

Design and Development of an Automated Double-Ring Infiltrometer for Soil Infiltration Measurement

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Abstract

Accurate and effective measurement of soil rate of infiltration is extremely crucial in hydrological modeling, irrigation planning, and soil conservation. Traditional double-ring infiltrimeters, despite their dominance, are labor-intensive and beset by labor intensiveness and limitations in live data recording. This study presents the development and construction of an automated double-ring infiltrimeter system that features a constant head system, ultrasonic level sensors, microcontroller (Arduino Uno Rev3), and solar-powered control and logging unit. A designed 25-liter calibrated cylindrical plastic reservoir mounted on trolley offers water supply via sensor-controlled pump-based supply. The system uses an ultrasonic sensor to read the water level in the calibrated tank that maintains a constant head inside a double ring infiltrimeter through an automated refilling system. The water level is read every 5 minutes and displayed on an LCD display, and logged on an SD card with timestamping. Water supply is controlled automatically to provide constant head conditions, records infiltration data with time-stamped records on an SD card, and gives real-time reading. Power is supplied using an independent solar power system in the shape of a solar panel, battery, charge controller, and inverter. The solar powering system includes a 230Ah deep-cycle battery, solar panel, charge controller, and inverter for off-grid functionality. Field validation involved comparative tests with a standard manual double-ring infiltrimeter under loamy soil conditions. The automated system achieved an average infiltration rate measurement deviation of ± 3.2 mm/h compared to the manual method, with a data logging frequency of 5 minutes. The setup operated for over 48 hours on solar power with minimal human intervention. Results indicate improved operational efficiency and potential applicability in remote field environments. The prototype was found to be accurate, responsive, and stand-alone with excellent potential for application in field-based soil infiltration research in remote fields. The design system is an economic, labor-saving solution when compared to the conventional methods, with the potential to save labor and improve the accuracy of measurement. Wireless data transmission for remote monitoring is an area with future potential development. This study contributes to the development of automated hydrological instrumentation, providing researchers and engineers with an optimum instrument for high-resolution infiltration studies.

Keywords: Automatic Infiltrimeter, Arduino, Ultrasonic Sensor, Double-Ring Infiltrimeter, Hydrological Monitoring, Data Logging.

Introduction

Efficient management of water remains a corner-stone of sustainable agriculture, especially under climate variability and increasing demand. Infiltration capacity of soils is a critical parameter influencing irrigation scheduling, groundwater recharge, and surface runoff. Traditional double-ring infiltrometers, though accurate, require constant observational monitoring. The double-ring infiltrometer (DRI) has long been a standard instrument for infiltration measurement due to its simplicity and reliability in minimizing lateral flow (Bouwer, 1986). Manual operation, however, is the demerit of traditional DRIs, being time-consuming and susceptible to observational errors, especially for long-duration experiments or changing field conditions (Reynolds *et al.*, 2002).

Such a process is made more precise, less subject to human error, and permits real-time data gathering (Abdelmoneim *et al.*, 2021). While infiltration information is critical, there remains a dependence on manual infiltrometer measurements in the majority of developing regions, which are time-intensive and variable. The absence of low-cost automated options limits the scalability of accurate infiltration assessments (Celik and Diker, 2021).

Advances in microcontroller and sensor technologies make upgrading traditional DRI systems possible. Automation provides the capability to monitor in real-time, improves measurement accuracy, reduces human error, and provides unmanned operation (Singh *et al.*, 2021). Additionally, solar-powered electronics make such systems possible to install in distant or off-grid agricultural fields, where monitoring of infiltration is needed most.

Low-cost, solar-powered automated infiltrometer made with open-source electronics and locally available materials offers an affordable solution to precision agriculture and hydrological studies. The system meets both the sustainability and the affordability requirements (Nwanya and Akinola, 2019).

Recent studies have discussed the upgrade of traditional double-ring infiltrometers to make them automated. Di Prima (2015) and Fatehnia *et al.* (2016) demonstrated the potential of microcontrollers to reduce manual labor. Arduino-based systems have been used universally for environmental monitoring due to their cost-effectiveness and adaptability. Lima *et al.* (2019) developed a wireless system for soil moisture monitoring using the same material elements in this study.

