Agricultural Water Management 328 (2026) 110286

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Integrated analysis of key parameters in the design of a gravity-fed subsurface drip irrigation system under low pressure for predominantly sandy soil

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ARTICLE INFO

Keywords:
Mungbean
Gravity-fed
Subsurface drip irrigation
Performance metrics
Smallholder irrigation

ABSTRACT

Gravity-fed subsurface drip irrigation (GSDI) supplies water directly to the root zone without the need for pumping, which makes it particularly suitable for areas with limited energy access. In areas where food scarcity and insecurity remain major problems, GSDI offers a promising opportunity to boost agricultural production. This study assessed the design and performance of the GSDI system for growing mungbean in predominantly sandy soils through field trials, laboratory tests and analytical modelling. The maximum irrigation depth for the mungbean was 5.94 mm, corresponding to 90 litres per 15.12 m^2 of wetted area per 2.5-day irrigation cycle. When scaled to 0.25 ha, the system requires an average daily irrigation volume of approximately 3.62 m^3 , applied over about 63 % of the cultivated area. This corresponds to an irrigation interval of 2.58 days and an average irrigation duration of approximately 1.5 h day^{-1} under gravity-fed operating conditions. Performance indicators confirmed satisfactory results: the uniformity coefficient (CU) ranged from 0.9 to 0.94, the emission uniformity (EU) from 0.88 to 0.91 and the distribution uniformity (DU) from 0.88 to 0.91, reflecting a uniform distribution of water with minimal friction losses and an adequate pressure head. The rate of soil infiltration (365 mm per hour) was consistently higher than the application rate (1.6 mm per hour), indicating a negligible risk of surface runoff or deep percolation. Overall, GSDI has a strong potential as a cost-effective, efficient and appropriate solution for smallholder farmers in water-limited environments.

1. Introduction

Subsurface drip irrigation has emerged as a highly efficient irrigation method, able to deliver water directly to the root zone through a network of buried conduits and emitters (Guo et al., 2023; Kandelous and Šimůnek 2010a; Wan et al., 2024). It minimises water losses from surface runoff and evaporation, improves nutrient provision (Zhao et al., 2024a) and promotes precision farming, especially in water-scarce environments (Zai et al., 2025). Subsurface Drip Irrigation may be driven by pumps or by gravity (Gunarathna et al., 2017). If the gradient is used to generate the necessary pressure, this system is called gravity-subsurface drip irrigation. This latter is particularly attractive for small farmers in rural areas where electricity is not available, and is therefore a cost-effective and energy-independent solution (Wang et al., 2021).

In smallholder agricultural systems with limited access to energy, irrigation technologies are typically low-tech, prioritising affordability, simplicity, and adaptability over high levels of mechanisation (Darouich et al., 2014; Orge and Sawey, 2019). In sub-Saharan Africa, irrigation systems must function under conditions of unpredictable water availability, limited capital investment, and unreliable energy supply. Consequently, a range of low-pressure and traditional irrigation methods continues to be widely employed.

Traditional surface irrigation methods, including basin and furrow irrigation, require minimal capital investment and simple infrastructure. However, they are characterised by low application efficiency due to substantial evaporation, runoff, and deep percolation losses, and they often demand frequent labour inputs for land preparation and water conveyance (Tadele et al., 2019; Teshome et al., 2018). Similarly, hand irrigation using buckets or watering cans is commonly practiced on very

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https://doi.org/10.1016/j.agwat.2026.110286
Received 11 October 2025; Received in revised form 10 February 2026; Accepted 8 March 2026

small plots or kitchen gardens (Woltering et al., 2011). Although this method requires almost no infrastructure, it is highly labour-intensive, offers poor control over soil moisture dynamics, and results in highly variable water distribution. As plot size or dry-season production increases, the physical demands of hand watering become a major constraint, limiting its scalability and long-term viability (Von Westarp et al., 2004).

Pitcher (clay pot) irrigation is a traditional subsurface technique in which porous, unglazed clay pots are buried in the soil and slowly release water into the root zone (Adhikary and Pal 2020a). This method is considered suitable for small-scale farmers due to its low cost, self-regulating nature, and high water-use efficiency. Studies have shown that pitcher irrigation can improve soil structure, enhance soil organic carbon, and contribute to improved soil fertility and crop water productivity (Adhikary and Pal, 2020; Mahler, 2024; Sarangi et al., 2024). Despite these benefits, system expansion requires substantial labour for installation and maintenance, and the method is poorly suited to permanent field cultivation or larger production areas. Its applicability is therefore largely confined to small gardens or widely spaced crops (Mahler, 2024). Another low-pressure, subsurface-oriented method is the use of wicking beds, in which plants draw water upwards from an underlying reservoir through capillary action (Greeshma et al., 2023; Semananda et al., 2016a**).** Wicking beds can maintain relatively stable soil moisture conditions and achieve high water-use efficiency, particularly in vegetable production systems (Ferrarezi and Testezlaf, 2016; Semananda et al., 2016b). However, their construction requires impermeable liners, careful layering of soil and aggregates, and precise installation. These requirements increase initial investment costs and often limit adoption in rural areas with constrained financial and technical resources.

Micro-irrigation technologies, such as drip and sprinkler systems, are widely recognised for their high water-use efficiency. Nevertheless, adoption by smallholder farmers remains limited due to high initial investment costs, technical complexity, maintenance requirements, and sociocultural barriers (Oweis and Hachum, 2004; Adhikary and Pal, 2020). Sprinkler systems, in particular, require higher operating pressures and energy inputs, making them unsuitable for areas with limited or unreliable power supply.

Low-pressure surface drip irrigation systems have been developed to bridge the gap between conventional surface irrigation and full-pressure micro-irrigation (Rowell and Soe, 2015). These systems can operate using gravity or hand-pump-driven water sources and significantly improve water productivity and distribution uniformity compared to traditional methods, while reducing weed growth and surface evaporation. However, because emitters are placed at or near the soil surface, water losses through evaporation persist, and system performance remains sensitive to pressure variations and emitter clogging, particularly under conditions of inadequate filtration (J. Li et al., 2009).

Gravity-fed subsurface drip irrigation (GSDI) builds upon the principles of low-pressure drip irrigation by placing emitters below the soil surface and eliminating the need for external energy inputs (Traore et al., 2024). Water is supplied from an elevated storage tank, generating sufficient hydrostatic pressure to deliver water directly to the active root zone. This configuration reduces evaporation and surface runoff, enhances application efficiency, and allows relatively uniform water distribution under very low operating pressures. When properly designed and managed, Gravity-fed subsurface drip irrigation systems can achieve application efficiencies of approximately 70–90%, outperforming most conventional and low-tech irrigation alternatives in terms of energy and water savings (Smajstrla et al., 2000; Worstell 1976).

