The following sections describe the mentioned accuracy and linearity tests, as well as the evaluation of the error caused by not equipping the SmartWT with a thermometer and the current consumption tests related to battery life. Table 1 summarises the tests that were carried out.

2.4.1. Linearity test

Linearity is a characteristic of the sensor indicating that its output is directly proportional to the input within measurement range. In other

Table 1
Number of experiments performed for the laboratory tests and parameters taken into account.

Laboratory tests	Number of experiments	Parameters
Linearity	6	diameter, pipe cap
Accuracy	10	temperature, diameter, distance
Lack of temperature sensor	12	temperature, distance
Battery	2	base consumption, spikes

words, linearity implies that small variations in the actual measured value should produce proportional changes in the sensor output.

To verify a possible lack of sensor linearity, a series of experiments was conducted in a room maintained at a constant temperature of 20 °C, during which the measured distance was gradually increased. In each experiment, the sensor was placed on top of the test chamber (described above), and the chamber was initially filled with water up to a few centimetres from the sensor (ranging from 0 to 7 cm). A siphon equipped with a valve was arranged over the rim of the chamber, allowing a controlled water discharge. The resulting decrease in water level approximately follows a first-order dynamic behaviour (exponential decay), as the outflow rate is mainly driven by the hydrostatic pressure at the base of the chamber, which depends on the water height.

Sensor measurements of the distance were collected every five minutes, and each experiment ended when the water level dropped to approximately 80–100 cm from the sensor (i.e., after about 40 h). The test was repeated with and without a pipe cap, and with three Polyvinyl Chloride (PVC) pipes having inner diameters of 7 cm, 9.5 cm and 13.5 cm (with wall thickness between 2 and 4 mm). A total of six experiments were conducted.

2.4.2. Accuracy test

The same experimental setup was used to assess the sensor's accuracy, defined as the degree to which the measurement result is close to the true value.

The accuracy tests were replicated with two pipe diameters (inner diameters: 13.5 cm and 7 cm), two different temperature conditions (20–25 °C and 3–4 °C), and two distance classes (20–30 cm and 80–90 cm). This leads to eight sets of experiments. Two more were added (warm temperatures and long distances for both pipe diameters), enriching the dataset for the most relevant conditions and bringing the total to ten experiments, all of them performed with the pipe cap holding the SmartWT.

Four SmartWT devices were used in every experiment, with each device acquiring approximately ten sensor measurements per experiment.

For each experiment and distance class, the mean of three manual distance measurements was used as a reference for the true distance. Each manual measurement was made by vertically inserting a long, pointed pin through a holder placed on top of the pipe to clearly see the water reflection when the pin touched the water' surface, and then measuring the length of the pin from its tip to the holder (with a measurement uncertainty of a few millimetres).

Each sensor measurement gives the travel time of the ultrasonic signal (t, μs) obtained as the median of 10 travel time readings taken by the sensor. The corresponding distance estimation was obtained using Eq.1:

$$H_T = \frac{t}{2} \bullet \frac{v_T}{10000} + 2.6 \tag{1}$$

Where H_T is the distance measured by the sensor (cm), t is the two-way travel time (sensor-water-sensor, divided by two to obtain the one-way distance), and v_T (m/s) is the speed of sound in air (divided by 10,000 to convert the speed into cm/μs). The 2.6 cm term accounts for the sensor tip length to express the distance between the water surface and the top of the pipe (which corresponds to the base of the SmartWT).

The sound speed in air, v_T, is temperature-dependent and was calculated according to Eq. (2) (Huang and Young, 2009).

$$v_T = 331.45 \times \sqrt{1 + \frac{T}{273}} \tag{2}$$

To assess the accuracy of the measurements and to verify possible dependencies of the sensor reading on pipe diameter and temperature, a set of linear mixed-effect models (LM models) was tested for exploratory purposes in order to account for repeated non-independent sensor measurements. LM models account for both fixed and random effects Schielzeth et al. (2020). Fixed effect parameters affect the entire dataset (e.g., the slope and intercept of the regression curve), while random effects affect each group of measurements separately (e.g., the error affecting manual measurements).

The models considered the following random effects: manual measurement error affecting each experiment separately (manual measurement error); small sensor length error due to misplacement of the sensor within the single SmartWT device (manufacturing error); error in placing the device on the pipe affecting each experiment and device (positioning error); and sensor measurement error affecting each measurement of the sensors individually (sensor measurement error). Fixed effects included: the intercept, the sensor measurement (slope), the diameter effect, and the temperature effect. Model calibration was carried out by including, excluding, and combining these fixed parameters. The model fitting was performed using the MATLAB fitlme routine (Statistics and Machine Learning Toolbox).

2.4.3. Relevance of the temperature sensor

To assess the relevance of including a thermometer in the device, the potential error introduced by omitting the air temperature measurement inside the WT was estimated. If this error is smaller than a few centimetres, the device accuracy can be considered sufficient for the AWD irrigation management.