The design of this device for an autonomy is based on the reservoir capacity and power requirement and this in turn borders on the locality of consideration. The table 1 shown the infiltration of different soil type as reported by different authors and this will assist in sizing the capacities. Peak infiltration rate of different soils in Nigeria is as shown in Table 1.

Table 1: Peak Infiltration of different soil in Southwestern state of Nigeria

S/N	Soil Types	Peak infiltration rate (mm/hr.)	Region	Citations
1	Sandy soil	50-75mm	Oyo/Ogun	Aina and Periaswamy, 1985
2	Loamy	30-50	Oyo	Adeyemo and Oyediran 2016
3	Clayey	5-15	Ondo/ Osun	Olorunfemi and Olorunfemi, 2015
4	Lateritic	10-25	Ekiti/Osun	Akintola and Areola, 2017

Soil infiltration is a required hydrological parameter in irrigation planning, erosion control, and environmental impact assessment. Traditional double-ring infiltrometers are labor-intensive, require constant human observation, and are susceptible to human error. These limitations hinder long-term and large-scale infiltration studies, especially in remote or resource-limited settings. There is a need for an affordable, autonomous solution that simplifies infiltration data collection while improving accuracy and frequency.

This paper outlines the design and construction of an automated double-ring infiltrometer with a constant head system, sensor-controlled water supply system, and sun-powered autonomous power system. It aims to reduce operator interference while maintaining the measurements precise and continuous with the following objectives:

- To design and construct an automated double-ring infiltrometer with a constant head system.
- To achieve Arduino-based control with ultrasonic sensors, pump automation, and data logging.
- To possess a solar-powered system to attain field independence.
- To pilot and calibrate the device using local soil and climatic conditions.

Solar systems are increasingly being used in precision agriculture for providing autonomy in remote areas. Zubair and Ahmad (2020) and Zhou *et al.* (2015) cited the reliability of such a system for powering field sensors and irrigation systems.

Materials and Methods

System Components

Components and parts used in the study are:

- Double-ring infiltrometer (inner: 30 cm, outer: 60 cm): Inner and outer rings of galvanized steel, 300 mm and 600 mm diameter, respectively, of depth 300 mm.
- Plastic cylindrical water reservoir (25 L): 25-liter cylindrical plastic water reservoir of size 200mm x 800mm (diameter x height) provisions with inlet and outlet.
- Ultrasonic sensor (HC-SR04): Two HC-SR04 ultrasonic sensors—one for monitoring reservoir level, the other to be used for future soil surface monitoring.
- Arduino Uno Rev3 microcontroller: Arduino Uno Rev3 for managing sensor input, pump operation, and data logging.
- 12V water pump: 12V submersible pump regulated by water level and microcontroller commands.

- vi. Solar panel (150W), charge controller, 230Ah battery, 20A charge controller, and 300W inverter.
- vii. SD card module and LCD display: Micro SD module with RTC (real-time clock) for time-stamped data storage. And 16x2 LCD for real-time display of infiltration rate and water level.
- viii. Steel trolley frame for portability and support

Design Approach

The design of this automated infiltrometer involves automation of double ring infiltrometer by employing Arduino system to monitor water level in a sensed reservoir which feeds internal ring of the system. Figure 1 illustrates the schematic diagram of the system.