Despite these advantages, gravity-fed subsurface drip irrigation systems require more careful technical design than pitcher or surface irrigation methods. Key considerations include hydraulic head losses along laterals, emitter discharge characteristics under low pressure, soil infiltration behaviour, and the risk of emitter clogging (de Camargo et al., 2014; Salvador Esteban and Aragüés Lafarga, 2013). These design and maintenance requirements represent a potential barrier where technical support is limited. However, once installed, gravity-fed subsurface drip irrigation systems offer favourable scalability: additional laterals and sub-units can be incrementally added as water availability or farm size increases, without proportional increases in energy demand or labour inputs (Chigerwe et al., 2004).

Although gravity-fed subsurface drip irrigation systems are designed to operate with minimal energy input, their long-term performance depends on regular monitoring, cleaning, and maintenance of reservoirs, pipelines, and emitters. In practice, these requirements often translate into high labour demands and inconsistent system performance when maintenance is irregular. To address these constraints, recent research highlights the potential integration of Internet of Things (IoT) (Arjun and R 2024a; Seyar and Ahamed 2023a), artificial intelligence (AI) (Parthasarathy and Manikandasaran, 2024), and machine learning (ML) technologies as decision-support layers that reduce human intervention while improving water productivity and system reliability.

Recent studies on subsurface drip irrigation systems integrated with IoT technologies demonstrate that low-cost sensors can be used to continuously monitor key hydraulic and soil parameters, including soil moisture content, pressure gradients along laterals, emitter discharge variability, and reservoir water levels (Arjun and R 2024b; Boukri et al., 2026; Comegna et al., 2024a; b; Seyar and Ahamed 2023b; Sudha and Loret, 2026). These real-time measurements enable early detection of pressure losses, partial clogging, or abnormal flow conditions that are otherwise difficult to identify in gravity-fed systems operating at very low heads. By providing continuous feedback, IoT-based monitoring improves operational control without requiring constant field inspections.

Artificial intelligence and machine-learning-based decision tools further enhance the value of sensor data by enabling predictive and adaptive irrigation management (Lakshmi et al., 2023; SRIRAM et al., 2024). ML algorithms can analyse historical and real-time datasets to predict soil moisture dynamics, crop water demand, emitter clogging probability, and pressure instability under varying operating conditions (Ali et al., 2025a; b; Challa et al., 2024a; b; Reddy et al., 2024; Roy B.P et al., 2024). In low-pressure gravity-fed subsurface drip irrigation systems, such as predictive capabilities are particularly valuable for optimising irrigation scheduling, stabilising discharge uniformity, and preventing system failures before they occur. AI-based control strategies can enhance irrigation system management by supporting automated valve operation and irrigation scheduling, thereby ensuring that water is applied only when and where it is required based on soil, crop, and hydraulic conditions. Beyond irrigation scheduling, smart monitoring systems have been increasingly explored for maintenance-oriented applications (El-Sheshny et al., 2024; Jaiswal et al., 2025; Kunt, 2025; Tace et al., 2023). Sensor-based pressure and flow diagnostics, combined with AI-driven anomaly detection, can signal the need for reservoir cleaning, filter flushing, or localised emitter maintenance. This approach shifts system management from reactive, labour-intensive maintenance to condition-based maintenance, thereby reducing labour requirements and prolonging system lifespan of irrigation systems (Boukri et al., 2026).

The performance and efficient implementation of Gravity-fed Subsurface Drip Irrigation systems requires a thorough understanding of the dynamics of the soil, water and critical parameters of the hydraulic design. These parameters include the rate of infiltration, the maximum irrigation depth, the pipe diameter, the length of the pipe, the pressure head of the emitters, the flow rate of the emitters, the consistency of the system and the interaction between these factors (Abbas et al., 2016; Kargas et al., 2023; Zai et al., 2025). When the discharge of the emitter exceeds the infiltration capacity of the soil, pressure builds up at the outlet, reducing the flow rate. Variability of soil characteristics affects the flow rate and the uniformity of irrigation; higher design discharges or lower hydraulic conductivity of the soil, increased pressure and reduced flow rate (Nogueira et al.,2021b; Wang et al., 2024a). These observations highlight the important influence of hydraulic properties of the soil on the performance of subsurface drip irrigation systems, especially under gravity-fed low pressure conditions. In such systems, which typically operate with a hydraulic head of about 2 m, the accumulation of positive water pressure around the emitters may significantly reduce the discharge and compromise the uniformity as demonstrated in coupled modelling studies (Lazarovitch et al., 2006). Laboratory and field observations confirm that soil-induced excess pressure at the outlet of the emitter changes the discharge rate of buried emitters (Gil et al., 2008a; Hammami et al., 2013a; Jia et al., 2025). Taken together, these findings highlight the need for an integrated design approach for GSDI, which includes soil hydraulic characteristics, emission behaviour and system hydraulics, especially when pumps are not used for pressure regulation.

Gravity-fed subsurface drip irrigation systems are very sensitive to hydraulic losses as they operate at very low input pressures usually in the range of 1.5–2 m head of water (Raphael et al., 2018a; Patle 2024a). In such conditions, even small head losses from pipe friction, fittings (local losses) or elevation differences consume a significant proportion of available pressure, resulting in a large variation in emission and a reduced emission uniformity (poor emissions) (Provenzano and Pumo, 2004). This is in contrast to pressure systems, where higher operating pressures may compensate for such losses and thus maintain a more stable flow condition throughout the network.

The accuracy of the assessment of total head losses, taking into account both friction and local losses, is a key issue in designing the GSDI system (El-Mansy et al., 2024a; Martí et al., 2023; Nogueira et al., 2021; Patle, 2024b; Wang et al., 2024a, 2020). Strategies to mitigate these losses include optimising the length of the pipe, selecting the appropriate pipe diameters and using the right spacing and types of emitters (Keller and Karmeli,1975; El-Mansy et al., 2024a). Ensuring a consistent emitter flow rate throughout the field is essential to achieve uniform water usage and overall system efficiency.