The distance obtained with a fixed reference temperature instead of the true one can be obtained by applying Eq. (3):

$$H_R = \frac{H}{v_T} v_R \tag{3}$$

Where H_R is the distance estimated without temperature reading, H is the true distance, v_T is the speed of sound computed at the true temperature (Eq. (2), and v_R is the sound speed at the reference temperature. The difference between H and H_R represents the temperature-induced measurement error.

2.4.4. Battery consumption and duration test

To evaluate the device's operating time, the current consumption during data acquisition and transmission, as well as during the standby, was measured. For the first test, the internal multimeter of the Peak Tech 1356 oscilloscope was set to measure the mA consumption every 500 ms. A 25-minute test was carried out with data transmission every two minutes (11 transmissions in total). The multimeter range was set to 400 mA, which correctly recorded the energy consumption except for very fast transient peaks exceeding this limit.

To quantify these transient peaks, an additional test was performed using the oscilloscope, which revealed maximum current absorption values of 1.2 A lasting less than 500 ms. For simplicity and to avoid underestimation, a value of 1.2 A was assigned to unrecorded peaks. The standby current consumption of the timer was obtained from its datasheet, as the current flow was too low to measure directly (0.005 mAh).

2.5. Field test

At the end of the prototyping phase, the instrument was tested under field conditions. Nine devices were installed at three experimental sites located in the municipalities of Zeme, Castel D'Agogna and Robbio, within the main Italian rice-growing area (Pavia province). The aim of the field tests was to evaluate the reliability of the SmartWT in the paddy environment along the whole crop season and to verify its data transmission capacity.

At each site, two devices were installed in plots managed with AWD irrigation, while a third was placed in a rice plot with traditional irrigation (wet seeding and continuous flooding). AWD was applied from the beginning of the tillering phase until maturity. An AWD irrigation event (raising the ponded water level to between 10 and 15 cm) was initiated each time the water level inside the WT fell below a given threshold (25 or 30 cm, depending on the site).

The nine devices transmitted data every two hours and were mounted on pipes with an internal diameter of 13.5 cm and a length of 50 cm (a different length is suggested at the end of this paper, as a result of the experiments carried out, for improving reliability). The pipes were perforated along 30 cm of their length to allow water flow, with this section buried in the soil and the remaining part above ground. Soil was removed from inside the pipes along their entire length. The sensors were mounted on top of the pipes using a 3D-printed support made of weather-resistant Pet-G, as shown in Fig. 3.

During the field experiment, along the entire crop season (26 May to 19 September 2024), 140 temperature measurements were taken inside one of the WT to define the actual working conditions of the SmartWT.

3. Results

3.1. Linearity assessment

The experiments on the linearity test were expected to produce measured distances that follow an exponential decay similar to the black dashed line reported in Fig. 4. However, in all experiments and notwithstanding pipe diameter nor the presence of the pipe cap, the sensor measurements showed a pattern like the blue line in Fig. 4, with frequent periods featuring an anomalous increase of the measured distance. The results of the six experiments showed different amplitudes, durations and positions of the anomalies, without any common pattern.

Fig. 3. Picture of one of the field installations (short pipes) made at the end of May 2024, after rice emergence, in Robbio (PV), Italy.

However, as can be seen in Fig. 4, there are also sections where the measured distance behaves as expected, and these become dominant as the distance increases. The anomalies tend to disappear at distances greater than 20 cm, and no significant deviations were ever found in the tests for distances greater than 30 cm.

3.2. Accuracy assessment

Fig. 5 shows the dataset collected during the accuracy tests. The combination of symbols and colours refer to different pipe diameters and air temperatures, while panels A and B refer to short and long distances, respectively. A total of 396 measurements were collected across ten experiments, forming as many distinct data clusters in Fig. 5.

In the figure, the points are clearly aligned on the straight black line (linear regression), indicating a strong linear relationship between the manual measurements and the sensor readings. However, the black line differs systematically from the bisector of the quadrant (dashed line), indicating a consistent deviation of the measurements. Furthermore, the data clusters occasionally deviate somewhat from the regression line.

Mixed-effect models with all possible combinations of fixed effects were calibrated (see Section 2.4.2) to inspect possible effects due to influencing factors. The MATLAB routine gave p-values higher than 0.1 (poor significance) for all the fixed effect parameters listed in section 2.4.2, apart from the dependency on the sensor's measurement, stating no proof of a distortion effect on the measurements due to pipe size or temperature (apart from the sound speed already considered by Eq. (2). Therefore, the linear model that best represents the dataset is:

$$\widehat{H} = 1.028 \bullet H_T \tag{4}$$

Where $\widehat{H}$ is the best estimation of the distance between the SmartWT and the water surface, H_T is the sensor temperature-corrected estimation given by Eq. (1).