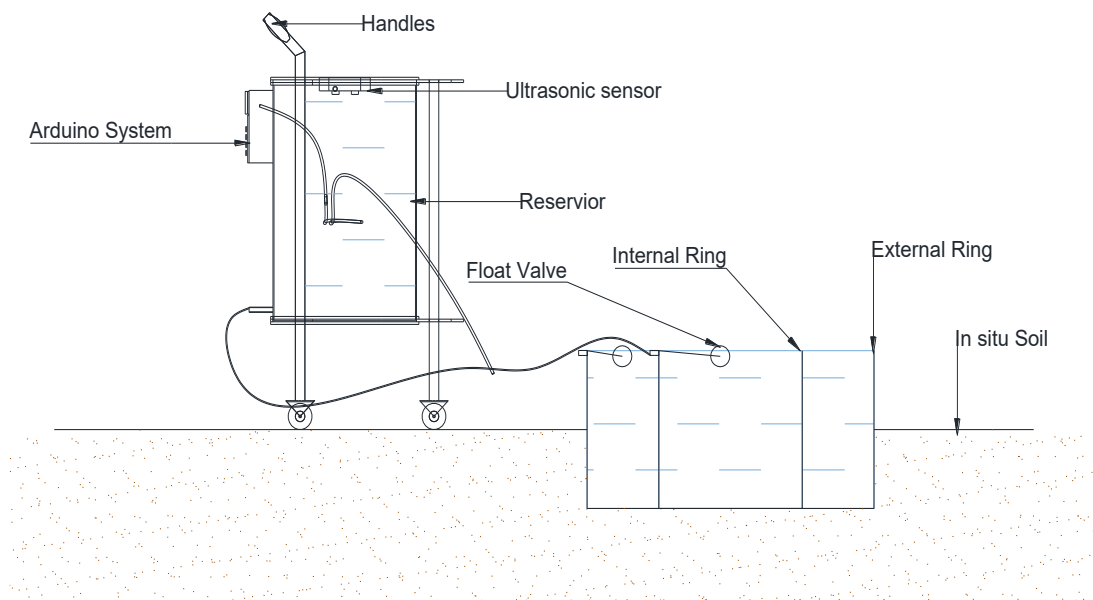


Figure 1: Schematic diagram of the automated infiltrometer system

Control Algorithm

It is controlled by comparing water level data from the ultrasonic sensor to preselected levels for ON and OFF control (Adeyemi *et al.*, 2020). The water level observation in the reservoir is observed using an ultrasonic sensor. Arduino receives distance value from the ultrasonic sensor, performs the calculation of the water level, and turns the pump on if the level falls below the low threshold (50 mm from base), turn pump ON and turn pump off when the top threshold (300 mm) is reached. Arduino connection diagram is Figure 2 whereas the exploded 3D AutoCAD design of the Automated infiltrometer is Figure 3. The choice of ultrasonic sensor for water level determination is justified by its accuracy, non-contact measurement, cost effectiveness, ease of integration and performance in different environmental condition. (Usman, *et al.*, 2022)

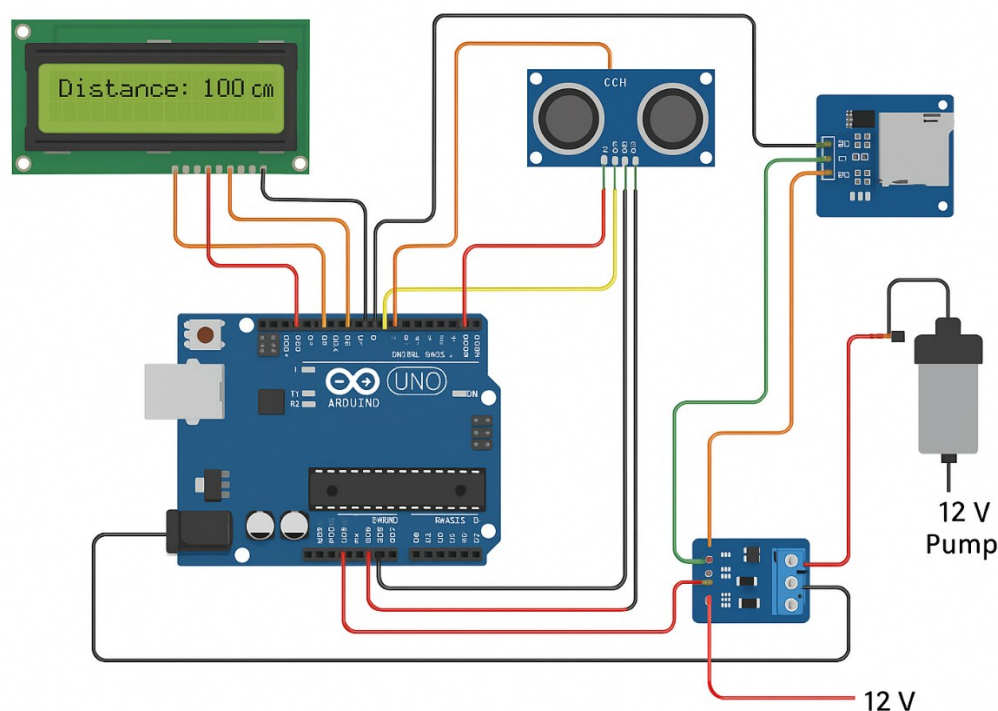


Figure 2: Arduino System Connection Diagram

The method approximated the distance between the ultrasonic proximity sensor and the water. The sensor sends an ultrasonic wave and calculates its wave travel time to the sensor once reflected by the water.