At global level, many researchers (e.g. Abbas et al., 2016; Annan and Gooda, 2018; Gil et al.,; 2008b; Guo et al., 2023; Patle 2024a; Zhao et al., 2024b) focused on design, optimisation and performance assessment of localised drip irrigation systems, in particular drip and sub-drip irrigation. Various indicators were used to assess the hydraulic behaviour and uniformity of water application in drip and subsurface drip irrigation systems. These indicators are the Christiansen coefficient of uniformity (CU), distributional uniformity (DU), emissions uniformity (EU), application efficiency (AE) and coefficient of variation (CV) (Sadatiya et al., 2019; Elnemr and Amer, 2020). The most frequently used indicator is CU. Originally developed for spray-pricing, it was adapted for localised irrigation for the statistical evaluation of the dispersion of water (Christiansen, 1942). DU focuses on the adequacy of irrigation by comparing the lowest quarter of irrigated land with the average over the whole area (Sadatiya et al.,2019). The EU measures the variability of emissions from emitters, with higher values indicating more consistent water flows (Keller and Karmeli, 1975). AE assesses the share of applied water that is effectively stored in the crop root zone and CV quantifies the variability of emissions and provides information on the accuracy of production and hydraulic performance (Sinha,2015). The findings of the reported studies generally show that a high degree of consistency can be achieved if the systems are correctly designed, installed and maintained. In addition, the studies provide practical recommendations on emitter spacing, operating pressure, irrigation depth, infiltration characteristics and system design, all of which are adapted to the specific soil structure, crop types and climatic conditions.

However, irrigation in Sub-Saharan Africa (SSA) remains significantly under-used worldwide (Haile et al., 2022), despite its key role in increasing food production and reducing hunger in the region. This under-use of irrigation is further exacerbated by the limited research effort on context-specific irrigation technologies (Pavelic et al., 2013; Bjornlund et al., 2020) in predominantly tropical sandy soils. In particular, there are no comprehensive studies addressing the multiple factors that influence the design and performance of gravity-fed drip irrigation systems in the context of SSA (e.g., Darimani et al., 2021; Ouédraogo et al., 2021).

The general situation of underdeveloped irrigation infrastructure in Sub-Saharan Africa is also extended to the Democratic Republic of Congo (DRC), where agriculture is mainly rain-fed and therefore highly sensitive to rainfall variations. There is a chronic water shortage which makes motorised irrigation systems impractical for the majority of smallholder farmers. These constraints contribute to persistent low agricultural productivity, widespread food insecurity and increased climatic vulnerability. Although gravity-fed subsurface drip irrigation systems offer a promising solution in providing efficient water supply without relying on external sources of supply, empirical research and design methods in agro-hydrological conditions where sandy soils predominate, including on the basis of soil infiltration characteristics, pressure variations and emission performance under low pressure conditions, are lacking.

The objective of the study is to analyse the design and hydraulic performance of gravity-fed subsurface drip irrigation systems adapted to sandy soils predominantly of tropical origin. It presents a case study conducted in the Tshilenge territory of DRC. Specifically, the study seeks to: (i) determine the design parameters of the gravity-fed subsurface drip irrigation system in relation to the soil class; (ii) analyse the behaviour of the hydraulics head and the variability of the flow rate in the gravity-fed subsurface drip irrigation system; (iii) evaluate discharge variability and emission uniformity of lateral valves in the GSDI system; (iv) assess the hydraulic compatibility between emitter flow rate and soil infiltration characteristics, ensuring stable wetting patterns under GSDI conditions.

By addressing these objectives, the study aims to generate practical and contextually relevant knowledge to support the uptake and optimisation of sustainable gravity-fed irrigation as a water and energy efficient option in the DRC and other regions facing similar water and energy constraints.

2. Materials and methods

2.1. Experimental site

The research was conducted in an experimental facility belonging to the Community Solutions Research Centre (COSR) of the Partnership for Congolese Development (PCD) in the Tshilenge area of the Democratic Republic of the Congo (DRC). The study site is situated at 6.22 ° S and 23.73 ° E. The soils of the test site are predominantly sandy with a marked transition to sandy loam with a relatively low water retention and a rapid drainage.

2.2. Physical characteristics

For the proper assessment of physical characteristics, 24 sub-samples were taken from 12 plots, considering two depth ranges of 0–15 cm and 15–30 cm (USDA-NRCS, 2014). In addition, six core samples of undisturbed soil were taken for the determination of hydraulic conductivity. However, during the infiltration tests, 30 samples of ploughed soil were taken with manual hand augers to determine moisture content before and after the infiltration test.

Laboratory analyses included determination of the soil structure, gravimetric moisture content, bulk density and saturated hydraulic conductivity (K_s) according to USDA-NRCS (2014). standard laboratory procedures. Soil structure classification has been performed in accordance with the USDA soil taxonomy, which classifies soils according to the relative proportions of sand, silt and clay (Wang et al., 2024b). The moisture content of the soil was measured gravimetrically after drying at 105 ° Celsius until a constant weight as described by Yeshaneh (2015). Bulk density has been determined by the core method. The saturated hydraulic conductivity was measured in accordance with the Klute and Dirksen (1986) method of constant head permeameter for coarse-textured soil samples.

The laboratory soil parameters were processed as inputs for the Soil, Plants, Atmosphere and Water (SPAW) model (Saxton and Rawls, 2006) and used to estimate soil moisture at field capacity, permanent wilting point, saturated hydraulic conductivity and water content at saturation (Saha and McMaine, 2023). Analysis was carried out on individual soil samples collected and averages calculated to represent the average physical characteristics of the soil over the entire study site. Table 1 summarises the main physical characteristics of the soil derived from this analysis.

2.3. *Estimation of Infiltration rate*

The double ring infiltrometer method described by Subramanya (2021) was used to estimate the soil infiltration rate. The initial moisture content of the soil was measured with the TEROS10 sensor over a 20-minute pre-test period. This procedure was repeated after the test with the same sensor.

Microsoft Excel and Python scripts have helped to trend visualization and basic descriptive statistics.

Based on soil infiltration characterisation, the next step is to determine the appropriate irrigation depth and interval to ensure that the water applied meets the needs of the crop without exceeding the infiltration capacity of the soil.

2.4. *Irrigation depth and interval*

The maximum net irrigation depth (Idx) of each irrigation application was calculated by the following equation:

$$\mathrm{Idx} = P \times (\mathrm{FC\text{-}WP}) \times \mathrm{Z}/100 \tag{1}$$

Idx is the maximum net depth of each application of irrigation over the entire area, in mm; P is the portion of available moisture depletion allowed or desired, also known as the Management Allowable Depletion (MAD). Its value depends on the type of crop and its water-sensitivity. For this study, the value of 0.6 was used for mungbean (Keller and Karmeli, 1975). FC is the soil moisture at field capacity, mm/m; WP is the soil moisture at wilting point, mm/m; Z is the depth of the soil to be taken into account, m.

The appropriate irrigation interval, i.e. the time between two consecutive irrigations, is determined by Keller and Bliesner (1990a) as follows:

$$f' = \frac{Idn}{U_d} \tag{2}$$

f' = irrigation interval or frequency, days; Idn = net depth of water application per irrigation, to meet consumptive use requirements, mm; $\mathrm{U_d}$ = conventionally computed average daily crop water requirement, or use rate, during the peak-use month (mm/day).