According to the calibration results, the standard error of the coefficient of Eq. (4) is 0.0020 (95 % confidence interval ranging from 1.024 to 1.032) and the standard deviations of the random effects are: manual measurement error 3.4 mm, sensor placement error 1.7 mm, manufacturing error 1.5 mm, standard error of the sensor estimations 0.8 mm. The bias of the estimations in Eq. (4) is 0.036 mm, and the Nash Sutcliff model efficiency is 0.9998.

This results in an expected standard deviation of 2.4 mm for instrument measurements (due to placement, manufacturing and sensor errors), corresponding to a 95 % confidence interval of approximately ± 4 mm from the true value.

The model's hypotheses were tested and found to be valid, apart from the residuals that are not normally distributed according to the test. While the residuals appear normal-like and symmetric (not shown), a small number of extreme values caused the test to fail. We considered the calibrated model to be reliable, also in light of the results of Schielzeth et al. (2020).

3.3. Temperature error

The computations described in Section 2.4.3 are performed for identifying the differences between the true distance (H_T) and the distance obtained without the temperature sensor (H_R). The adopted reference temperature is 24 °C, that is the average temperature measured in the WT during the 2024 crop season. The range of temperatures observed in the WT ranged from 14 to 40 °C, which are respectively the minimum and maximum temperatures measured in the WT during the 2024 crop season (Section 3.5).

Table 2 shows the estimated values of H_R, based on the reference

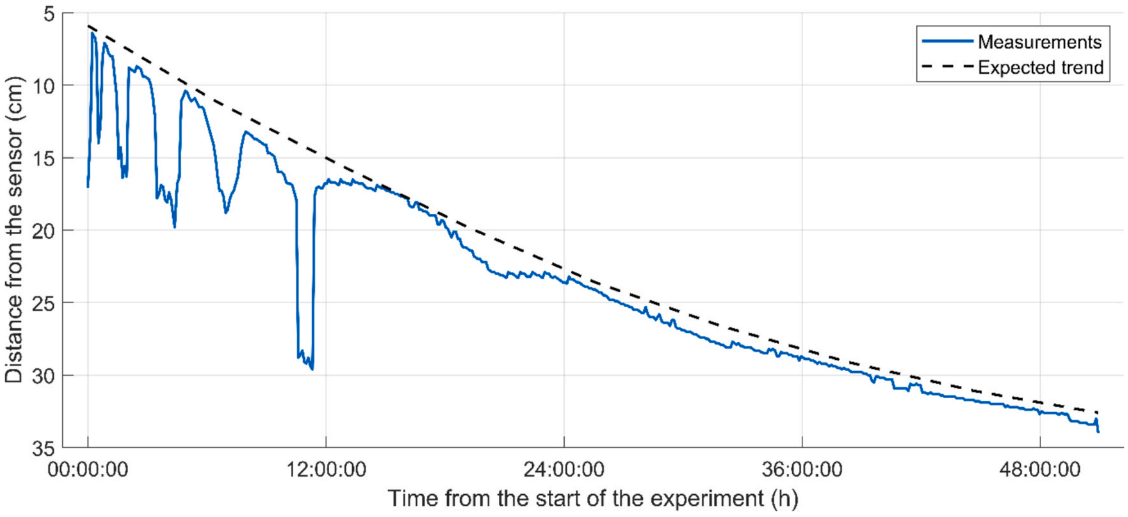

Fig. 4. Distance between the top of the pipe and the water surface during a falling water level experiment with a pipe diameter of 13.5 cm and with the pipe cap. The y axes is reverted to resemble the water level. The lines shown are the expected trend (black dashed line) and the actual measured values (blue line).