Distance, d between water level and sensor = speed of the wave $\times$ time taken

Height of the water in a container, H is gotten by subtracted the distance, d from the height T of the container.

$$\text{Height of water, } H = T - d \quad 1$$

The Arduino will use this data to process and obtain the height of the water in a container and subsequently the volume of water infiltrated as in equation 2.

$$V = a . H \quad 2$$

Where:

V = volume of water infiltrated (m^3)

A = cross-sectional area of cylindrical reservoir (m^2)

The ultrasonic sensor readings were recorded every 5 minutes as real-time rate of infiltration data to an SD card with time stamps and display on-site for convenient reference.

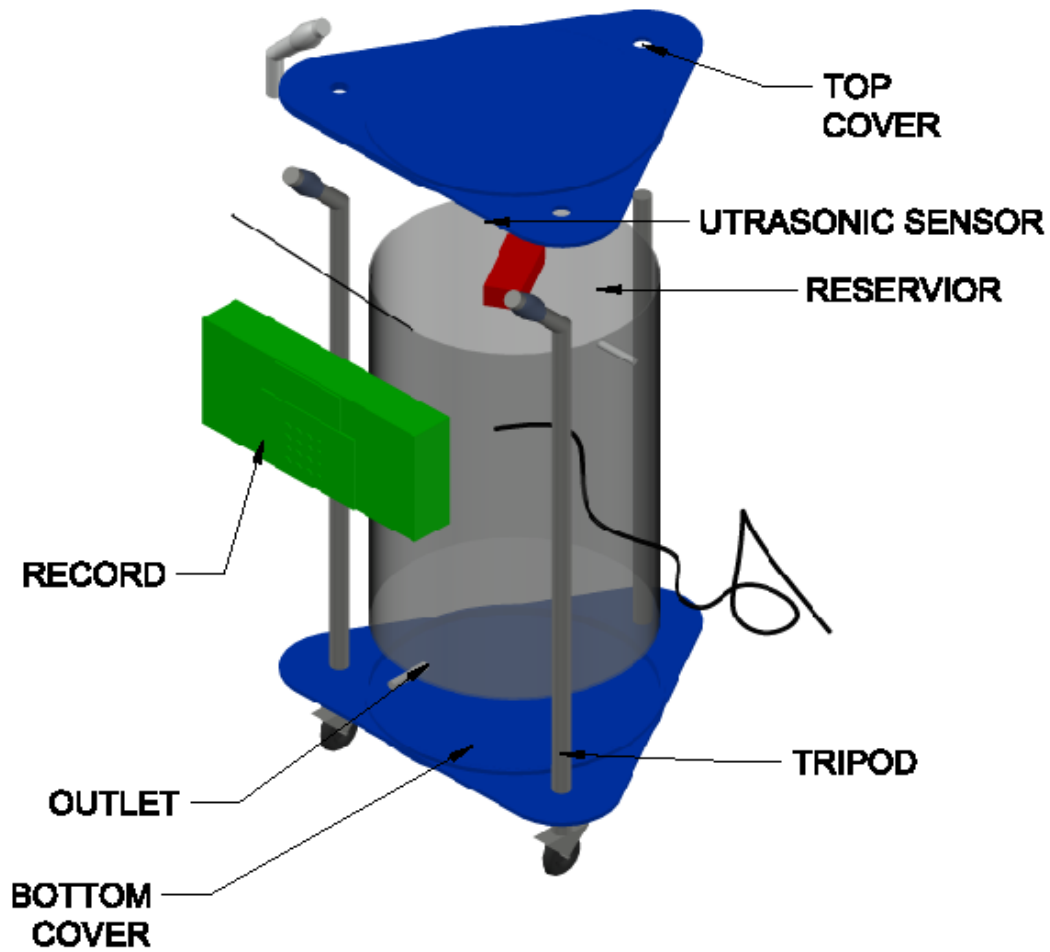


Figure 3: Exploded View of the Automated Infiltrometer

Timestamp, level, and pump status are recorded to an SD card and displayed in real-time. Infiltration rate (q_s) is derived by:

$$q_s = \frac{V}{A \times t} \quad 3$$

Where:

V = volume of infiltrated water (m^3)

A = inner ring cross-sectional area (m^2)

t = time (hr.)

