Smart Agricultural Technology 3 (2023) 100085

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

A data-driven Kalman filter-PID controller for fibrous capillary irrigation

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ARTICLE INFO

Keywords:
Kalman filter
PID
IoT
Fibrous capillary irrigation
Water supply depth

ABSTRACT

Subsurface fibrous capillary irrigation has a great potential for high water-saving capability compared to other irrigation methods. However, it suffers from under-performance due to inaccurate estimation and manipulation of water supply depth (Δh) in the water wetting zone of the plant root, in accordance with the changing dynamics of soil, plant growth, and weather. This work presents the design and experimental implementation of Kalman filter-proportional integral derivative (KF-PID) controller for the subsurface fibrous capillary irrigation system. This controller is designed to control the optimal water supply depth (Δh) between the fibrous capillary interface and the surface of the water, through which water is wicked through the fibrous capillary interface to the root zone of the plant. The designed Kalman filter (KF) uses a dynamic model of the system which was obtained using historical real-time data through data-driven system identification. This yields a state-space model to describe the plant's dynamic characteristics. In addition, the KF will reduce the noise sensor output which will improve the accuracy of Δh estimation. Furthermore, a PID controller was designed to control minimizes the error between the estimated Δh and reference Δh to find an optimal value for Δh. An experimental investigation on the performance comparison of the designed controller on the cultivation of the Mustard leaf plant is also presented in this paper. To access the performance of the designed control system, three performance indices are used to compare the performance of the proposed controller with a fuzzy controller through simulation using integral absolute error (IAE), integral square error (ISE), and integral absolute square error (ITAE). The results show that the proposed controller has lower values of these indices compared to the fuzzy logic controller. Also, the proposed KF-PID controller was able to estimate the optimal Δh accurately to ensure supply of water to the fibrous capillary material for effective wetting of the plant root zone. This is evident from water saved in treatment A controlled by KF-PID which is 56.3% greater than the treatment B controlled by the adaptive fuzzy logic. The KF-PID controller shows a slightly better performance in terms of controller performance and water productivity index (WPI) which is 16 g/ Liters higher than the adaptive fuzzy logic controller.

1. Introduction

The increase in world population has consistently placed a lot of demand on food and water usage, thereby calling for increasing research that focuses on precision and water-saving agricultural industry to increase the food production and prevent water scarcity. Agriculture account for the highest consumption of water resources, as 70% of the world's water resources is utilized for plant irrigation [1–5]. This is because farmers cannot depend on rainfall for plant water needs. After all, climate change and global warming will affect the consistency of rainfall, and increase the rate of water loss, which also causes drought in some parts of the world. Hence the need to investigate high water-saving agricultural techniques such as capillary irrigation is important for plant cultivation in such areas.

Plants require a suitable amount of water supply for a desired growth and development, hence, irrigation is applied when rainfall is

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https://doi.org/10.1016/j.atech.2022.100085
Received 21 April 2022; Received in revised form 14 June 2022; Accepted 17 June 2022
Available online 18 June 2022

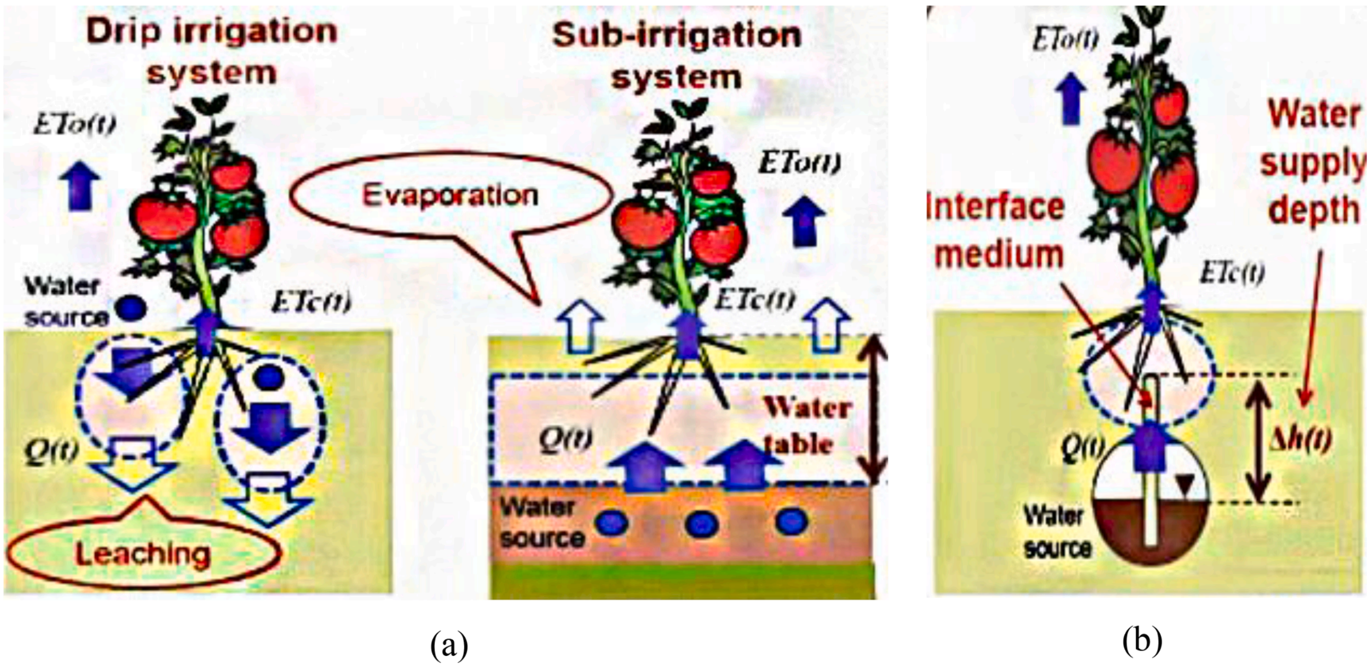

Fig. 1. (a) Comparison between surface drip and subsurface irrigation System (b) Fibrous capillary irrigation operational mechanism.

considered inadequate but with a controlled measure [6]. The volume of irrigation water applied to plants depends on the adopted method of irrigation, plant water demand, and soil type. Other factors include water loss due to evapotranspiration, infiltration rate, water absorption pattern, nutrients, and deep percolation of the soil. Irrigation systems can be classified as surface and subsurface methods based on their tendency to be precisely managed in terms of monitored, scheduled, and controlled [7,8].

Surface irrigation is part of the most common irrigation method which has been widely practiced by peasant farmers all over the world [9–13]. However, these irrigation methods such as drip, sprinkler, and furrow requires good soil surface leveling to ensure adequate distribution of water to reduce surface runoff and deep percolation [14]. Also, the water-saving capacity of these methods is low due to susceptibility to water loss as a result of high rate of evaporation, as well as the high cost of installation [15]. Fig. 1(a) shows a comparison between surface and subsurface irrigation, where the effect of leaching and water loss is becoming an issue in drip irrigation. Therefore, surface irrigation suffers higher water loss even under precision irrigation management compared to subsurface irrigation. Subsurface capillary irrigation is a type of irrigation that works based on the action of gradually supplying water from the water source directly to the root area by using a capillary medium based on the water level depth (Δh) shown in Fig. 1(b). Some capillary mediums which are usually used for subsurface irrigation are wicks, mats, ebbs, porous ceramics and flow through which negative pressure is used to transport water using the capillary interface to the root zone of the plant [16–18].

Few works have investigated subsurface capillary irrigation with findings that it offers higher water-saving and better yield output when compared with the surface irrigation [19–25]. The design of vertical and horizontal fibrous capillary interface to transfer water from the supply tank to the root zone of the plant was used in subsurface irrigation management. The findings of the studies shows that the horizontal type interface used for fibrous capillary irrigation offers higher water saving potential and produced better yield when compared to the vertical type interface for capillary irrigation system [26–28]. An analysis on water infiltration and wetting zone of fibrous capillary medium for irrigation using Hydrus multidimensional software was carried out by through simulation considering the soil hydraulic and physical properties. The results show that different water supply depth for the soil produces different reaching area of the soil moisture content, wetting front, and discharge rate [29].

Furthermore, performance evaluation of subsurface irrigation using wick on the growth of the plant, soil moisture, and surface temperature of green roof with rain storage was also investigated [30]. The research outcome shows a better plant growth with heat preservation in winter and cooling in the summer due to the green roof used for the plant protection. However, it was observed that the upward movement action of water through fibrous capillary material can irreversibly accumulate salts in the plant growing medium, thereby increasing the salinity of the soil, which can be reduced by leaching of nutrient and water in the growing medium via water supply depth manipulation [30]. Some other relevant research works on capillary irrigation has also highlighted the advantage of this method to provide higher water saving in performing the irrigation process in agriculture compared to other methods [31–37]. Whatever method of irrigation adopted by farmers or researchers, either subsurface or surface irrigation, there is a necessity to consider improvising for its shortcoming through the integration of real-time monitoring and advanced control technique aimed to enhance the performance and the water productivity index. The solution can be designed using the application of relevant sensing devices internet of things (IoT) to measure the soil, plant, and weather parameters as well as designing controllers for their irrigation scheduling [38,39].