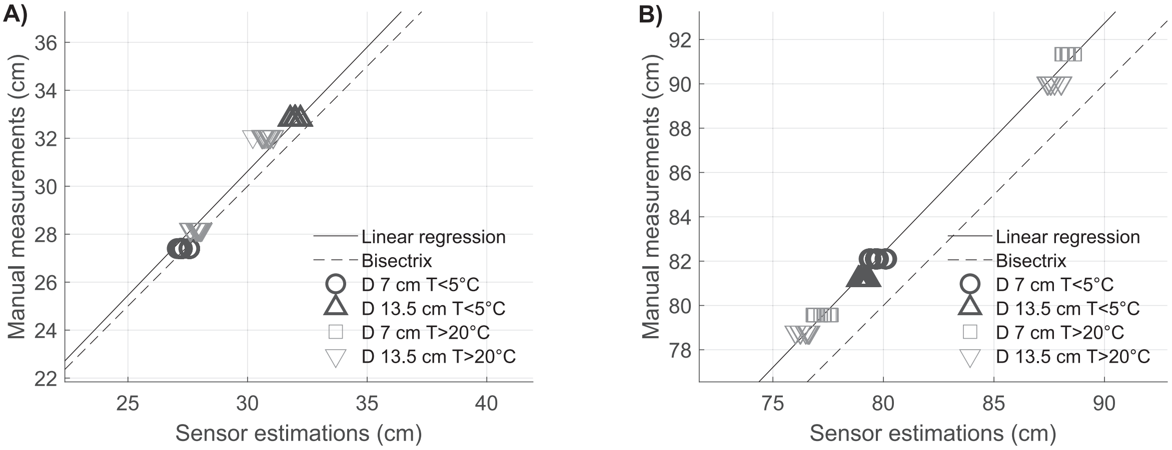

Fig. 5. Dataset showing the sensor estimation vs manual measurements of the distance between sensor and water table, with 'small' distances in panel (A) and 'long' distances in panel (B). Colours and symbols refer to different temperatures and pipe diameters. Linear regression (continuous line) and the bisector of the first quadrant (dotted line) are also shown.

Table 2
Expected measurements obtained by the device using a reference temperature of 24 °C instead of the actual temperature. Error introduced by using the reference temperature instead of the actual one is reported in brackets.

	Distance (cm)		
T (°C)	30	50	80
14	30.5 (0.52)	50.9 (0.86)	81.4 (1.38)
20	30.2 (0.20)	50.3 (0.34)	80.5 (0.54)
30	29.7 (−0.30)	49.5 (−0.50)	79.2 (−0.80)
40	29.2 (−0.78)	48.7 (−1.29)	77.9 (−2.07)

temperature, for different temperatures observed in the installed WT. The 30 cm and 80 cm distances used in the table are the minimum and maximum lengths recommended inside the WT. Table 2 also shows the difference between the H_R and H_T values in brackets, which is the error added to the measure when a thermometer is not installed in the SmartWT.

According to the results, the measurement error increases both with the measured distance and with the temperature deviation from the reference value used to compute the sound speed. When the air temperature inside the tube is lower than the reference value, the sensor overestimates the distance (i.e., the reported water level is higher than the real one) with a maximum overestimation of 1.4 cm at 14 °C for an 80 cm distance. Conversely, higher air temperatures lead to an underestimation of the distance with a maximum underestimation of about 2.1 cm at 40 °C (the highest recorded temperature) for the same distance.

Therefore, the maximum errors that could affect SmartWT measurements without a thermometer in the worst-case scenario are + 1.8 cm and −2.4 cm. These values are obtained by adding the maximum temperature errors to the 95th percentile of the instrument's uncertainty determined in Section 3.2.

3.4. Battery consumption

Fig. 6 shows the electric current consumption during 11 data acquisitions. With the system kept on, a constant consumption of around 70 mA is recorded, with peaks exceeding 1.2 A during GPRS communications. Based on this data, the average consumption for a data transmission is 1.33 mAh (1.56 mAh, if the 90th percentile is considered, with a standard deviation of 0.21 mAh).

Dividing the battery charge (assumed to be 4.0 Ah) by the consumption of a data transmission, gives around 2500 transmissions per

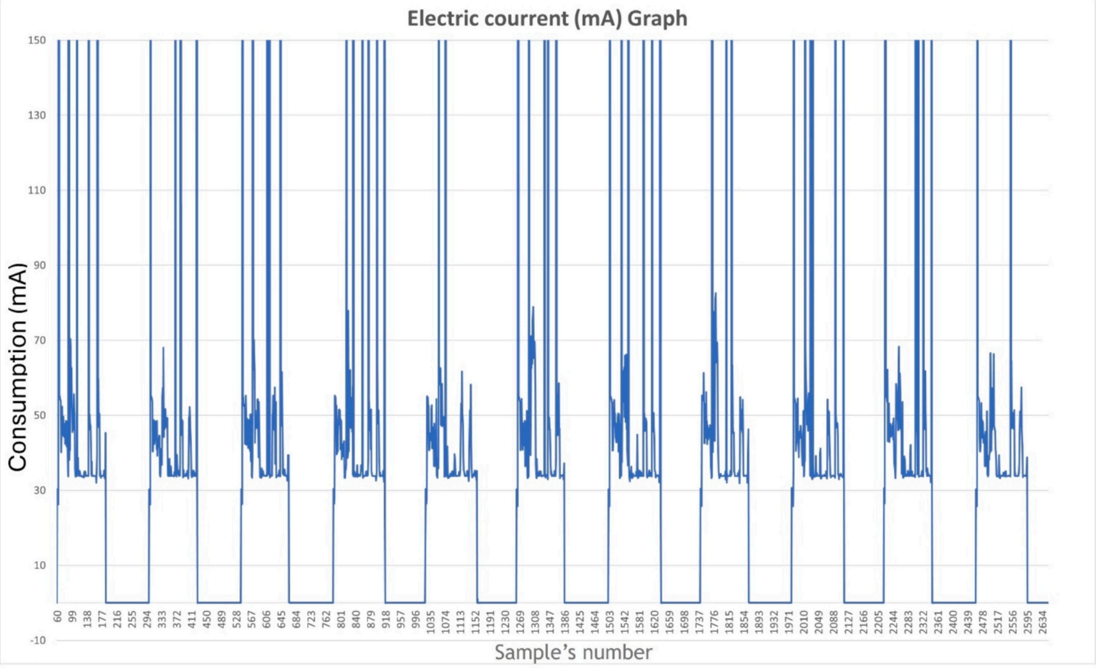

Fig. 6. Current consumption of the SmartWT measured in mA during 11 operating cycles. The plot has been truncated to improve visibility of the lower values (i.e. peak values reach up to ~1200 mA).