The daily crop water requirement during the experimental period was calculated on the basis of meteorological data collected from the ATMOS 41 W agroclimatic station. The reference evapotranspiration value was estimated using the modified FAO Penman-Monteith Equation recommended by Allen et al. (1998):

$$\mathrm{ETo} = 0.408\ \Delta\ (\mathrm{Rn\text{-}G}) + \gamma\ (900/\mathrm{T} + 273)\mathrm{U_2}(\mathrm{e_a\text{-}e_d}) /\ (\Delta + \gamma(1 + 0.34\mathrm{U_2}) \tag{3}$$

Where: *ETo*= Reference evapotranspiration (mm $\mathrm{day^{-1}}$); *Rn* = Net radiation at the crop surface (MJ $\mathrm{m^2\ day^{-1}}$); *G* = soil heat flux density ($\mathrm{MJm^{-2}\ day^{-1}}$); *T* = mean daily air temperature at 2 m height (°C); U_2 = wind speed at 2 m height ($\mathrm{m\ s^{-1}}$); es=saturation vapour pressure (kPa); *ea* = actual vapour pressure (kPa); *es-ea* = saturation vapour pressure deficit (kPa); Δ = slope vapour pressure curve ($\mathrm{kPa°C^{-1}}$); and γ is psychrometric constant ($\mathrm{kPa\ °C^{-1}}$).

The Crop Water Requirement (CWR) for mungbean was calculated as given in Eq. 4 (Allen et al., 1998):

$$\mathrm{CWR} = \mathrm{ET_c} = \mathrm{ET_o} \times \mathrm{K_c} \tag{4}$$

Where: *CWR* or ET_c = crop evapotranspiration (mm/day); ET_0 = reference evapotranspiration (mm/day); and *Kc* = crop coefficient, which varies with the growth stage of mungbean.

The crop coefficient (Kc) values for the various phenological stages of mungbean have been established on the basis of FAO-56 (Allen et al., 1998 et al., 1998). Kc values for the start, middle and end of the period were 0.40, 1.05 and 0.60–0.35, respectively. Estimating the volume of water to be irrigated requires an estimation of the wetted area as described in Section 2.5.

2.5. *Wetted area calculation*

The semi-empirical Kandelous et al. (2008) equation was used to estimate the wetted area as given by the Eqs. 5,6, 7, and 8.

$$W = 4.244 V_w^{0.526} (Ks/QZ)^{(0.026)} \tag{5}$$

$$\mathrm{Z}+\ = 0.72 V_w^{0.344} (Ks/QZ)^{(-0.156)} \tag{6}$$

$$\mathrm{Z}-\ = 0.66 V_w^{0.333} (Ks/QZ)^{(-0.167)} \tag{7}$$

$$V_w = Q \times t \tag{8}$$

Where: *W*: is the horizontal (m); *Z* is vertical upward (m); and *Z-* is downward distances (m) of the wetting front from the subsurface emitter; V_w is the volume of applied infiltrating water ($\mathrm{m^3}$); *Q* is the emitter discharge ($\mathrm{m^3/s}$ or L/h); *K* is the saturated hydraulic conductivity ($\mathrm{ms^{-1}}$) determined from the laboratory; *Z* is the emitter installation depth (m); and t is the irrigation time expressed either in second, minutes, or hours.

This approach used for wetted area calculation is particularly suitable for subsurface drip irrigation (Kandelous and Šimůnek 2010b) in resource-limited environments such as the Tshilenge area, where detailed soil characterisation and computational resources may be limited for applying physical modelling. The installation depth (Z) of the emitters was chosen at 10 cm for this study because a shallower installation of the emitters improves water efficiency, especially in crops with shallow root systems such as mungbean (Sheini-Dashtgol et al.,2022; Wang et al., 2024).

2.6. *Setup of gravity-fed drip irrigation and reservoir management*

The experimental system was designed to clearly define the physical arrangement of all components, ensure hydraulic and statistical independence among experimental units, and allow rigorous evaluation of gravity-fed subsurface drip irrigation (GSDI) performance. The system consisted of a 1000-L elevated storage tank mounted 2.0 m above the reference datum for the collection and supply of rainfall water.

Water was conveyed from the main tank through a buried 26-mm diameter main pipeline (manifold) to a sequence of intermediate reservoirs installed downslope. The first intermediate tank was located at a horizontal distance of 5.56 m from the main tank, corresponding to a vertical elevation drop of 0.5 m, which generated the initial

Table 1
Physical soil properties of the tropical zone of the Tshilenge, DRC.

Soil class	Sand	
Parameters	Values	Units
Hydraulic Conductivity Ks	0.0002	(mm/hr)
Wilting point (Vol)	2.9	%
Field capacity (Vol)	7.85	%
Saturation (Vol)	51.73	%

gravitational pressure head required for flow. In gravity-fed irrigation systems, even small variations in elevation strongly influence the available pressure head and emitter performance (Ella et al., 2008; Raphael et al., 2018b; Sarker et al., 2019a; Zhang et al., 2011).

Along the main pipeline, four intermediate tanks, each with a capacity of 20 L, were installed at intervals of 1.6 m. At each tank location, a T-junction fitted with a hand-operated valve allowed controlled diversion of water from the main pipeline into the intermediate tank. These reservoirs were not interconnected, and each was hydraulically isolated except for its controlled connection to the main pipeline.

To avoid large, simultaneous withdrawals from the main pipeline and the resulting transient pressure drops, the intermediate tanks were filled sequentially rather than concurrently. In practice, the valve feeding the first tank was opened until the tank reached its full capacity and was then closed before opening the valve supplying the second tank; the same procedure was applied successively to the third and fourth tanks. Sequential valve operation is recommended for low-pressure drip and gravity-fed subsurface drip irrigation systems because it stabilises the hydraulic head and minimises pressure fluctuations throughout the network (Marlim and Kang, 2024; Skulovich et al., 2016; Zeidan and Ostfeld, 2022).

This operational strategy maintained stable inlet conditions at the 1000-L tank and ensured consistent and repeatable filling cycles for all intermediate reservoirs. As each tank was filled and operated independently, hydraulic interference among downstream units was avoided, thereby addressing concerns regarding uncontrolled reservoir operation.

Each 20-L intermediate tank was equipped with three outlet ports, each fitted with an independent control valve regulating flow into 16-mm diameter lateral pipes. Each control regulating valve was connected to the irrigation plot of a 2.0 m segment of length and 1 m of width, which was replicated two times, and the distance separating each plot was 1 m. Connecting pipes of 1 m were used to link consecutive 2.0 m lateral segments across three cascade plots, ensuring continuous hydraulic flow along each plot. For each irrigation plot, a 2.0 m segment of the lateral pipe was buried at a depth of 0.10 m to enable subsurface water application. The laterals were 8.35 m in length and equipped with emitters spaced at 0.30 m intervals.