Calculations of design were derived from infiltration measurement equations such as in equations 4 and pump flow estimation indicated in Zhang (1997) and ASTM D3385-09 standards.

$$K_{fs} = \frac{q_s}{1 + \frac{H}{d + \beta a}} \quad 4$$

Where:

K_{fs} = field-saturated hydraulic conductivity (cm/hr. or mm/hr.)

q_s = steady-state infiltration rate (cm/hr. or mm/hr.)

H = ponded water depth (cm)

d = depth of ring insertion (cm)

a = radius of the inner ring (cm)

β = empirical constant (~0.5–1.0 depending on soil type)

Arduino programming sketch/algorithm was programmed using the above process and uploaded to Arduino board to operate the system.

Constant Head Mechanism

The system is pre-designed such that a level of water in double-ring is maintained constant with float valve. In constant head systems, the float-controlled mechanism is generally utilized. In this design, Arduino controls the pump based on ultrasonic values. With the decrease in the water level in infiltrometer ring, the system senses the reservoir variation and starts the pump again.

Frame and Reservoir Design

In relation to the overall infiltration rate (30-50mm/h / loamy soil) (Adeyemo and Oyediran 2016) as shown in table 1 for Oyo and assuming a 6 hrs duration, a reservoir capacity was developed as shown in Figure 3 with equations:

$$\text{Area of inner ring (A)} = \pi \cdot \left(\frac{D}{2}\right)^2 \quad 5$$

This area is used to calculate Volume of infiltration over a period,

$$\Delta V = I \cdot (A \cdot \Delta t) \quad 6$$

$$H = \frac{V}{\pi \cdot r^2} \quad 7$$

Where V is the volume of the cylindrical reservoir,

r = radius of the cylindrical reservoir

H = height of the cylindrical reservoir

An 800mm height of the reservoir is assumed for stability and mobility. The plastic cylindrical reservoir is provided with an inlet from the pump and an outlet to the double ring infiltrometer through tubing. Flow is regulated by a flow control valve and silicone tubing (10 mm).

Structural Analysis

A. Load Analysis

Weight of the water in the reservoir, W was determined by

$$W = \gamma_w \cdot V \quad 8$$

Where γ_w = unit weight of water

A flat platform for the reservoir and electronics bracket was designed using a mild steel frame.

B. Structural Support of Tripod Legs

Assuming equal load sharing across 3 legs:

$$F_{leg} = \frac{W}{3} \quad 9$$

C. Buckling Resistance (Euler's formula for pinned ends) was checked by the equation below

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \quad 10$$

Where:

$$I = \frac{\pi d^4}{64} \text{ (Moment of inertia for circular cross-section)}$$

E = Modulus of elasticity

L = Length of leg

K = 1 (Pinned-pinned configuration)