A method to monitor and control the capillary irrigation system made use of simple open loop control with on and off control command through the use of sensor feedback and IoT monitoring [30]. Also, the control of fibrous capillary irrigation using fuzzy logic has recorded a major advancement with the integration of IoT-based soil moisture content and weather monitoring to improve the efficiency of the controller [26]. Similarly, an investigation using intelligent control of fibrous capillary irrigation using adaptive fuzzy expert system has been implemented to estimate the optimal water supply depth needed for plant water supply to the plant root zone [27,40]. The fuzzy rules were formulated considering the dynamics of the system and based on the designer's experience, the result proved the feasibility of high water saving in fibrous capillary irrigation.

Furthermore, the manipulation of negative pressure for subsurface irrigation using open-loop control timer to activate the duration of

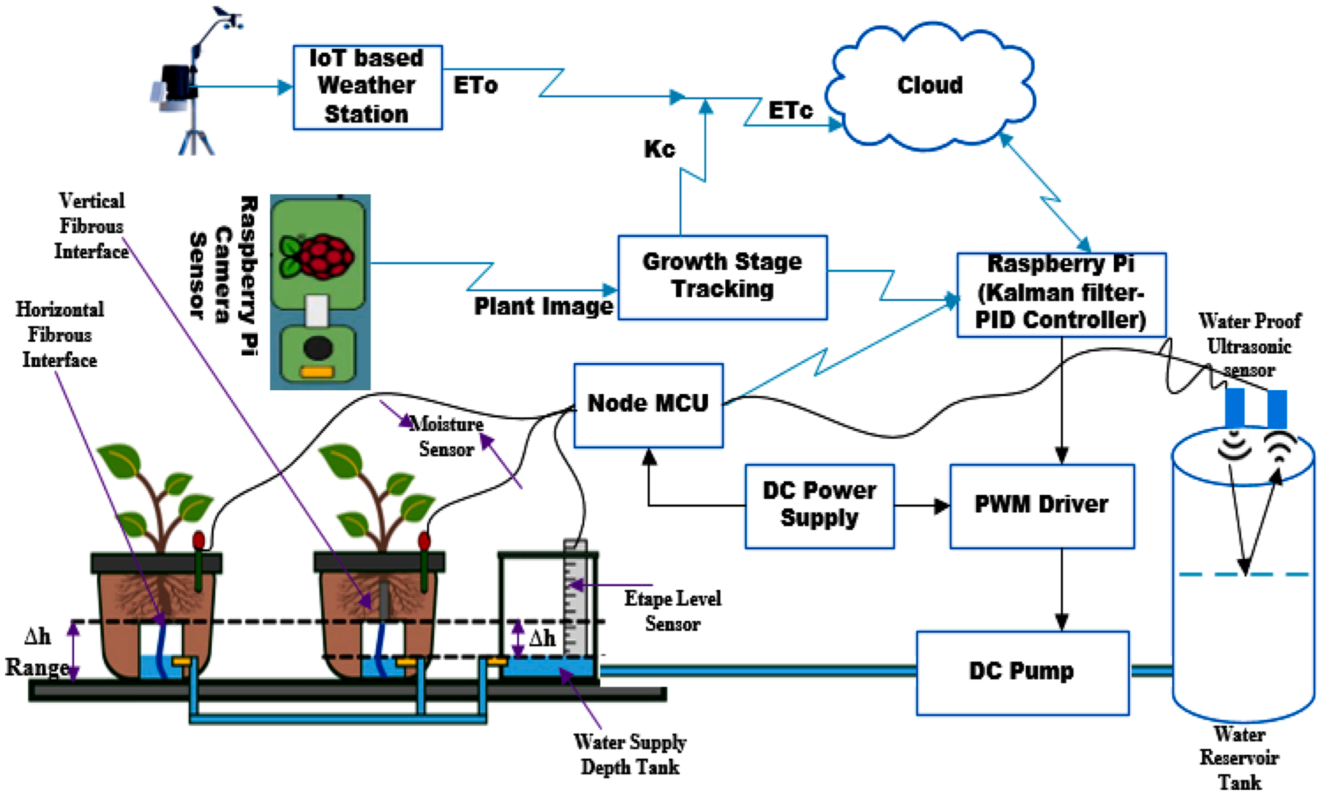

Fig. 2. Conceptual diagram of the proposed Kalman filter-PID controller for fibrous capillary irrigation with IoT integration.

pumping to the capillary wick and mat without considering the changing dynamics of soil, plant, and weather effect on the system has been proposed [16]. A humidity control strategy using negative pressure which controlled the capillary irrigation system autonomously for solid station fermentation was able to significantly increased enzyme activity during the fermentation and provide water to address the issue of water loss in the substrate [41]. Also, a semi-automatic subsurface irrigation system for soil cooling for lettuce plant growth with the aid of negative pressure for irrigating soil in a porous ceramic pipeline full of capillaries has been implemented [42]. The results obtained shows that an improved yield and soil cooling was achieved when tested on lettuce plant cultivation. Previous investigations have revealed that subsurface fibrous capillary irrigation has a great potential for high water saving capability. However, it suffers from under-performance due to inaccurate estimation and manipulation of the water supply depth (Δh) for water wetting zone in the plant root, in accordance to the changing dynamics of soil, plant and weather.

Therefore, this paper seeks to address these issues through a focus on the design, simulation and experimental implementation of a Kalman filter-proportional integral derivative (KF-PID) based controller for fibrous capillary irrigation scheme using a data-driven state-space model developed from the dataset obtained from open-loop cultivation. The significant contribution of this paper includes capturing the changing dynamics of soil, plant and weather effect using a data driven model. The KF can filter the sensor noise and estimate the optimal Δh for the water supply depth tank. In addition, the control and manipulation of the water level depth using PID controller with real-time IoT monitoring for fibrous capillary irrigation is also proposed in this paper. The performance of the proposed KF-PID based control algorithm on Raspberry Pi with IoT monitoring was tested in a greenhouse with cultivated Mustard leaf plant which distinguish it over existing works in this area. The layout of the paper starts with the background as well as the review related existing work in literature. Section 2 describes the methodology. Section 3 presents the data-driven modelling through system identification, while Section 4 presents the design of the proposed control strategy in Simulink as well as the hardware implementation. Section 5 presents the results and discussion on the performance analysis of the proposed technique. Finally, the paper conclusion is presented in Section 6.

2. Methodology

The methodology that was adopted in this research includes the operational principle of subsurface fibrous capillary irrigation process, using of the fibrous capillary interface (vertical and horizontal) as media to transport water to the root zone based on the negative capillary pressure property of the fibrous material. The multilayer system dynamics of a fibrous capillary irrigation system can be described using flow analogy for liquid transport through a porous medium is formulated as Richards's model modified from Darcy-Buckingham equation for vertical flow and water infiltration [43]. The Darcy-Buckingham equation describes the movement of water after infiltration into upward and downward directed hydraulic pressure gradients develop in different parts due to evapotranspiration and drainage [29,44]. The upper boundary part of the model in Eq. (1) is denoted by the surface of the soil where reference evapotranspiration (ET_o) occurs as described by Eq. (2), which is the rate of water loss from the greenhouse environment. It is further related with the crop coefficient (K_c) which is the properties of plant at different growth stage that is used to predict the actual evapotranspiration (ET_c) shown in Eq. (3). The sink term $S(z,t)$ of Eq. (1) is the volume of water per unit volume of the soil per unit time is referred to as the root water uptake [40,45].

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K(h)}{\partial z} + S(-z,t) \tag{1}$$

where θ is the volumetric water content of the soil (m^3/m^3) and h is the soil water pressure head (cm).

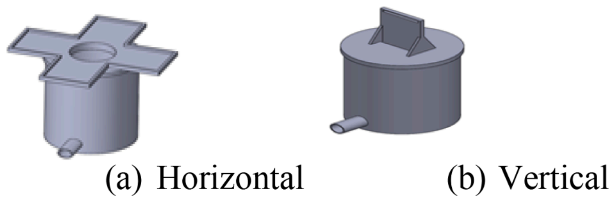

Fig. 3. Fibrous capillary interface [45].

$$ET_{O=}\frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2\ (e_s\ - e_a\ )}{\Delta + \gamma(1 + 0.34U_2\ )} \tag{2}$$

$$ET_C = ET_O * K_C \tag{3}$$

Where R_n is the soil and crop surface solar radiation, U_2 is the speed of the wind at height above 2m, T is the daily mean temperature of the air, G is soil heat flux density, $e_s\ - e_a$ is the saturation vapour pressure deficit, Δ is the gradient of the vapour pressure curve, and γ the psychometric constant as inputs. The lower boundary part of Eq. (4), is denoted by controllable pressure head at the bottom of the soil through the regulation of dh as represented in Eq. (5) [27].

$$h(0,t) = h_b(t) \tag{4}$$

$$q(t) = -K(z)\left(\rho g + \frac{d\psi_m(z)}{dz}\right)\ where\ (-z) = \mathrm{dh} = \Delta\mathrm{h} \tag{5}$$

Where $q(t)$ denote the water consumed per unit cross-sectional area per unit time, $K(z)$ the hydraulic conductivity of the fibrous capillary interface material, ρ is the mass density of water, and g is the gravitational acceleration and $\psi_m(z)$ is the hydraulic pressure head induced by the capillary action. The pressure head applied to the soil subsurface to supply water into the root zone of the plant can be varied by manipulating the water supply depth (Δh) in the subsurface tank using the proposed KF-PID control system. This control system will then adaptively regulate the supply of water to the plant root area base on the plant demand through the fibrous capillary interface, while considering the soil moisture content and weather condition as illustrated in the conceptual diagram shown in Fig. 2.