Each intermediate tank–lateral–plot combination constituted an independent experimental unit. Because each unit was supplied through its own control valve and operated under identical initial head conditions but without direct hydraulic interaction during measurement, the resulting observations of discharge, pressure head, and emission uniformity can be considered statistically independent.

During irrigation events, all control valves supplying the lateral pipes connected to a given intermediate tank were opened simultaneously to ensure uniform water delivery across the three associated plots. Measurements were conducted only after steady-state flow conditions were achieved, as indicated by stable emitter discharge over time.

This configuration allowed accurate and efficient delivery of irrigation water from the elevated storage tank through the intermediate reservoirs and buried lateral pipes, ensuring consistent subsurface application directly within the crop root zone. The use of sequential reservoir management improved system stability under low-pressure operation, which is essential in gravity-fed subsurface drip irrigation systems where emitter discharge is highly sensitive to small variations in pressure head (Fan and Li, 2018; Sarker et al., 2019b; Lazarovitch et al., 2006).

Fig. 1 illustrates the complete experimental layout, including the arrangement of tanks, pipelines, valves, laterals, elevation differences, and independent experiments units.

2.6.1. *Pressure head and different losses in gravity-fed subsurface drip irrigation*

The assessment of the total head of gravity-fed subsurface-drip irrigation systems took into account all components contributing to head gain and head loss along the distribution network. The flow rate of the non-pressurised pipeline has been determined by the equation adapted to the pressure flow of the irrigation pipeline (Eq. 9). It takes account of frictional losses along the buried main and secondary pipes and local

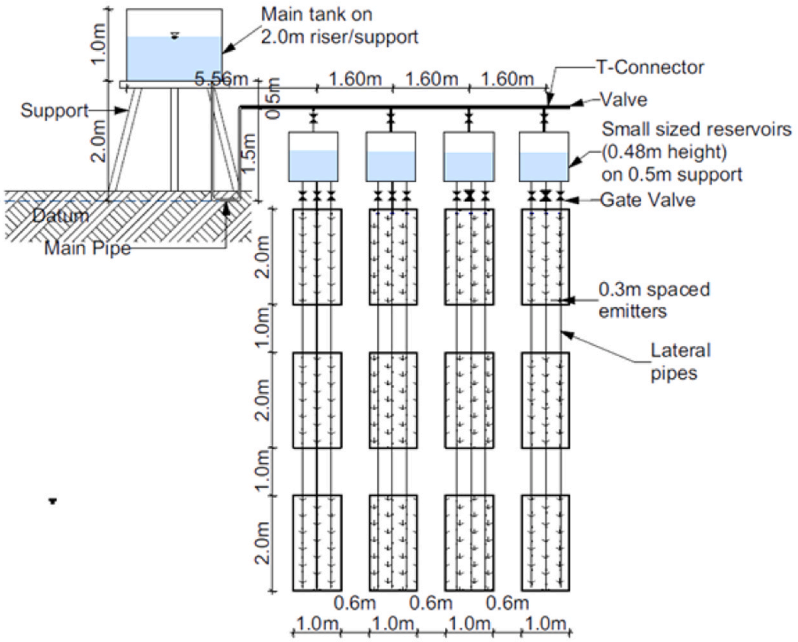

Fig. 1. Setup of gravity-fed subsurface drip irrigation.

(smaller) losses associated with pipe fittings, junctions, valves, inlet connectors, and emitters.

$$Ex = h+z + V^2/2g \tag{9}$$

Where *: Ex:* total energy head at point x (in meters); *h:* Pressure head (height of a fluid column due to pressure) (m); z: Elevation head (height relative to a datum) (m); $V^2/2g$: Velocity head (kinetic energy component per unit weight) (m/s); and *g* is gravitational acceleration (9.81 m/s^2).

The total hydraulic head at a point slightly downstream in a lateral pipe can be estimated using the Eq. 10.

$$E(x + dx) = (h + \partial h/\partial x \cdot dx) + (z + \partial z/\partial x \cdot dx) + [(v + \partial v/\partial x \cdot dx)^2] / (2g) \tag{10}$$

where: *h:* Pressure head at location x (m); *z:* Elevation head at location x (m); *v:* Velocity at location x (m/s); *g:* Acceleration due to gravity (9.81 m/s^2); *dx:* is the length of the element (m); *∂h/∂x:* gradient of pressure head (m/m); *∂z/∂x:* Slope of the terrain (m/m); *∂v/∂x:* velocity gradient due to emitter discharge (m/m).

In the irrigation sub-unit (lateral pipes located on plots), the kinetic head $V^2/2g$ is usually much smaller than the pressure head h and elevation head z. Therefore, the kinetic head is neglected (Wang et al., 2021). The application of the energy conservation principle to a straight pipe element is:

$$H = (H + \partial H/\partial X \cdot dx) + h_f + h_l \tag{11}$$

where H is the hydraulic head (m), $H = h + z$; *hf* is the continuous friction head loss between two consecutive emitters in the laterals (m); h_l is the local head loss induced by the presence of emitters (m). Eq. (12) is converted as follows by subtracting the item H from both sides:

$$\partial H/\partial x dx + h_f + h_l = 0 \tag{12}$$

For the calculation of friction losses, Darcy-Weisbach equation was used as it is more accurate and suitable for modelling friction losses (Abdulameer et al., 2022):

$$h_f = f \times L/D \times V^2/2g \tag{13}$$

where *f* is the Darcy–Weisbach friction coefficient; *L* is the length of pipe (m); *D* is the internal diameter of pipe (m). The friction coefficient depends on the Reynolds number and pipe roughness.

Different approaches may be used for estimating the friction coefficients. However, in the context of drip irrigation, researchers (Von Bernuth and Wilson, 1989) have shown that the Blasius equation works well for small diameter plastic pipes for calculating friction losses (Valiantzas, 2005). The equation of the friction coefficient of the Blasius may therefore be defined as:

$$f = a \times R^b \tag{14}$$

$$Re = \rho \times V \times d/\mu \tag{15}$$

Where: R is Reynolds number; a and b are coefficients that have been empirically established. b is equal to −0.25 (Von Bernuth and Wilson, 1989); *ρ*: flow density (kg/m^3); *V*: average flow rate (m/s); *d*: pipe diameter (m); *μ*: dynamic viscosity (kg/m.s); and Kinematic viscosity is approximately $1.01\ 10^{-6}\ m^2/s$ (Von Bernuth and Wilson, 1989).

Since the calculation of small (local) losses may be time-consuming, a number of empirical guidelines are commonly used to estimate their value (Annan and Gooda, 2018). One widely accepted approach is that small losses account for about 10 % of the total friction losses (Kahramaa, 2014). This simplification has been taken up in this study in order to simplify the calculation of energy losses.