charge. This, neglecting the consumption at rest, and with data sent every two hours, brings to a battery lifetime of approximately 200 days.

3.5. *Field test*

The SmartWT devices provided reliable measurements throughout the whole growing season in the challenging rice paddy environment

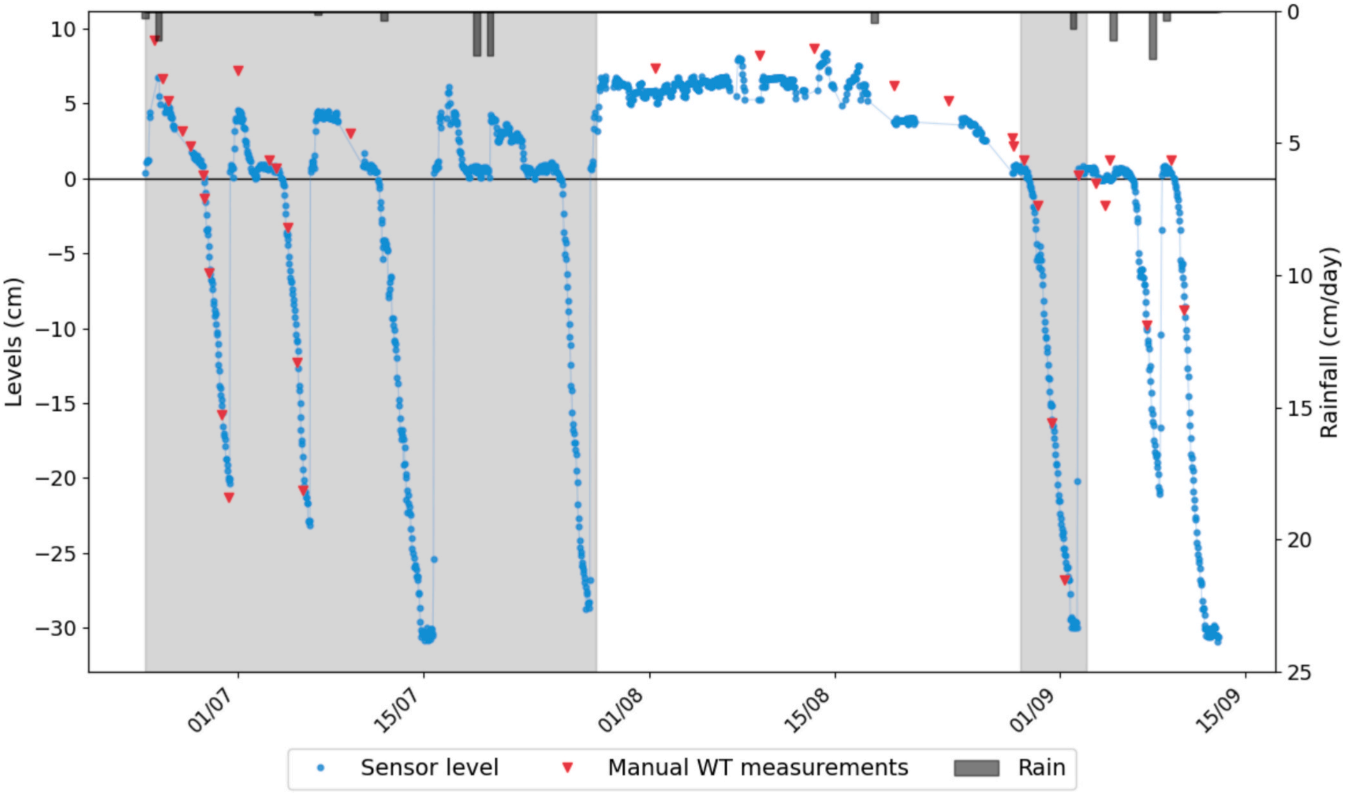

Fig. 7. Time series collected during the 2024 rice-growing season: water level measured by the tube sensor (blue dots), manual measurements (red triangles), and daily rainfall (grey bars). The light grey shaded areas indicate AWD management periods, while the rest was irrigated with continuous flooding up to September the 6th, when the final drying phase began.

(apart from the issues reported in the linearity tests). Fig. 7 shows one of the water level time series measured by a SmartWT in a field from the third week of June to second week of September.