Fig. 2 illustrates an IoT based experimental framework setup of the proposed KF-PID controller is similar to what was proposed by [46], but with improvement on the control algorithm for the management of fibrous capillary irrigation. The experimental investigation of the performance of the implemented KF-PID controller on the cultivation of mustard leaf plant was tested as treatment A. This was validated with treatment B, which is an adaptive fuzzy controller previously implemented by Rahman et al. [26], for the control of fibrous capillary irrigation. Both controllers were used to regulate the water supply depth (Δh) to irrigate mustard leaf concurrently throughout the cultivation period of 30 days in a greenhouse within Universiti Teknologi Malaysia.

Based on Fig. 2, as the level of water inside the water depth tank rises, the water that flows through the outlet pipe to each polybag will increase towards the fibrous material to the root zone of the plant thus increase the wetted area in the root zone increases diffusely with time-based on the capillary and gravitation action of the medium. The horizontal and vertical fibrous capillary interface used inside the poly bags with coco peat as the growing medium is illustrated in Fig. 3(a) and (b). The nature of the capillary interface determines the wetting pattern at the root zone of the plant.

The type of capillary interface used (Horizontal or vertical), as well as the manipulation of Δh in the reservoir, have some effects on the moisture wetting pattern around the root zone of the plant, the crop water uptake and evapotranspiration. In order to properly ensure a proper wetting inside the root zone as well as the soil moisture content which affects the crop evapotranspiration and water uptake, a suitable Δh is needed. The Δh is the height between the fibrous interface and the surface of water in the small water supply depth tank. This proposed controller is needed to control the optimal required Δh, to aid the supply of water to the root zone through the fibrous capillary material based on plant demand, soil and weather condition. The Δh is measured using the e tape water level sensor submerged inside the water depth tank, while an ultrasonic sensor (US015) is used to track the volume of water utilized for irrigation in the water reservoir tank. The data of the various sensor's values, as well as the captures images of the plants, were stored to a cloud server every 10 minutes and daily respectively.

To measure the height of the water between the fibrous capillary and the surface of water in the small water supply depth tank otherwise

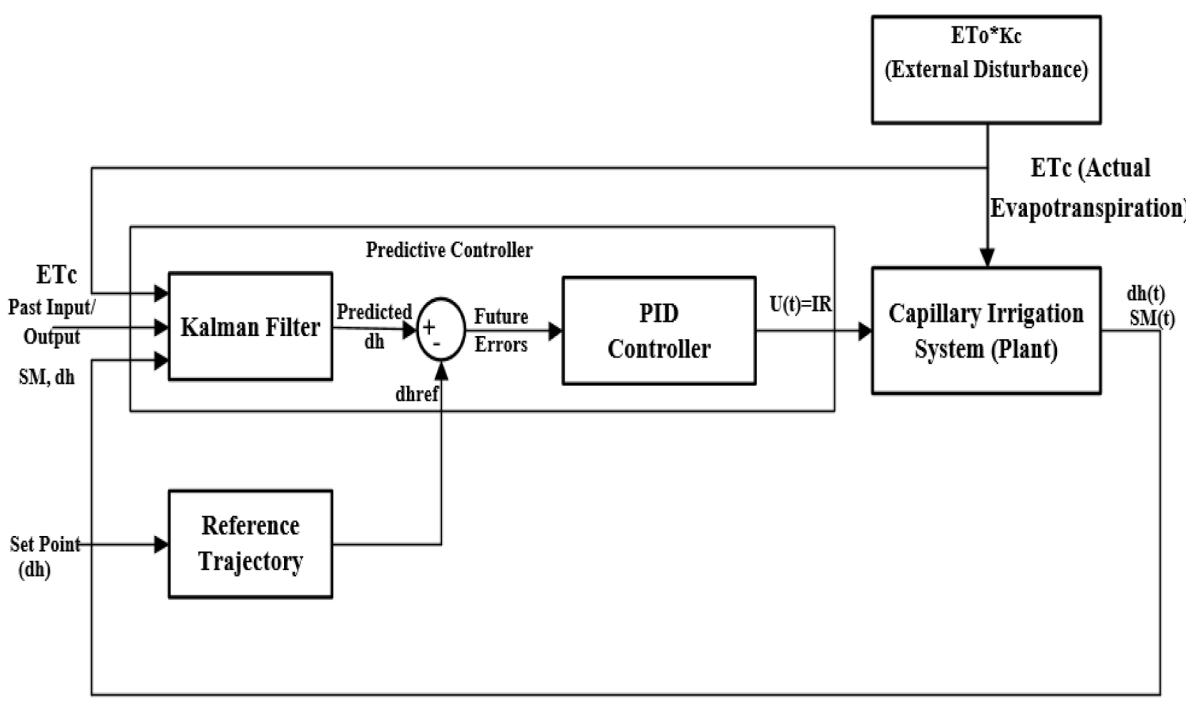

Fig. 4. Proposed Kalman filter-PID control strategy for capillary irrigation.

Fig. 5. Model formulation for input and output data.

known as Δh, a 256.5mm e-tap Milone level sensor was utilized. The e-tape sensor consists of a voltage divider circuit used to convert the varying resistance values to a voltage that can be measured and converted by the Arduino analogue to digital converter. The resistive output of the sensor is inversely proportional to the height of the liquid. As the water level, fall and rise in the tank also result in increases and decrease respectively which corresponds to the distance from the top of the sensor to the fluid surface. The varying resistance is converted to the corresponding voltage by the analogue to a digital circuit of Arduino. The e-tape sensor has lower resistance at higher liquid levels and higher resistance at lower liquid levels. Therefore, the maximum digital voltage reading corresponds to an empty tank and minimum digital voltage reading corresponds to the full tank.

The water level of the water reservoir tank was measured using the HC-SR04 ultrasonic sensor interfaced with IoT enabled Arduino board, to be able to track the volume of water used daily using Eq. (6). The sensor uses the transmitter and receiver namely trig and echoes pin to measure the distance with the range of 2cm to 450cm with an accuracy of 2mm. The sensor senses the initial level of water l_1 in the tank, before irrigation at 7.00 am and the final level l_2 of water in the tank at the end of irrigation in the evening around 5.00 pm. The volume of the water in liters utilized daily is estimated using the volume of the cylindrical tank in cm^3 .

$$\mathrm{V} = \mathrm{pi}\ r^2 h \tag{6}$$

where $h = l_2 - l_1$, is the height of water level utilized, r is the radius of the cylindrical tank.

Through the aid of IoT monitoring integration, the real-time sensing of soil moisture content of the soilless coco peat using a VH400 moisture sensor, reference evapotranspiration (ETo) was computed using the IoT based weather station monitoring system. Water loss is also known as disturbance of the process plant thus it requires a real-time estimation to produce an efficient water management for the plants [8,47]. To accurately estimate the actual evapotranspiration (ETc) as expressed in Eq. (3), the crop coefficient (Kc) for a specific plant at different growth stage as well as the measurement of the real-time of reference evapotranspiration (ETo) was computed on the IoT based weather station monitoring system to estimate an accurate actual water loss within the greenhouse environment, while enabling the proposed controller to be able to regulate the irrigation that will compensate for the loss.

The proposed control strategy for smart fibrous irrigation management system comprises of the integration of both KF and PID controller as illustrated in Fig. 4. The KF is used to filter off the noise from the level sensor, as well as estimate the optimal water supply depth (Δh). Then the PID controller will accept both the reference Δh and the estimated Δh and sums up the proportional, integral and derivative effect to generate the new control action to minimize the error. The control action is translated into PWM signal to drive the pump, to supply water into the water supply depth tank. As water is being pumped into the water supply depth tank, it circulates through the pipe into the fibrous capillary interface of each poly bags, after which water is transported to the root zone of the plant while creating a wetting pattern. The controller also receives feedback from the level sensor inside the water depth tank, soil moisture sensor as well as the computed actual disturbance to determine the next optimal value of Δh.

3. Data-driven modelling of the system using system identification

The performance of the KF to estimate the optimal value of sensor value depends on how good its model is and how well its covariance is selected. To get a good model that captures the dynamics of the system, a data-driven model is obtained using a state space model structure of system identification method, in which a one-month time-series input and output of previous experimental dataset comprising of 3560 data points with a sampling time of 10 minutes was used for the identification. The dataset was then pre-processed and split into two parts of 70% for model estimation and 30% for model validation, while the appropriate model structure was selected to fit the estimated data. Different model structures were fitted into the processed data, but the state-space model outperformed others model structures having the highest estimated fit of 96% and hence selected for the controller design. The process of the multiple input single output for the model can be seen in Fig. 5.