2.6.2. *Flow rate estimate at emitter*

Data were collected from 12 lateral pipes installed on the experimental plots, each fitted with 15 evenly spaced emitters (a total of 180 emitters in all). Laterals were laid out on plots of 24 m square with the same spacing and emission pattern for all plots in order to ensure consistency. The discharge measurements were obtained by volumetric methods in accordance with Faloye et al. (2025). Emissions along each axis were sampled and five emitters along each axis were selected to provide a representative estimate of the discharge. An operating pressure of 1.4 m was maintained on all lines to minimise variability. Each emitter in the sample was measured three times and the mean value taken as the analytical average. For each of the lateral pipes, individual emission measurements were averaged to characterise the hydraulic behaviour of the pipes and the results of three replicates feeding each tank were then evaluated. Processing data were analysed using Python scripts for descriptive statistics and conformity assessment. The statistical analysis was performed at three levels: (i) in each of the lateral pipes connected to its respective storage tank, (ii) in each of the three replicating pipes supplying each storage tank, and (iii) in the whole system. This multi-level approach enabled hydraulic performance to be assessed at both the local and the system level.

2.7. *Assessment of hydraulic performance of gravity-fed subsurface drip irrigation*

Various parameters have been identified and used to assess the uniformity of gravity-fed subsurface drip irrigation (Pereira, 1999). These parameters include the average emission discharge rate (q_a), the standard deviation of the emission flow rate (Sq), the emission flow variation coefficient (Cv), the uniformity coefficient (UC), and the distribution uniformity (DU) (Yacoubi, 2012).

The average flow rate is calculated as below:

$$q_a = 1 \Big/ n \sum_{i=1}^{n} q_i \tag{16}$$

Where: q_a= Average emitter discharge rate (litres per hour, l/h); qi = Discharge rate of the ith emitter (l/h); n = Total number of emitters tested.

The Standard Deviation of the Emitter Flow Rate (Sq) is defined as:

$$Sq = \sqrt{\sum_{i=1}^{n} (qi - qa)^2 \Big/ n - 1} \tag{17}$$

Where: Sq = Standard deviation of emitter discharge (l/h); qi= Discharge rate of the ith emitter (l/h); qa= Average emitter discharge rate (l/h); and n = Number of emitters tested.

The flow variation is defined as:

$$qvar = q_{max} - q_{min}/qmax \tag{18}$$

Where: q_{var} = Emitter flow variation (dimensionless); q_{max} = Maximum emitter discharge rate (l/h*);* q_{min} = Minimum emitter discharge rate (l/h).

Coefficient of variation of emitter flow is described as below:

$$CV = Sq/q_a \tag{19}$$

Where: *Cv* = coefficient of variation of emitter discharge (manufacturing variation) (dimensionless); *Sq*= Standard deviation of emitter discharge (l/h); and q_a= Average emitter discharge rate (l/h).

The Christiansen's Uniformity Coefficient (CUC) is a widely used indicator of water application uniformity in irrigation systems, and is defined as:

$$CUC = 100\left[1 - 1 \Big/ nq_a \sum_{i=1}^{n} |q_a - q_i|\right] \tag{20}$$

Where: *CUC* = Christiansen's uniformity coefficient (%); *qi* = Discharge rate of the ith emitter (l/h); *qa*= Average emitter discharge rate (l/h);

and n = Total number of emitters tested.

Emission uniformity is calculated as below:

$$EU = \left[1.0 - 1.27cv/\sqrt{n}\right] \times q_n/q_a \quad (21)$$

where: Cv = coefficient of variation of emitter discharge (manufacturing variation); n = 1.0 or the number of emitters per plant; q_n is the minimum flow rate of the sampling group emitters; and q_a = average emitter discharge of all the emitters under consideration (l/h).

The Distribution Uniformity (DU) is a measure of how evenly water is distributed by the emitters in a drip irrigation system. This metric (Eq. 22) is similar to Emission Uniformity but focuses specifically on the lower quartile average, highlighting how well the least-performing parts of the system operate:

$$DU = 100\ (q_m/q_a) \quad (22)$$

Once the hydraulic efficiency of drip irrigation has been assessed, the risk of surface runoff must be minimised. In order to minimise the risk of surface runoff and deep percolation, the irrigation depth and the flow rate of the emitters were analysed together with the soil infiltration properties. This integrated approach ensures that the rate of water application does not exceed the water absorption and retention capacity of the soil, thus increasing the efficiency of irrigation. The application rate may therefore be calculated as follows (Keller and Bliesner 1990a):

Application rate (mm/h) = Emitter flow (l/h)/Wetted area per emitter (m^2) 23

2.8. Assessment of Agronomic Performance

To provide context for the hydraulic performance evaluation, the agronomic performance of mungbean (*Vigna radiata* L.) grown under the gravity-fed subsurface drip irrigation (GSDI) system was also assessed. Agronomic indicators commonly used to evaluate crop response under irrigation systems include germination rate, plant height, biomass accumulation, and final yield (Gölgül et al., 2023). However, in this study, only germination data were systematically collected (Rogers et al.,2010) during the early growth stages, as the primary objective was to design, characterise, and evaluate the hydraulic performance of a gravity-fed SDI system. Germination assessment followed standard agronomic field trial procedures, which involve daily counting of emerging seedlings until the germination curve stabilizes (Frasier, 1989). The germination percentage (G%) was calculated as:

$$G\% = \frac{N_g}{N_t} \quad (24)$$

where N_g is the number of germinated seedlings and N_t is the total number of seeds sown per plot.

This germination test was carried out during the dry season.

2.9. Upscaling of experimental results

The extrapolation was done by analysing the experimental results at plot scale and extrapolating them to the field scale, paying particular attention to irrigation volume, number of emitters, irrigation duration, tank storage requirements and pressure losses in the distribution network. The area affected by the scaling was 0.25 ha (Mathias, 2017). At this field scale, the gravity-fed subsurface drip irrigation system consists of a main raised tank with a 2.0 m elevation head and four secondary tanks, each raised 1.4 m, each serving one irrigation unit. Water is supplied through a hierarchical distribution network consisting of main, secondary and tertiary pipes feeding subsurface drip emitters. The increase was based on hydraulic path analysis to assess whether the available elevation head could meet the irrigation requirements under field conditions.

2.9.1. Determination of irrigation water needs, tank volume, duration, Emitter and Lateral Design

The maximum irrigation depth was calculated as given by Eq. 1. The Eq. 2 was employed to estimate the irrigation frequency.