In some cases, a few missed transmissions were observed, due to the temporary lack of connection to the GPRS network. These accounted for around 5 % of the total transmissions during the field experiment, further upgrades in the data-sending protocol reduced this amount to 1 % or less (data not shown).

The thermometer in the instrumented WT recorded temperatures ranging from 15 to 40 °C, with an average of 24 °C.

Finally, in all nine installations, the SmartWT batteries lasted for the entire season (120 days) and enabled continuous recording with data transmission every two hours without the need for recharging or replacing the batteries.

4. Discussion

The SmartWT experimentation included laboratory tests under controlled conditions (linearity, accuracy, temperature error and battery consumption), as well as a field test performed throughout the rice crop season 2024 in the real production environment.

The set of laboratory tests was carried out to provide a comprehensive characterisation of the instrument features, as well as to identify potential problems and corresponding countermeasures.

The linearity test shed light on an unexpected distortion of the measures occurring when the water surface is closer than 25–30 cm to the device. This deviation could be due to phenomena occurring in the pipe-water system under certain conditions that interfere with the ultrasonic signal. In such disturbed conditions, it seems that the sensor fails to recognise the signal travelling the shorter path to the water and back. It probably recognises another signal (e.g. one that bounces off the pipe walls), resulting in a longer transit time and a measured distance greater than the true one. The tests and the analysis were unable to suggest a clear, stable rule to describe and correct this phenomenon. However, the tests did not reveal any dependency on the diameter of the pipe or the presence of the cap on top of the pipe. It may, however, be correlated with the material and thickness of the pipe.

Nevertheless, we found that, for the range of pipe sizes tested and the setup described in Section 2.4, sensor readings are reliable for distances greater than 25–30 cm between the sensor and the water surface. Therefore, we recommend for the field measurement the setup showed in Fig. 8, with a distance of 30 cm between the SmartWT and the maximum water level to be measured (which is usually around 20 cm in north of Italy).

The accuracy test revealed that the instrument exhibited unexpected behaviour under the experimental conditions (i.e. measurement of the distance to the water surface inside a tube), characterised by a systematic deviation proportional to the measured distance. However, the accuracy test also showed that the measurement is unaffected by pipe size or air temperature (i.e. air temperature has no further effect beyond what was already considered in the sound speed calculation with Eq. (2). Additional experiments showed that the cap, which holds the device in place and covers the WT, does not affect the other tested characteristics (not shown). Consequently, the deviation was easily quantified in the data analysis and can be corrected by applying Eq. (4), which has been added to the SmartWT firmware.

During the accuracy test, which involved measuring the air temperature inside the tube, the SmartWT demonstrated a measurement error of less than ±4 mm (95th percentile). This level of accuracy exceeds that required for field operations and is in any case overwhelmed by the various sources of uncertainty that affect the estimation of water levels in rice paddies (Section 1). Moreover, measuring the temperature inside the WT might be inconvenient as it would require a wire to come out of the shell and connect to the temperature sensor inside the WT. This, in turn, could lead to drawbacks such as reduced mechanical resistance and sealing of the shell, large measurement errors due to the