A discrete-time state-space model was used to represent the dynamics of the real system

$$x[k] = \boldsymbol{A}x[k] \ + \ \boldsymbol{B}u[k] \tag{7}$$

$$y[k] \ = \ \boldsymbol{C}\mu[k] \ + \boldsymbol{D}u[k] \tag{8}$$

With

$$\boldsymbol{A} = \begin{bmatrix} 0.9887 & 0.0705 \\ -0.0279 & 0.7707 \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} -0.0079 & 0.0430 \\ -0.0333 & -0.0018 \end{bmatrix}$$

$$\boldsymbol{C} = \begin{bmatrix} 12.7566 & -3.8895 \end{bmatrix}$$

$$\boldsymbol{D} = \begin{bmatrix} -0.5624 & 0.1816 \end{bmatrix}$$

3.1. *Discrete Kalman filter for estimation of Sensor measured Δh*

Kalman filter is an optimal estimation algorithm that uses a set of model equations as well as sensor data set to implement a predictor-corrector type estimator that is optimal in the sense that it minimizes the estimated error covariance [48,49]. This is crucial because the algorithm can be used to reduce the measurement noise as well as other inaccuracies of the sensor caused due to external signal disturbances and the complexity of the measured variable to produce estimates of unknown variables that are more precise than those based only the sensor measurement [50]. In this paper, Kalman filter (KF) is use to reduce the noise from the level sensor measuring the Δh taken at discrete time instance using the discrete-time linear model formulated in form of Eqs. (9) and (10).

$$x_k = \boldsymbol{A}x_{k-1} + \boldsymbol{B}u_{k-1} + w_{k-1} \tag{9}$$

$$y_k = \boldsymbol{H}x_k + v_k \tag{10}$$

Where A $\in \mathbb{R}^{nxn}$, B $\in \mathbb{R}^{nxl}$, H $\in \mathbb{R}^{mxn}$ are the constant state matrix, w_k and v_k is the noise vector and measurement process noise, while

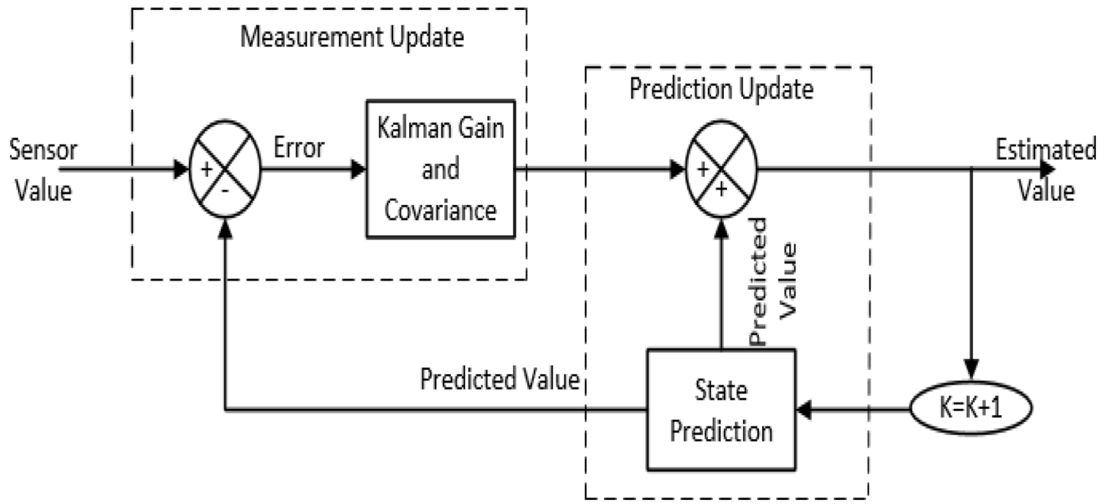

Fig. 6. Kalman filter estimation process.

$x_k \in \mathbb{R}^n$, $u_k \in \mathbb{R}^l$ and $y_k \in \mathbb{R}^m$ are the state vector of the process, process input and measured process output respectively. The sensor data for the system is taken at discrete time instance. There is no association between the process noise w_{k-1} and measurement noise v_k. The process noise and measurement noise are described by their covariance matrices Q_w and R_v in Eqs. (11) and (12). Both matrices are the tuning filter parameters crucial for the optimal performance of the KF. The covariance matrices can be written as:

$$Q_w = E\left[w_k \ w_k^T\ \right] \tag{11}$$

$$R_v = E\left[v_k \ \ v_k^T\right] \tag{12}$$

Where E denotes the expected estimated value, and T is the transpose of the matrix. The design of the KF estimator for the e-tape sensor it was designed based on two processes that occurs in KF, which is the time update and measurement update. The time update equations can be formularized as predictor equation, while the measurement update equations can be formularized of as corrector equation. The final estimation algorithm resembles the predictor-corrector algorithm in solving numerical problems as shown in Fig. 6. Prediction of $\widehat{P}_k$ at each stage is given by Eqs. (13) and (14), where the system model will be produced based on the estimated value of previous state $\widehat{x}_k$ and the error covariance matrix $\widehat{P}_k$.

Prediction:

$$\widehat{x}_k = Ax_{k-1} + Bu_{k-1} \tag{13}$$

$$\widehat{P}_k = \ AP_{k-1}\ A^T\ +\ Q \tag{14}$$

Update:

$$G_k = P_k H^T\left(HP_{k-1}H^T + R\right)^{-1} \tag{15}$$

$$P_k = \widehat{P}_k - G_k H \widehat{P}_k \tag{16}$$

$$x_k = \widehat{x}_k + G_k(Y_k - H\widehat{x}_k) \tag{17}$$

In the update stage, the update or correct values of x_k and P_k will use the data from the actual sensor which are illustrated in by the Eqs. (15), (16), (17). The relationship between the state vector and the sensor data is denoted by Eq. (17). Where P_k is the current predicted estimate, P_{t-1} is the previous estimate, Y_k is the measured sensor value, and G in Eq. (15) is the measured gain that ranges from $0 \leq G \leq 1$, which helps to reduce the previous error covariance matrix. Similarly, the measurement update process will continue to determine the Kalman gain G_k, and prediction value x_k. The output of the KF x_k will be and used as feedback in the control system where H is the identity matrix and R is the standard deviation. The matrix Q was determined arbitrarily, whereas the matrix R is determined based on the variance of the raw sensor measurement of the level. The Δh data from the e-tape sensors was fed through the Kalman filter and then the process of prediction and correction will simultaneously be executed to remove the measurement noise and provide the optimal estimate of Δh.

Table 1
System parameters.

Parameters	Values/Dimensions
Horizontal fibrous capillary interface	120 × 120 × 5 mm
Vertical fibrous capillary interface	40 × 30 × 40 mm
Water supply depth (Δh) range	0 -20 cm
Soil moisture content range	0-0.6 m^3/m^3
Crop coefficient (kc)	0 - 0.75
Reference evapotranspiration	0 - 1.5 mm/day

3.2. The proportional integral and derivative (PID) controller

The PID controller consists of the proportional (P), integral (I) and derivative (D) which signifies the present error, past error and future error respectively as described by Eq. (18). The controller continuously regulates the error value $e(t)$, which is the difference between the set point and the measured output parameter. The proportional integral and derivative (PID) control algorithm is used to correct the error between the measured and the estimated Δh as seen in Eq. (19). The PID can be referred to as three-part controller with each part carrying out the different task in the control process and generate the control input $u(k)$.

$$u(t) = k_p e(k) + k_d\frac{de(k)}{dt} + k_i\int_o^t e(k)dt \tag{18}$$

$$e(k) = k_p\left[dh_m - dh_p\right] \tag{19}$$

where (k), $e(k)$ k_p, k_d and k_i denotes the effective control action, error in the process, proportional gain, derivative gain, and integral gain respectively.

4. Simulink design of the proposed Kalman filter-PID controller

This section describes the Simulink design of the KF-PID controller for fibrous capillary irrigation using different Simulink blocks to simulate the behaviour of the proposed controller. The KF based estimation

Table 2
Algorithm.

KF-PID Algorithm for the Fibrous Capillary Irrigation
Required: Input $Ir[k_i-1]$, $ETc[k_i-1]$, $SM[k_i-1]$, Output $dh[k_i-1]$ **Initialize** Use the previous input and output data to identify a state-space model **Loop** Estimate the process output $dh_p[k_i]$ Read $dh[k_i]$ //Current process output Estimate the error $e[k_i]$ i.e., $dh_p[k_i] - dh[k_i]$ **If** $dh_p[k_i] - dh[k_i] > 0$ *or* $ETc \geq ETc_{max}$ Generate $u(k)$, using Eq. (9) Apply Wait for the next sampling time $k = k+1$ **End**

of delta *h* was complemented with a PID controller to minimize the error between the predicted and the reference trajectory of the Δh based on the algorithm 1 in Table 2 as shown in Simulink implementation in Fig. 7. In this paper, the chosen reference point is -9 cm. The PID parameters were tuned using the manual concept to obtain better control performance. Based on the tuning process, proportional gain of 0.8, integral of 0.1 and the derivative of 0 has been found to become the most optimized gains in this application. The controller works by subtracting the desired Δh set point from the KF estimated Δh. The subtraction generates an error, which was then fed onto the PID control algorithm. The PID controller processed the error to further generate a pulse width modulation drive signal to control the speed of the direct current (DC) pump as a control action. To ensure optimal computational and controller performance and the event-based generator was integrated to update the controller based on a triggering event.