The net irrigation requirement was first converted into the irrigated water volume per irrigation cycle. The irrigation volume for a given irrigated area was computed as:

$$V = A \times d \quad (25)$$

where (V) is the irrigation volume (m^3), (A) is the wetted irrigated area (m^2), and (d) is the irrigation depth (mm) (Allen et al., 1998).

Tank storage capacity for gravity-fed systems is evaluated by matching it to calculated irrigation water requirements, with specific capacity-to-demand (Bangi, 2016; Shin et al., 2020). The greater the capacity of the reservoir, the better able it is to meet water requirements (Shin et al., 2020). Caution should be exercised when increasing the capacity of the tank, as economic efficiency decreases when the size of the tank increases.

The total discharge capacity of the system (Qsys) was expressed as:

$$Q_{sys} = n \times q \quad (26)$$

where (n) is the total number of emitters and (q) is the emitter discharge rate ($L\ h^{-1}$).

The number of emitters was estimated based on the total length of dripperlines and emitter spacing, following the approach of Schwartzman and Zur (1986):

$$L = A/D \ (27)$$

$$n = L/E \quad (28)$$

where L is the total dripperline length (m), D is the spacing between adjacent dripperlines (m), and E is the emitter spacing along the dripperline (m).

The set time (duration of irrigation) at peak was determined from irrigation manual which applies the following expression (Krishna et al., 2020):

$$S_t = I_{reg} / Q_{sys} \quad (29)$$

The gross irrigation requirement was calculated as given:

$$I_{reg} = Idx/Ea \quad (30)$$

Where Idx is the maximum net depth of each application of irrigation over the entire area, in mm; I_{reg} is the gross irrigation requirement (mm). As, it is the micro-irrigation, the application efficiency was maintained at 0.95.

2.9.2. Hydraulic calculations, zoning in design block, and maintenance

Hydraulic analysis was performed to evaluate flow velocities, Reynolds numbers, and friction losses along individual laterals. For the calculation of friction losses, Hazen-Williams and Darcy-Weisbach were used as given by Eq. 13 (Abdulameer et al., 2022). The Reynolds number and average flow rate were computed by using the Eq. 15.

In order to control cumulative discharges and to ensure uniform pressure distribution, a zoning (block) design strategy has been adopted, based on established principles for drip irrigation (Keller and Bliesner 1990a). The zoning approach was based on the principles of pressure uniformity, flow matching, reduction of friction losses and operational flexibility. The uniform pressure was achieved by designing each irrigation zone to operate within a narrow pressure range, thus ensuring uniform emission discharge over the entire length of the irrigation strip. The flow matching involved matching the discharge requirements of each zone to the available gravity head in a gravity fed drip irrigation system, which helped to reduce excessive head losses and to maintain a stable flow. The friction losses have been reduced by reducing the number of connecting tubes, thus reducing head losses in the main and sub-main tubes. The operational flexibility was ensured by the sequential irrigation of the zones, which allowed for the adjustment of irrigation schedules and improved management of the system without any structural changes.

Low-discharge emitters are highly susceptible to clogging from sediments, biofilms, and dissolved salts. Maintenance measures included zoning for targeted flushing, enabling isolation of problem areas, filtration to protect emitters and maintain uniformity, and operational control to reduce mechanical stress and extend system lifespan (Bucks et al., 1979; Enciso-Medina et al., 2011; Mathias, 2017). These considerations are particularly relevant in rural, energy-limited contexts, where technical support and access to spare parts may be constrained.

2.10. Preliminary economic analysis

A Preliminary Economic Assessment (PEA) was carried out to assess the availability and financial feasibility of a gravity-fed subsurface drip irrigation system for smallholder farmers in energy and capital constrained environments such as rural areas in the DRC. The analysis focused on the estimation of initial capital investment and the annual operating and maintenance costs per 0.25 hectare, according to standard irrigation valuation procedures (Oosthuizen et al., 2005). At this stage, crop yield and farm income have been excluded in order to isolate the economic impact of the design and operation of the system from the variability of the agronomic situation, in line with the early-stage feasibility evaluations of irrigation technologies.

The analysis assumes constant local market prices, zero energy costs due to gravity operation, and excludes depreciation, system lifespan, and crop yield benefits.

3. Results and discussion

This section reports results for wetted areas, maximum irrigation depth and volume, statistics on emission flow rate, infiltration characteristics, head pressure distribution and hydraulic losses, with corresponding gross results and preliminary economic analysis. It also addresses critical design considerations for gravity-fed subsurface drip irrigation systems and assesses the hydraulic performance of the system. The analysis is set against the background of the predominantly sandy Tshilenge tropical soils.

The first part offers the results related to physical and hydraulic characteristics.

3.1. Soil Physical and Hydraulic Characteristics

The behaviour of infiltration and the related variation in volumetric water content of the ploughed sandy soil is summarised in Table 2, which highlights the rapid initial input and subsequent stabilisation of the soil.

The infiltration parameters given in Table 2 show that the Tshilenge ploughed sandy soils have a high infiltration rate, with an average infiltration rate of 36.5 cm per hour, a maximum of 64.1 cm per hour and a minimum of 18.7 cm per hour. The relatively high rate of infiltration means that water percolates quickly through the soil matrix, reducing the risk of surface ponds and runoff but potentially increasing the loss of depth in case of poorly managed irrigation (McIntyre et al., 1982). This means that the water goes down fast, so irrigation must be applied in small, well-managed quantities.

Table 2
Infiltration and Water Content of Ploughed Sandy Soil.

Ploughed sandy soil of Tshilenge	
Parameters	Values
Average (cm/h)	36.5
Maximum (cm/hour)	64.1
Minimum (cm/hour)	18.7
Mean standard deviation (cm/hour)	9.3
Range (cm/hour)	45.4
Median (cm/hour)	37.5
Average initial water content (m^3/m^3)	0.2
Average final water content (m^3/m^3)	0.3

The standard deviation of 9.3 cm/h and range of 45.4 cm/h indicate substantial variability in infiltration measurements across sampling locations. This variability may be attributed to heterogeneity in soil structure, ploughing depth, organic matter content, or spatial differences in compaction (Gülser et al., 2016; Özgöz, 2009). As a result, different parts of the field may absorb water at different rates. Such variability has implications for emitter spacing and pressure regulation in the subsurface drip irrigation design, as non-uniform infiltration rates can affect emission uniformity (EU) and distribution uniformity (DU) (Brito et al., 2011; Campozano et al., 2014; Dai et al., 2020). This highlights the need for careful hydraulic design to maintain uniform water application.