To avoid buckling: $P_{cr} > F_{leg}$

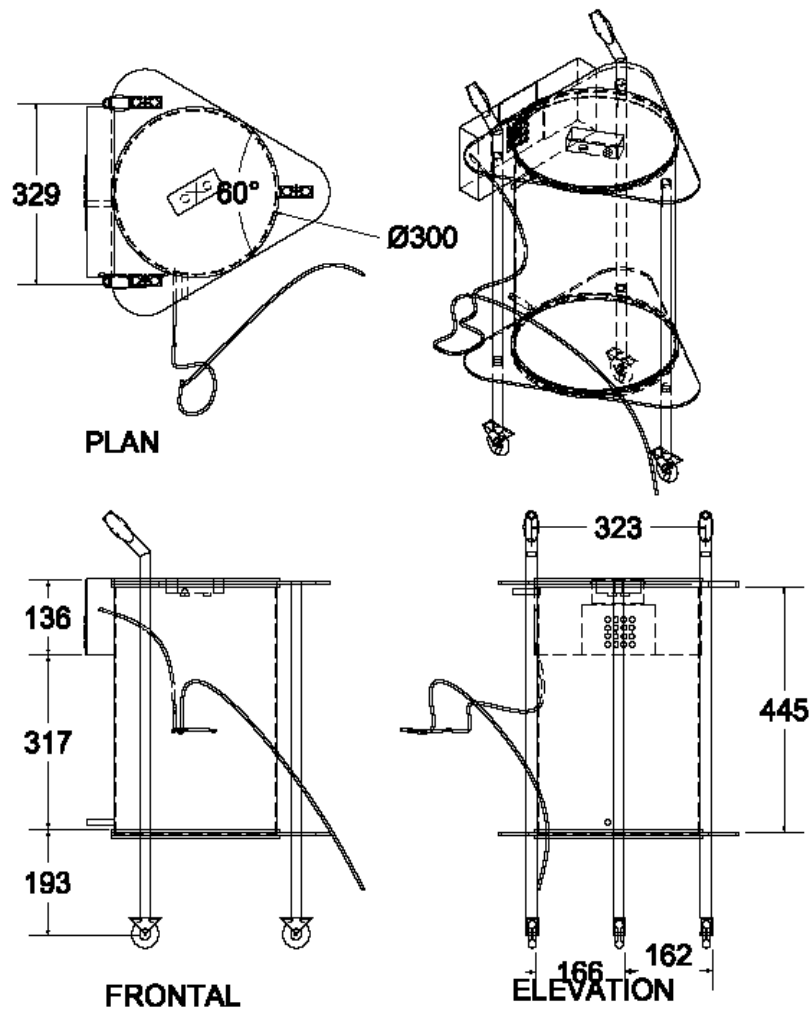


Figure 4: AutoCAD orthographic Projection of the Infiltrimeter.

D. Platform Stress Check

Assuming circular platform under uniformly distributed load:

$$\sigma = \frac{3W}{2\pi r^2} \quad 11$$

Factor of Safety (FoS) = Yield Strength / $\sigma \gg 1$

E. Wheel Load and Selection

Each caster wheel must support (dynamic load factor (1.5):

$$F_{wheel} = \frac{W}{3} \quad 12$$

F. Handle Deflection Check

Treat extended tripod legs (handles) as cantilevered beams:

$$\delta = \frac{FL^3}{3EI} \quad 13$$

Limit δ to < 5 mm for ergonomic performance

Solar Power Design

Using daily consumption estimates:

Arduino + sensors + SD module = ~0.2A

Pump = ~3A intermittently

Daily energy demand ≈ 15 Ah

Battery capacity selected = 230Ah (provides backup for 10+ sessions)

Solar panel = 100W with 6 peak sunlight hours

150W solar panel charges 230Ah battery via charge controller. Arduino, sensors, and pump are powered by the inverter. The system is configured to offer 48-hour independence.

Testing and Calibration: The tank was calibrated by correlating ultrasonic values with actual water volume ($R^2 = 0.998$). Field tests were also conducted in loamy soil to determine infiltration rate and system stability.

Results and Discussion

The automated system possessed a head of constant ± 2 mm. Data were recorded in a consistent way without losses for a number of cycles (Ogunleye and Akinbile, 2018). Figure 4 reveals the automated infiltrometer. Solar energy supplied sufficient energy to operate continuously, and the mobile frame ensured easy relocation. Challenges faced included intermittent airlocks in the pump line, solved with a one-way valve.

Structural Design Analysis of Frame Components

The frame was built as a tripod system for enhanced field stability. The frame structures being tested are circular-section tripod leg posts, a circular pipe handle, the top platform, and wheel supports. Circular mild steel pipes were utilized since they possess improved buckling resistance, torsional stress, and field vibration resistance.

A design load of 350 N, including the weight of the reservoir, instrumentation, and potential force of handling by the operator, was assumed. The tripod legs (2 mm thick, Ø32 mm) were modeled using Euler's buckling theory and provided a safety factor of 3.0. Top platform stress was designed assuming even load distribution using bending and shear analysis. Wheel brackets were designed to provide for localized loads and stress concentration at axle pins and bolt holes. Deflection of the handle, using cantilever beam theory, was calculated to be less than 1.5 mm, which falls within manual handling ergonomic tolerances. These design inspections ensure the mechanical durability and endurance of the field-deployable system, according to the plans of Abdelhadi and Alazba (2016) and the guidelines of ASAE EP542 (2015) for agricultural instrumentation support frames.