To access the performance of the proposed controller, error minimization analysis was used based on three commonly used indices such as integral absolute error(IAE), integral square error (ISE), and integral time-weighted absolute error ($ITAE$). The IAE is the integral of the absolute error value that does not add weight to any error in the systems response and has lesser sustained oscillation. The ITAE integrates the absolute error and multiply it by the time over time to weight errors that exist after a long time much more heavily than those that starts the response. Finally, ISE tends to minimise large errors very fast, but small errors persist for a long time [51]. From the Eqs. (20)–(22), the $y_{est}(t) - y_s(t)$ is the error between the estimated and set point Δh at the input of the PID controller, T is the simulation time, t penalises the later errors, while the square penalises larger errors

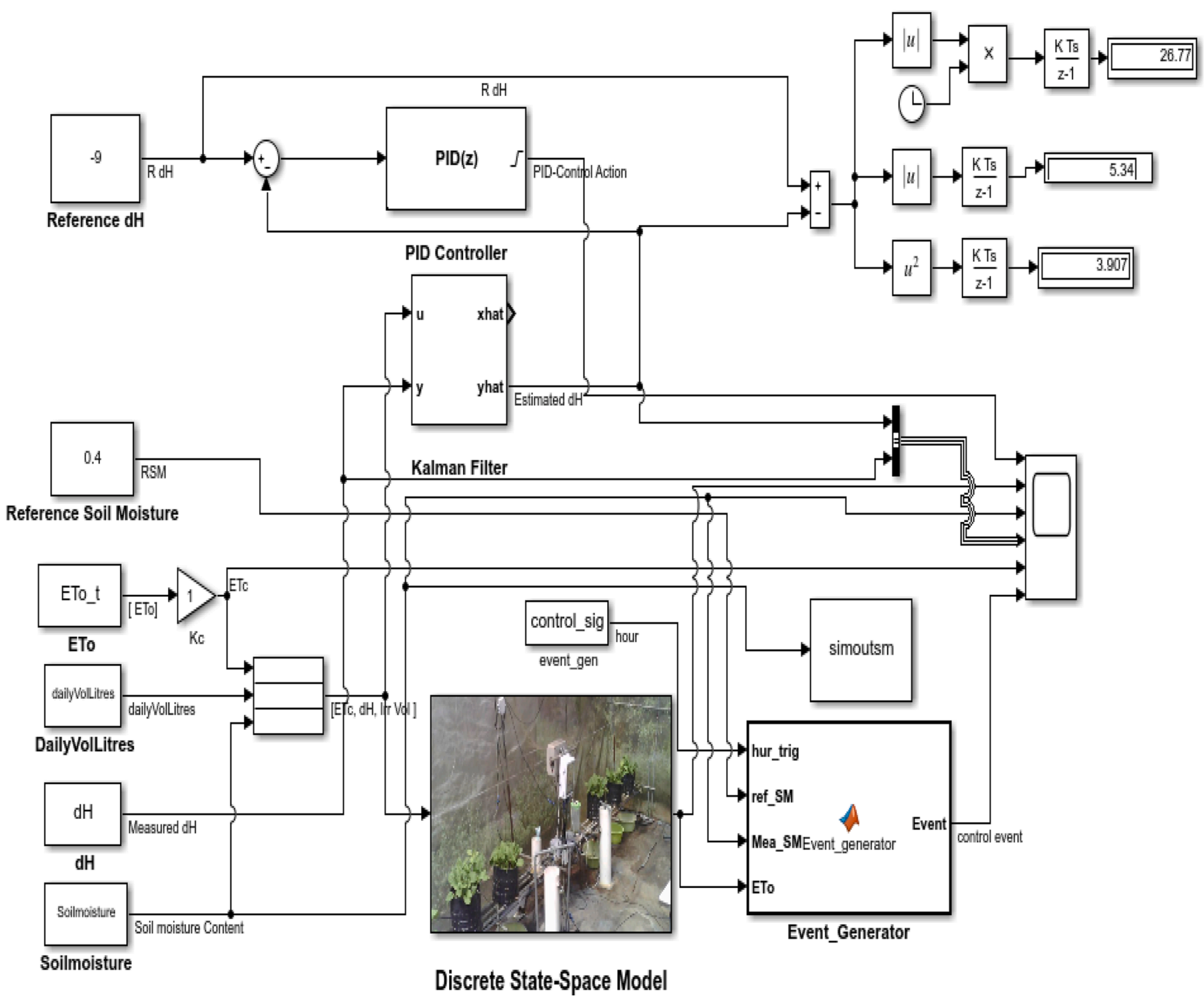

Fig. 7. Implementation diagram of Kalman filter PID based control of capillary irrigation.

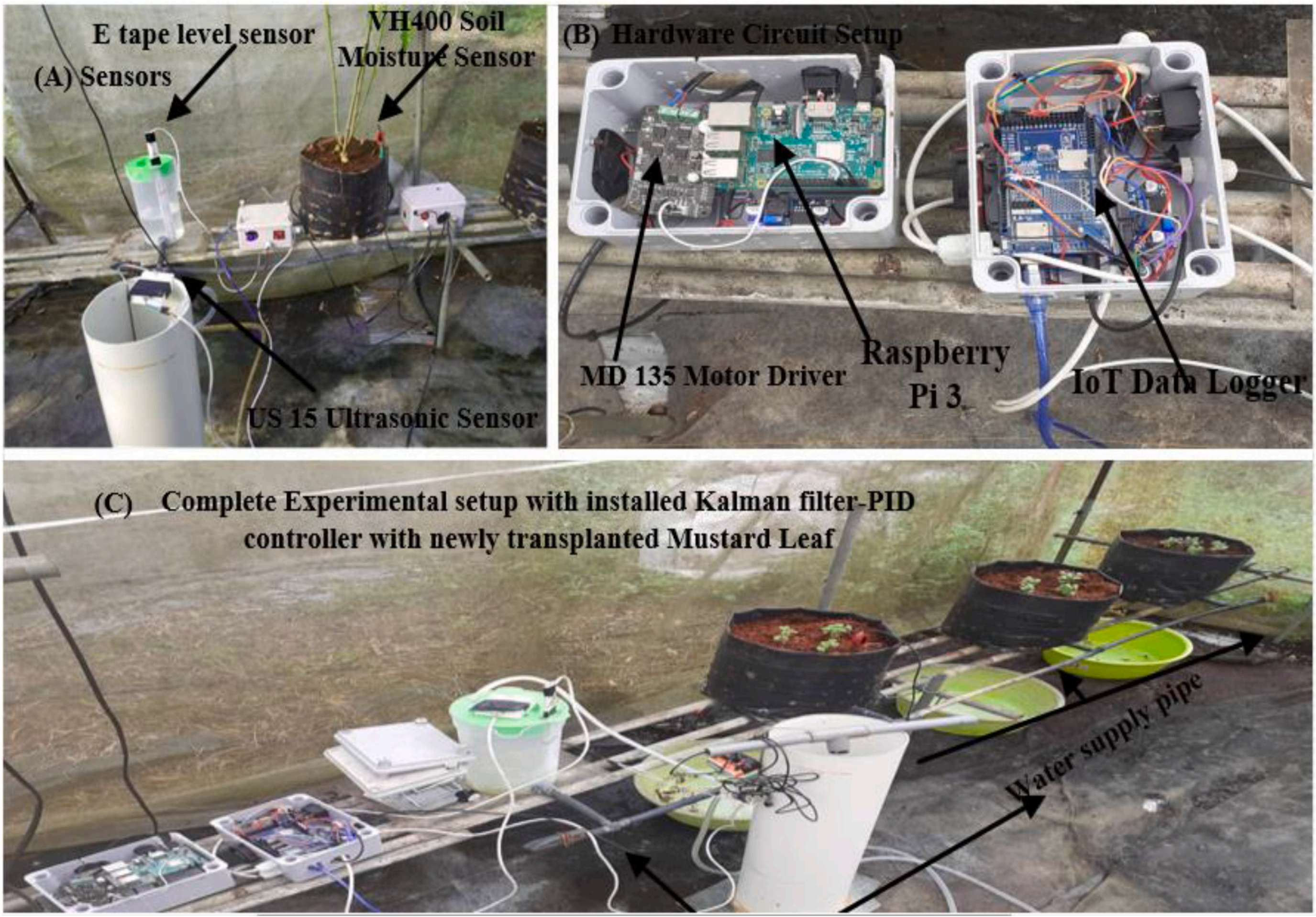

Fig. 8. Hardware implementation of the data-driven Kalman filter based PID controller on Raspberry Pi with IoT integration.

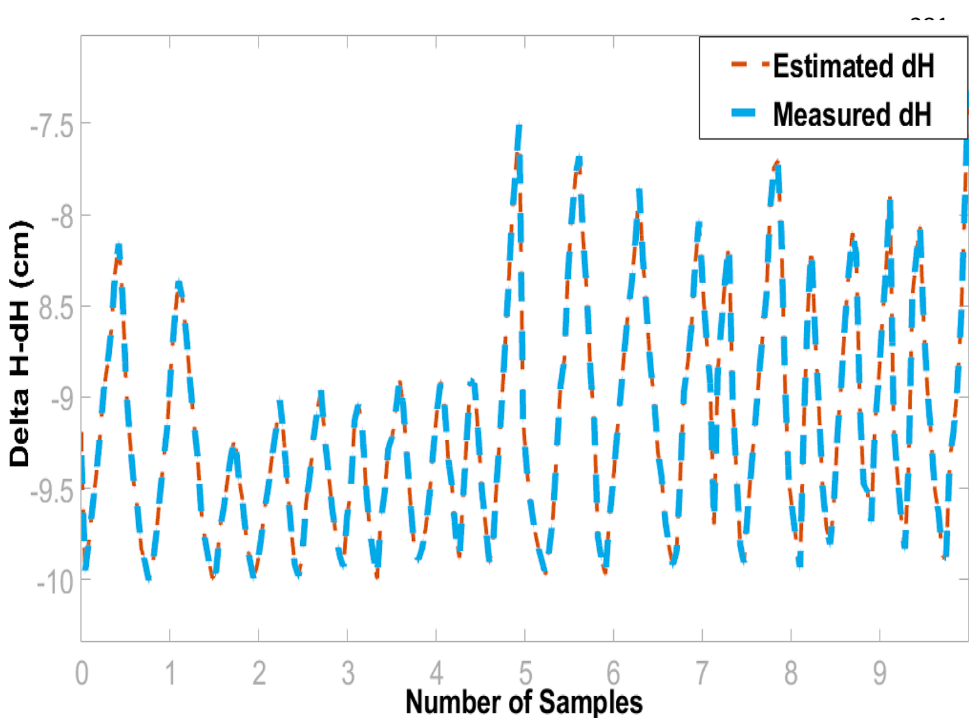

Fig. 9. Estimated and measured Δh response.