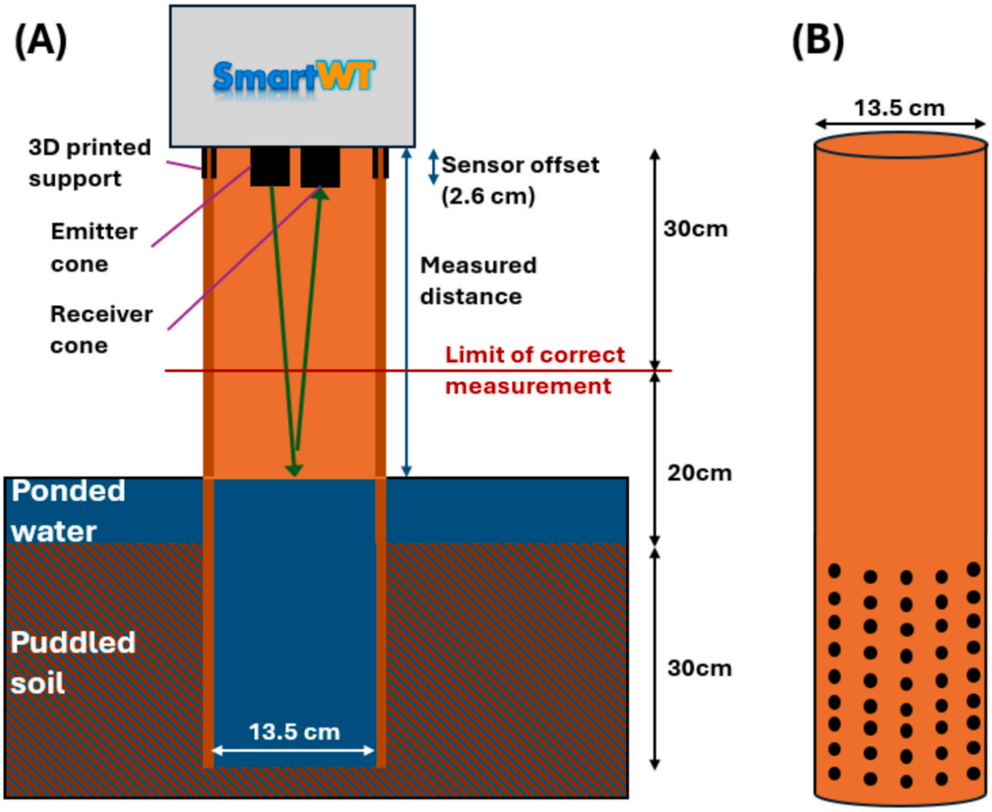

Fig. 8. Panel A – suggested installation of the SmartWT and the WT. The upper side of the pipe is covered with a cap welded with the SmartWT to prevent insects or plant matter from entering. Panel B – detail of the WT.

ultrasound signal bouncing off the thermometer, or other unexpected issues. Furthermore, this increases manufacturing complexity and construction time, as well as raises the cost of the device, which is a key parameter. The alternative of measuring the temperature inside the waterproof shell could produce misleading results.

By not installing a thermometer on the SmartWT, an error of approximately 1 cm at short distances and moderate temperatures can be observed, while the maximum expected error is around 2 cm at a distance of 80 cm and at the extreme temperatures of 14 or 40 °C (Section 3.3). These errors are suitable for in-field water level measurements (Section 1). Therefore, the SmartWT is currently being built without a temperature sensor to reduce costs and complexity, as well as to avoid the other problems listed above, while the possibility of equipping the SmartWT with an internal or external thermometer for applications requiring greater accuracy is a topic left to future research.

Coming to battery life, the laboratory tests estimated it at around 200 days with data transmission every two hours. A suitable duration is confirmed by the field test (conducted with nine SmartWT devices in nine rice fields located in three municipalities), where devices worked for a 120-day season, transmitting data every two hours without the need for recharging or replacing the battery.

The field test also provided an estimation of the effectiveness of transmitting data from the fields to the cloud database that, after some corrections, brought the average data loss to less than 1 %.

Finally, Table 3 summarises the main features of the SmartWT and the key results of the experimental activities discussed.

In recent literature, other authors have proposed novel devices for measuring water levels with the aim of optimizing irrigation management. Miskamet et al. (2009) made a preliminary design of a Wireless Sensor Network (WSN) for paddy rice cropping. In comparison with the sensors illustrated in this study, SmartWT is characterised by the fact that it does not require a solar panel. This is made possible by the size of the battery and the optimisation of the power management system, which can completely disconnect all non-essential components. Consequently, the system does not require any battery recharging throughout the entire irrigation season. In the authors' opinion, this may be a major advantage since dependence on a solar panel can be problematic. For example, vegetation growth may cover the panel, rendering it ineffective and limiting the device's operations. While the device could be installed at a height to prevent this, such positioning could cause issues during operations such as spraying. In addition, the WSN presented by Miskamet et al. (2009) is based on a ZigBee system, which offers the advantage of enabling networking among multiple sensors, but requires the presence of a gateway for data transmission. Conversely, the SmartWT device allows direct data communication to the server via GPRS protocols, without the need for external gateways or network integration. This results in easier and faster installation, while data integration across multiple devices can still be handled on the server side.

Table 3
Main features of the SmartWT.

Feature	Value
Expected battery duration	about 200 days
Tested operating time (in field)	120 days
Minimum reliable distance	25–30 cm (30 cm suggested)
Maximum tested distance	91 cm
Standard errors obtained from the accuracy test (with the thermometer):	
- sensor estimations	0.8 mm
- manufacturing error	1.5 mm
- placement error	1.7 mm
- overall measurement error	2.4 mm
- 95 % confidence interval	±4 mm
Maximum error expected without the thermometer with:	
- 14 °C and 80 cm of distance	1.4 cm
- 40 °C and 80 cm of distance	−2.1 cm
Standard data transmission interval	2 h
Data transmission success rate	>99 %
Device shell dimensions (H × W × T)	16 x 16 x 8 cm
Emitter and receiver cone length	2.6 cm
Device weight (mass)	2.1 kg
Device cost	About 200 €

Another comparable device is the ArduHydro, which was described by Galli et al. (2024). Like SmartWT, this system is based on open-hardware architecture and uses an ultrasonic level sensor to measure the water level. However, unlike SmartWT, ArduHydro includes a microSD card for data storage and uses an internal clock to associate each recorded measurement with the corresponding date and time. Additionally, the system is unable to transmit data, which can only be accessed after the device has been uninstalled. In contrast, SmartWT only relies on the Arduino's internal memory for temporary data buffering. Each measurement is then immediately transmitted to the server, where a timestamp is assigned to its reception. This results in a simpler, more robust system that does not require additional batteries or auxiliary components and offers a longer operating time for remote monitoring solutions.