Table 2: Structural Design Values for Frame Components

Component	Material	Dimension (mm)	Applied Load (N)	Stress (MPa)	Safety Factor
Tripod Leg	Mild Steel Circular Pipe	Ø25 × 2	350	65	3.0
Platform	Mild Steel Sheet	400 × 400 × 3	200	55	2.5
Wheel Bracket	Mild Steel Angle	30 × 30 × 3	150	45	2.2
Handle	Mild Steel Circular Pipe	Ø25 × 2	100	30	2.8

Solar Energy System Design and Evaluation

The parts of the automated system, including the ultrasonic sensors, pump, Arduino controller, and SD logger, together consumed an estimated amount of power per day, which was 12.6 Wh. To provide for this in a sustainable way, a solar power unit comprising a 150 W monocrystalline panel and 12V/230Ah battery was included.

Table 3 gives the energy computation, which shows a mean solar delivery of 28 Wh/day at 4.5 hours of peak sun. This gives a net surplus of 15.4 Wh/day, covering around 1.5 days of sunlight independence. The results are congruent with those of Akinwumi *et al.* (2021) and Maiti *et al.* (2018), who both demonstrated the adequacy of compact solar-battery systems for rural monitoring and automation of irrigation.

Additionally, use of a PWM charge controller helps in the protection of battery life and management of load cycles for long-term reliability.

Table 3: Solar Power System Design and Output Results

Parameter	Value	Unit	Notes
Solar Panel Power	150	W	Monocrystalline
Battery Capacity	230	Ah	12 V Sealed Lead Acid
Daily Energy Consumption	12.6	Wh	System Load
Daily Solar Energy Yield	28	Wh	Average
Energy Surplus	15.4	Wh	Energy Excess

Reservoir Design and Material Specification

A reservoir is a significant component for the intent of maintaining a consistent head when conducting infiltration testing. The 25-liter tank fabricated with 3 mm thickness high-density polyethylene (HDPE) was selected based on hydrostatic pressure calculation and field handling requirements. Table 4 indicates reservoir sizes, outlet connections, and material characteristics. HDPE was employed because of its light weight, UV stability, and chemical inertness, as proposed by Bautista *et al.* (2015) and field applications by Aliyu *et al.* (2022). 3 mm wall thickness ensures load-free deformation under full loading. The tank was mounted on an elevated portion of the trolley frame for gravity-discharge or pump discharge of water, allowing controlled measurements of infiltration.

Table 4: Reservoir Design Parameters

Parameter	Value	Unit	Notes
Reservoir Capacity	25	L	Water volume
Material	HDPE	-	High-density polyethylene
Wall Thickness	3	mm	Structural integrity
Height	800	mm	Tank height
Base Diameter	200	mm	Footprint size

Automating the double-ring infiltrometer system improves measurement accuracy, data continuity, and labor efficiency. However, several technical and contextual limitations may affect system performance and usability

Ultrasonic sensor accuracy and range may be affected by sensitivity to surface disturbances like ripples or bubbles, leading to false readings, alignment issues and obstructions leading to signal instability and temperature and humidity variations can affect measurement accuracy. Rapid infiltration in sandy soils may exceed the sensor’s sampling rate, missing key data points.

Low-cost pumps may have inconsistent flow rates due to voltage changes or clogging and this affects the maintenance of constant head conditions.

Weather and site conditions like rain, wind, or temperature extremes affect sensor readings and infiltration behavior and surface irregularities and soil heterogeneity lead to inconsistent results.

Power supply instability due to cloudy weather reduces solar power reliability unless backed by efficient batteries. With thoughtful design, training, and cost-effective sourcing, these limitations can be mitigated, enabling broader adoption in developing regions.

Conclusion and Recommendations

This study effectively developed and evaluated an automated double-ring infiltrometer system incorporating low-cost sensors, Arduino-based automation, and solar energy. The system was capable of maintaining constant head conditions, automatically collected infiltration data, and was field-capable and rugged. The developed system was successful in automating the measurement of infiltration with high accuracy and low human interaction. Its cost-effectiveness and independence of operation in the field make it suitable for large-scale application in water management.

Despite successful deployment, the system showed limited performance on heavily cloudy days and under high surface wind conditions affecting sensor stability. Future research should explore GSM-based wireless data transmission, multi-location validation, soil-type adaptability, and improved sensor robustness to expand applicability. Addition of GSM or LoRa modules for remote transmission and integration with soil moisture sensors can improve infiltration dynamics analysis. Additional field tests on various soil types and seasons are recommended for broader applicability. Use of waterproof casing for long-term field deployment.

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