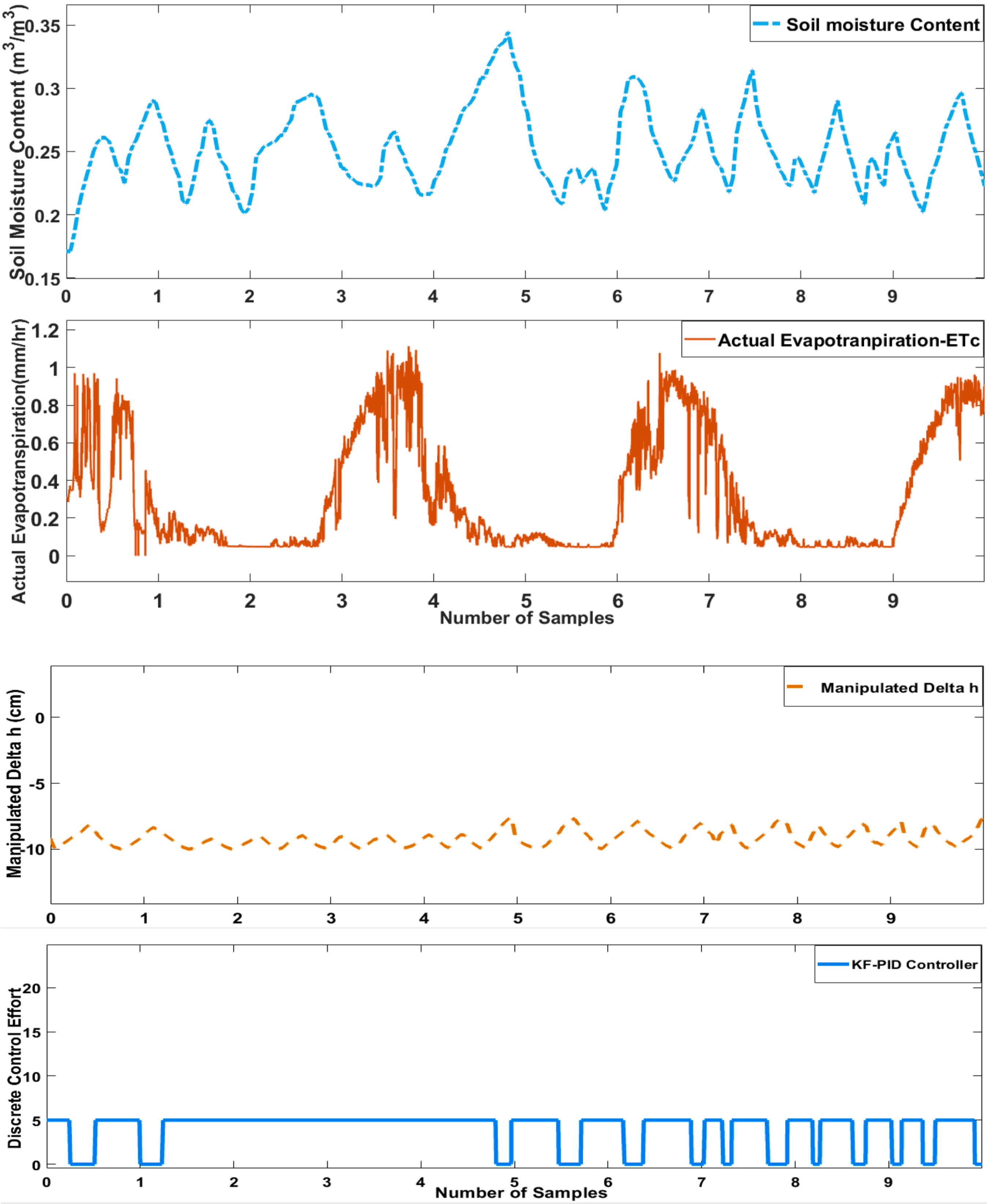

Fig. 10. Simulation of the proposed controller (a) Soil moisture content and Actual evapotranspiration (b) Manipulated Δh and discrete control Effort by the KF-PID Controller.

Table 3
Controller performance in terms of error minimization.

Controller Type/Parameters	IAE	ISE	ITAE
Kalman filter-PID	5.298	3.797	26.6
Adaptive Fuzzy	7.789	4.234	37.9

$$IAE = \int_0^T [y_{est}(t) - y_s(t)]dt \tag{20}$$

$$ISE = \int_0^T [[y_{est}(t) - y_s(t)]]^2 dt \tag{21}$$

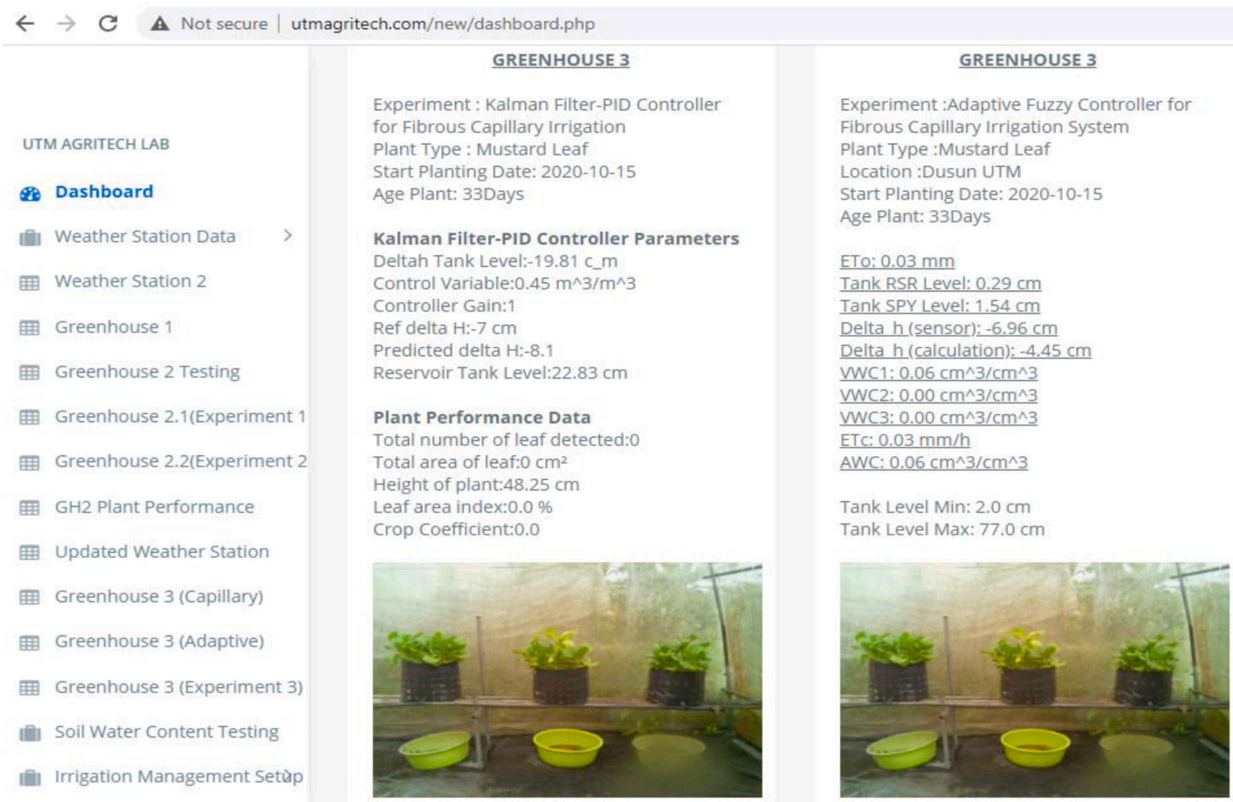

Fig. 11. IoT monitoring dashboard for the deployed Kalman filter-PID Controller and adaptive fuzzy controller in greenhouse 3.