Kabir et al. (2024) proposed a system for monitoring water levels in WTs based on a sensing pad composed of two open conductive layers that form a short circuit when the water reaches them, allowing the microcontroller to register the corresponding height. This system has an accuracy of 1 cm, which is acceptable for field WT measurements. However, it requires direct contact with water, which can lead to issues such as incrustation of algae or other microorganisms, or the sensor being covered by soil that enters the WT with the water. Another system that implies the contact of the sensor with the water is proposed by Kumar et al. (2024) which use magnetic float-based sensors and electronic circuits to detect water levels, converting them into electronic signals transmitted wirelessly via radio frequency (RF) to a controller. Unlike these two systems, the SmartWT device works without direct contact between the sensor and the water. This enables faster installation and improves long-term durability by preventing continuous submersion.

Tolentino et al. (2021) realised a system very similar to SmartWT but based on HC-SR04 ultrasonic sensor. This sensor is not waterproof and the authors think it is a huge limit in the application in rice paddy environments.

Hasan et al. (2025) proposes a system that integrates camera photography with AI algorithms to reach real time water level monitoring. Although this approach theoretically offers higher precision and accuracy than ultrasonic sensors, it has important limitations, such as reduced performance in low-light conditions. It is also important to note that installing a camera in the field may cause problems due to insects, larger animals or vegetation obstructing the view of the lens and compromising the system's ability to accurately estimate the water level.

Despite the advantages over the existing devices described above, there are some limitations of the SmartWT when coupled with a WT, which are listed below.

Indeed, the application for paddy water level monitoring and controlling are simple and rather cheap, but a device per field is required; this may imply the need for a relatively high number of units. In addition, although SmartWT significantly reduces labour requirements for water level monitoring and control during the growing season, manual intervention is still required when the device is installed (before sowing) and removed (before harvesting operations); however, these interventions are necessary for the installation and removal of the WT anyway.Some checks should be carried out during the season to verify that the device is in good condition in case of anomalous data (e.g. rice roots may have occluded the WT's holes or mechanical machinery may have damaged the device); anyway, this is usually done for any device placed in the field. At the end of the season, batteries must be recharged. As already mentioned, if for some reason accurate level measurement is required, a temperature sensor should be added to the existing level sensor. Finally, the system relies on a remote server for data visualization and processing, which requires the payment of a small service fee.

5. Conclusion

The paper introduces the SmartWT, an ultrasonic measurement and cloud-connected device designed for monitoring water levels inside AWD water tubes in rice fields. From a scientific standpoint, the study provides a rigorous evaluation of the sensor's performance, combining controlled laboratory experiments with full-season field testing to ensure the robustness and repeatability of the results, thereby strengthening the credibility and applicability of the findings.

Laboratory tests revealed two issues with the ultrasonic sensor measurement of the distance of the water surface inside a tube: a systematic underestimation of the measured distance and erratic fluctuations at distances shorter than 25–30 cm. Other potential sources of disturbance (e.g. unexpected impacts of the air temperature, pipe diameter and length) showed no measurable effect within the tested ranges. Both sources of error were successfully addressed by applying a correction factor and ensuring a measurement distance greater than 30 cm. Following these adjustments, the device, when operating without an air temperature sensor, achieves a measurement error of typically less than 1 cm. This level of accuracy is fully adequate to manage the ponded water level in rice fields, even in the context of implementing the AWD irrigation technique. Furthermore, field tests demonstrated the device's reliability under the harsh environmental conditions typical of flooded rice fields.

In addition, as predicted by the energy consumption tests, all nine devices operated autonomously in full field conditions for an entire rice irrigation season, transmitting data every two hours without the need for any in-season battery charging, replacement or additional solar panels. This reduces the costs and avoids the need for a support pole, making the sensor much easier to manage, install, move and replace. After some adjustments, the average failed transmission rate fell below 1 %.

In conclusion, with an estimated total cost of around € 200, the SmartWT has proven to be an efficient, autonomous, and cost-effective solution for monitoring water levels in rice fields, allowing the straightforward application of the AWD irrigation technique which enables water savings without yield penalties.

Future developments may include adding a temperature sensor for automatic thermal compensation and testing the device in other applications that require continuous monitoring of water levels.

CRediT authorship contribution statement

Pietro Mascherpa: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michele Rienzner:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Darya Tkachenko:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Roberto Garza:** Writing – original draft, Software, Methodology, Investigation. **Fabio Brandalese:** Writing – original draft, Software, Methodology, Investigation. **Ezio Naldi:** Writing – review & editing, Software, Methodology, Investigation. **Claudio Gandolfi:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Arianna Facchi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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