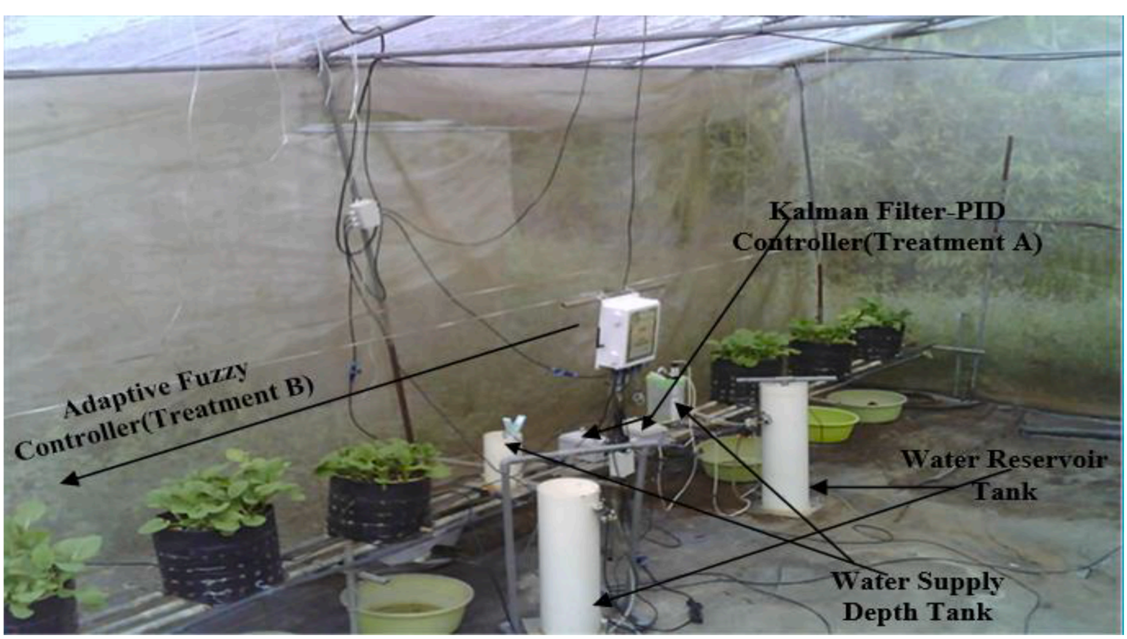

Fig. 12. Experimental setup for the Kalman filter-PID controller for cultivation of mustard leaf.

Table 4
Average weight of harvested mustard leaf plant (g).

Controller	Treatment A (Kalman filter – PID)		Treatment B (Fuzzy Logic)	
Capillary interface	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**
Weight (g)	165	195	265	205
Height(cm)	31.8	26.8	32	25.6
Leaf area(cm^2)	286	212	298	196

Table 5
Water productivity index of mustard leaf cultivation g/m^3.

Controller	Treatment A- (Kalman filter-PID)	Treatment B-(Fuzzy Logic)
Irrigation volume used (Liters)	**16**	**25**
Average weight of harvested leaf (g)	**180**	**235**
Water productivity index (g/ Liters)	**11.25**	**9.4**
Cumulative water leached (Liters)	**3.9**	**7.3**

$$ITAE = \int_0^T t[[y_{est}(t) - y_s(t)]]^2 dt \tag{22}$$

4.1. The Hardware implementation of the controller and experimental cultivation validation

The Raspberry Pi 4 micro-computer was used to implement the model-based irrigation control system in real-time. The Raspberry pi uses a 1.5 GHz quad-core Broadcom processor, 64-bit SoC with 4 GB DDR4 of RAM, GPU 500MHz video core vi [52]. With this Soc specification, the KF-PID control algorithm was able to run efficiently to control the irrigation system. The controller design was implemented in Simulink where the C code was generated, exported and further modified for the hardware implementation shown in Fig. 8. The PID controller generates the control action in form of pulse width modulated (PWM) signal a with a varying duty cycle to drive the manipulated variable while compensating for the loss and disturbance on the plant. The driver receives PWM control action signal from the GPIO pin 12 and 13 of the raspberry pi and provides the necessary driving current to the direct current (DC) water pump from the power supply.

5. Results and discussion

The graph of the measured Δh versus the estimated Δh response is presented in Fig. 9, where the KF can accurately filter the sensor noise and estimate the value of Δh. The simulation of the proposed KF-PID controller was carried out in Simulink, with the simulation result displayed in scope illustrated by Fig. 10. From Fig. 10, it can be observed that the controller was able to generate the control action to manipulate the Δh necessary to compensate for the actual water loss and maintain the soil moisture content within the field capacity ($0.45m^3/m^3$) and wilting point ($0.15m^3/m^3$).The performance of the proposed controller in terms of the error minimization is compared with the existing fuzzy controller shown in Table 3. Based on the results it can be observed that the proposed control system produced has lesser value of IAE, ISE and ITAE, denoting a good controller performance.

The dashboard in Fig. 11 shows the two experimental set up in the greenhouse with IoT monitoring system. The performance of the proposed KF-PID controller was compared with the adaptive fuzzy logic-based controller implemented by [26], in same greenhouse as shown in Fig. 12. The results of the proposed controller performance and experimental evaluation is presented in Tables 3–5 as well as in Figs. 13 to 16. Different indices were used to determine the performance comparison of the two irrigation methods on the cultivated Mustard plants, such as cumulative water consumption (liters), water productivity index, and weight of the harvested mustard leaf (g).

In Table 4, the measured average plant height and leaf area of the plant irrigated using both controllers were compared. From the table, the adaptive fuzzy logic control system produced higher plant and wider leaf area when compared with the KF-PID irrigated treatment. This is mainly due to higher water consumption produced by adaptive fuzzy logic control irrigation system. To further evaluate the performance of the controller, water productivity index (WPI) is calculated using the ratio of yield output to total crop water consumption as seen in Eq. (23). The value of WPI is shown in Table 5 for KF-PID and adaptive fuzzy logic control system respectively. The WPI of KF-PID is also slightly better

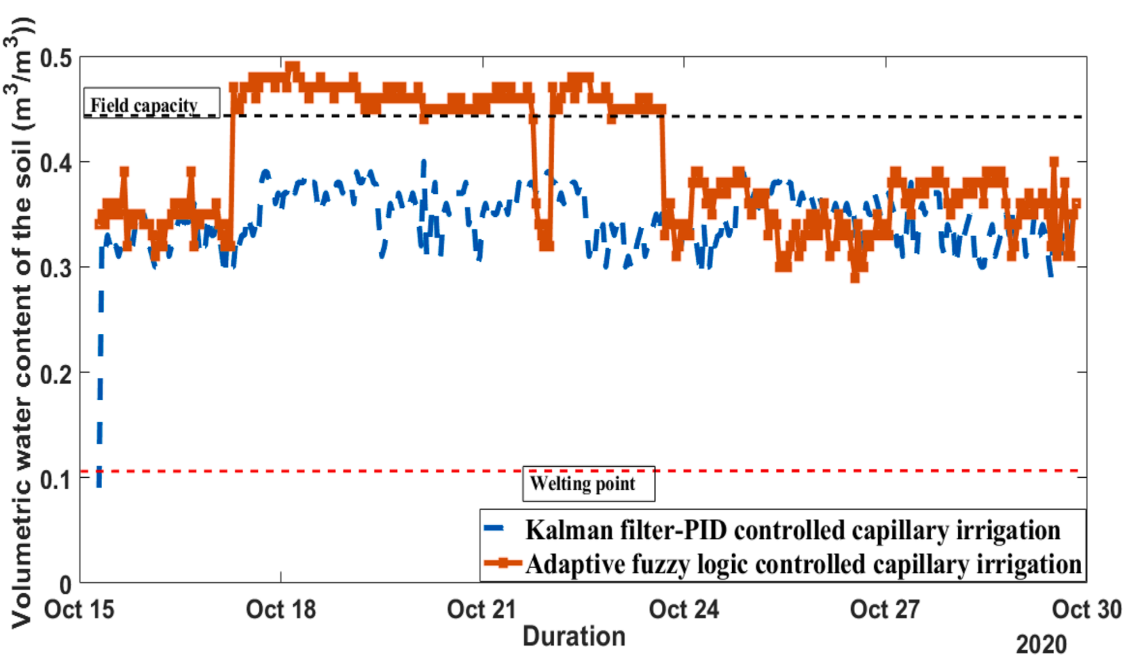

Fig. 13. Comparison of the volumetric water content (vwc) regulated by both controllers.

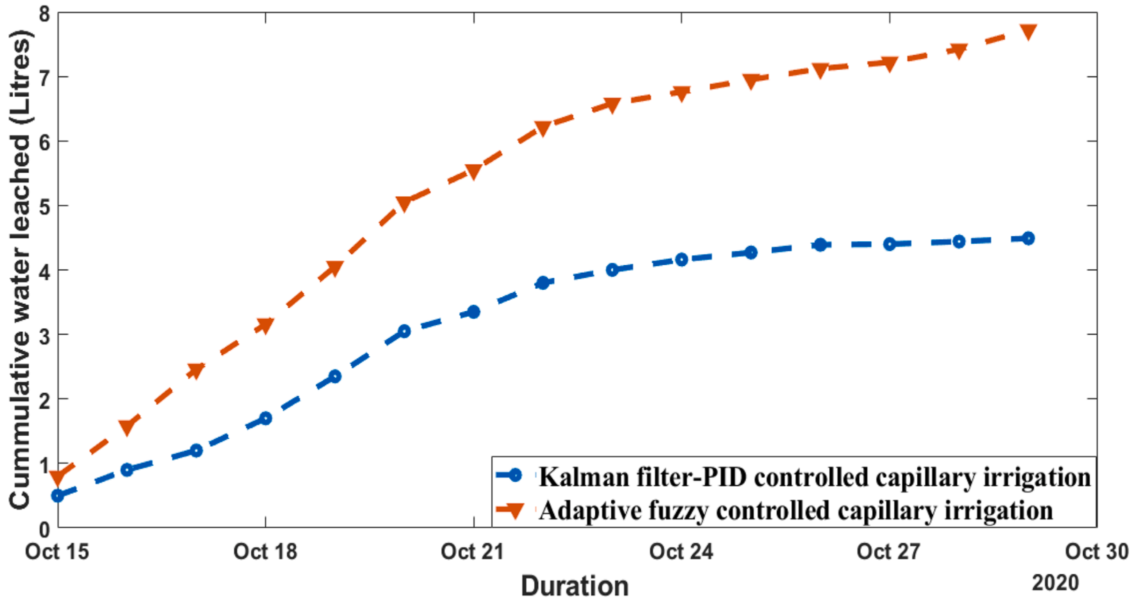

Fig. 14. Comparison graph of cumulative water leached for Adaptive fuzzy and Kalman filter-PID controlled capillary irrigation of mustard leaf.

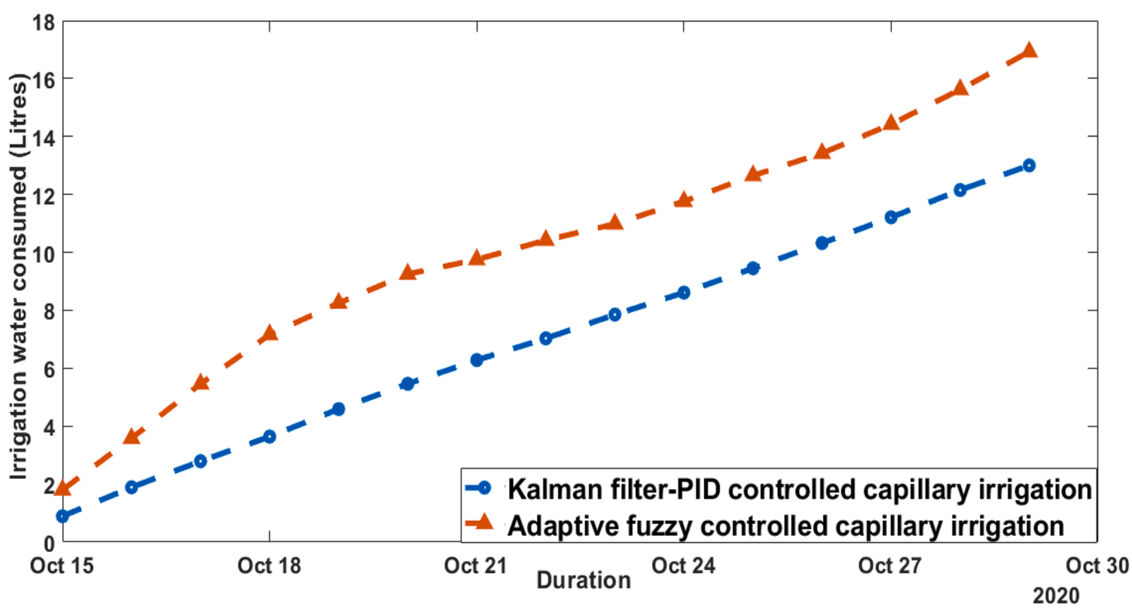

Fig. 15. Comparison graph of irrigation water consumption for Adaptive fuzzy logic and Kalman filter-PID controlled capillary irrigation of mustard leaf.

than that of adaptive fuzzy logic controller by 16%. This is because in the case of treatment A, 11.25 g of the Mustard leaf can be produced using 1 liter of water, as against that of treatment B which is 9.4 g per 1 liter of water. It can be further deduced from the result, that the WPI of the proposed KF-PID based controller is slightly better than that of the adaptive fuzzy logic controller. This could be due to gradual and optimal control of water supply to the plant wetting root area through the fibrous capillary interface, based on the plant, weather and soil demand.

$$\text{Water Productivity Index} = \frac{\text{Yield(g)}}{\text{Total Water Consumed(Litres)}} \tag{23}$$

Fig. 13. shows the soil moisture content variation as a comparison for both controller performances. It can be observed that the KF-PID controller was able to regulate and maintain the volumetric moisture content of the soil within the wilting point (0.15 m^3/m^3) and field capacity (0.45m^3/m^3), while some spikes were noticed which exceed the field capacity for the adaptive fuzzy logic control system. This has proven the reasons why higher water consumption produced by the fuzzy control system compared to the KF- PID control system.

The cumulative water leach throughout the cultivation period is illustrated in Fig. 14. It was observed that immediately after transplant, the water has been gradually leached thus reduce the, this crop water uptake and water loss was low, as well as the gradual tuning of the controller for optimal performance. When the plant begins to grow after transplants, the proper controller tuning to find an optimal Δh value has reduced the rate of water leaching from polybags. Therefore, hence, both curves begin to flatten starting from the first week after transplanting phase. Also, it can be observed that the total cumulative water leaching for treatment A is lesser that of B, which underscores the improved performance of the proposed controller

Fig. 15 illustrates the cumulative water consumed during the period of plant cultivation, from which the fuzzy controlled fibrous irrigated

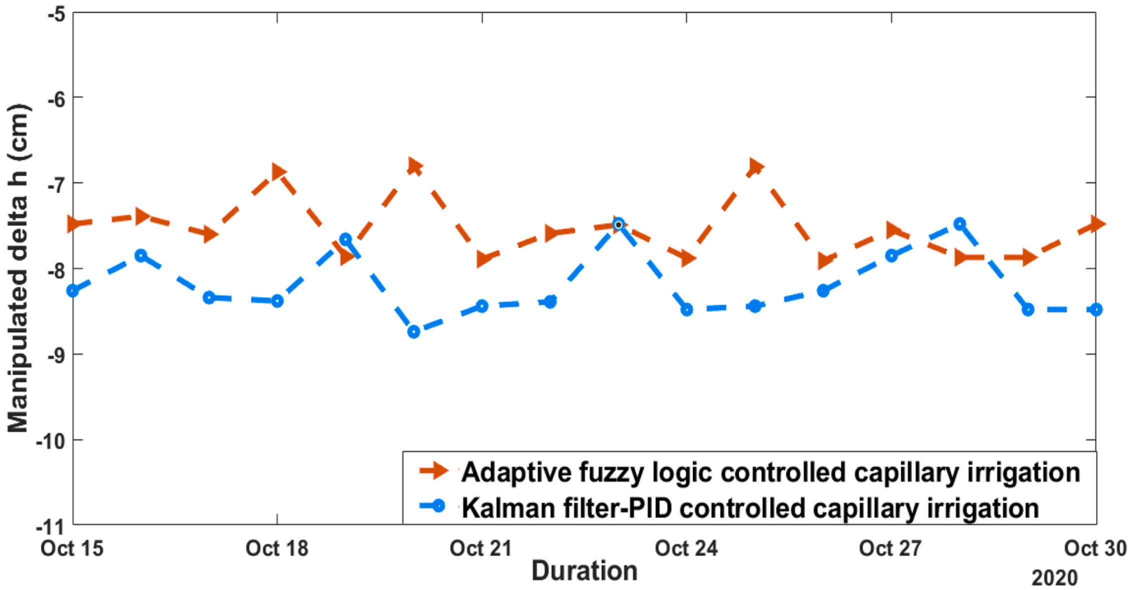

Fig. 16. Manipulated delta h for Adaptive fuzzy logic and Kalman filter-PID controlled capillary irrigation of mustard leaf.

plant has the highest water consumed during the cultivation period**.** This account for the fact that about 56.3% of water was reduced by treatment A when compared to treatment B. This, however, has a slight effect on the weight of the harvested leaf, as the harvested weight of treatment B which is higher than treatment A. This can be because more irrigation volume was utilized by treatment A. The result of the manipulated delta h for both controllers is illustrated in Fig. 16.

6. Conclusion

This paper presents the simulation and experimental implementation of a KF-PID controller for precision irrigation. The KF offers a solution associated with the problem of sensors output to estimate the optimal Δh while minimising and eliminating the unwanted output from the sensor. The PID controller is fed with input signal that is almost free from noise, and designed to minimise the error between the estimated Δh and the reference Δh. An experimental investigation on the performance comparison of the proposed controller on the cultivation of Mustard leaf plant has been presented in this paper. Based on the results, the proposed KF-PID controller is able to accurately estimate the optimal Δh for the control of the volumetric water content of the soil (vwc) within the field capacity and wilting point of the growing medium, which has helped to enhance the realization of high water-saving and improved yield. The water productivity index of the KF-PID controller shows a slightly better controller performance in terms of the error minimization, control action, water productivity index, and water wastage due to leaching immediately after transplants when compared with the adaptive fuzzy logic controller fibrous capillary irrigation. With proper monitoring and control strategies applied, a high amount of water can be saved with improved yield, using capillary irrigation method. Therefore, it is expected that this research effort will guide farmers to adopt an effective irrigation method which complies with their cultivation objective whether to produce a good quality or heavier yield.

Declaration of Competing Interest

The authors declares that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

The authors acknowledge the Universiti Teknologi Malaysia and the Ministry of Higher Education Malaysia (MOHE), for their partial financial support through their Prototype Research Grant Scheme (PRGS) Vote No. Q.J130000.2651.17J53.

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