The median infiltration rate of 37.5 cm per hour is close to the mean, indicating a fairly normal distribution of infiltration data, indicating that extreme infiltration events (very high or low rates) are not dominant in the data set. Furthermore, it shows a relatively symmetric distribution of soil intake capacity. High infiltration rates are attributed to the sandy texture and ploughing-induced macroporosity (Assouline, 2013), which increase saturated hydraulic conductivity and favour gravity-driven flow in accordance with Darcy's law. Volumetric soil water content increased from 0.20 to 0.30 $m^3 \cdot m^{-3}$, reflecting limited water retention despite rapid intake, a characteristic of coarse-textured soils. The soil water content retention indicate that the available water capacity of the soil is low. Sandy soils typically have low field capacity and high infiltration, which means that they are rapidly drained from the root zone (Ceballos et al., 2002; Sato and T., 2012). For Gravity-fed subsurface drip irrigation, this requires frequent but small-scale irrigation operations that are compatible with soil infiltration dynamics and minimise percolation losses (Michael D. Dukes and Johannes M. Scholberg, 2004). This ensures that the water used remains in the root zone as long as it is suitable for the crop. Moreover, the high infiltration rates observed are favourable for subsurface drip irrigation, as it allows for rapid vertical redistribution of water in the active root zone and minimisation of evaporation from the soil (Lamm, 2014; Sinobas and Gil Rodríguez, 2012). However, this advantage can only be fully realised if the emission rates and operating pressures are commensurate with the infiltration properties of the soil. If the discharge rate is too high, the soil may not absorb water fast enough, resulting in preferential flows or uneven distribution of moisture (Ajdary et al., 2007; Kandelous and Šimůnek, 2010b). This highlights the need to integrate IoT-based soil moisture sensors with AI-driven predictive algorithms capable of detecting spatial variability in soil infiltration and reducing deep percolation losses (Molin et al., 2020; Singh et al., 2019a).

In conclusion, the infiltration behaviour of the sandy soil of Tshilenge, characterised by high and spatially variable infiltration rates, highlights the critical importance of the precise hydraulic design and calibration of the system in Gravity-fed subsurface drip irrigation systems. Parameters such as emitter flow rate, spacing and irrigation planning shall be optimised in relation to the hydraulic characteristics of the soil to ensure uniform water distribution, maximise water efficiency and minimise percolation losses (Lamm, 2014; Vaughan et al., 2007). Therefore, the effective integration of soil infiltration dynamics and hydraulic performance of the subsurface drip irrigation is crucial to achieve efficient and sustainable irrigation management in sandy soils typical of tropical environments (Arbat et al., 2020; Lazarovitch et al., 2006).

3.2. Design parameters for gravity-fed subsurface drip irrigation system

Table 3 shows the classification of the soil and surface wetting parameters of the drip irrigation design used in the Tshilenge area.

Table 3
Soil classification and design parameters for subsurface drip irrigation system.

Soil class	Sand	
Parameters	Values	Units
Emitter Discharge q	1.50	(ml/min)
Wetted Width W	0.04	(m)
vertical upward, Z + (m)	0.02	(m)
vertical downward, Z- (m)	0.02	(m)
Wetted area	0.06	(m^2)
Total Wetted area	15.12	(m^2)
Total area of the plots	24.00	(m^2)
Total percent of Wetted area	63.00	%
I (Maximum net Irrigation depth)	5.94	(mm)
Average daily crop water requirement	2.3	mm/day
Irrigation Interval	2.58	Days
Volume of water	90.00	litres

The Volume of water is calculated based on the wetted area (63% of plot area) as required in the subsurface drip irrigation.

3.2.1. Irrigation depth and crop water requirement

The irrigation depth applied per event was 5.94 mm, based on an average daily crop water demand of 2.07 mm, which corresponds to an optimal irrigation interval of approximately 2.58 days. The cumulative demand over this interval is therefore about 5.18 mm, meaning that the applied depth slightly exceeds crop requirements. Mechanistically, porous coarse textures lead to high hydraulic conductivity and rapid gravitational drainage, making shallow, frequent irrigations preferable to deep, infrequent ones to maintain soil water within the crop root zone (Al-Nabulsi, 2001; Wesseling et al., 2009).

This small surplus provides a margin of safety against under irrigation without significantly increasing the risk of deep percolation. The slight surplus beyond cumulative crop demand provides a buffer against short-term soil moisture deficits, aligned with principles of soil-–plant–atmosphere continuum (SPAC) and capillary redistribution. However, maintaining this balance in spatially heterogeneous fields requires real-time soil water information and adaptive control because of the risk of deep percolation and nutrient leaching inherent in sandy soils. This strategy is in line with the hydraulic behaviour of sandy soils, which are characterised by rapid infiltration and limited water retention, requiring frequent, low volume application (Allen and Perrier, 1994; Keller and Bliesner, 1990a). This is because coarse soils cannot sustain large irrigation pulses and if the application depth is too deep or the spacing too wide, excess water quickly seeps down to the root zone. However, in sandy soils the exact timing and depth of irrigation remains crucial to avoid deep percolation and nutrient leaching (Alhammadi and Al-Shrouf, 2013).

This underlines the importance of using IoT technologies to continuously monitor soil moisture and microclimate conditions through distributed sensor networks, which provide the high-resolution data needed to accurately calibrate irrigation schedules and depth measurements (Abdelmoneim et al., 2025). Furthermore, the smart systems, including weather forecasting and machine learning, can predict irrigation water requirements more precisely than fixed schedules, reduce waste and increase water efficiency (Abo-Zahhad, 2023; E G and Bala, 2024). Artificial intelligence models further improve decision-making by learning patterns in soil moisture dynamics and water usage of crops, allowing for predictive irrigation planning that is adapted to time variability and local conditions. The assembly-learning models used on IoT platforms have demonstrated high accuracy in irrigation control tasks, enabling accurate water management with minimal computation (Srihar 2025; Syahputra and Andriani, 2025).

Overall, these findings confirm that the Gravity-fed subsurface drip irrigation is well adapted to sandy soils, provided that the irrigation schedule is carefully adapted. The calculated interval of ~2.5 days in this study is in line with crop demand, minimising inefficiencies and reflects good practice. However, achieving sustainable efficacy requires careful selection of the depth of the emitter, monitoring of the water dynamics in the soil and consideration of possible preferential flow paths.

3.2.2. Emitter Discharge and Wetted Pattern

The average discharge of the emitters was 1.50 ml min^{-1} , which is in line with the design of low flow emitters in Gravity-fed subsurface drip irrigation systems to match the soil infiltration capacity and to minimise the risk of ponding or runoff. The wetting horizontal was 0.04 m with equal vertical movements up ($Z^{+} = 0.02$ m) and down ($Z^{-} = 0.02$ m) over a one-hour averaging period. The wetted area per emitter was 0.06 m^2, resulting in a total of 15.12 m^2, which corresponds to 63.00 % of the total plot area (24.00 m^2) used for the calculation of the total water requirement of the mungbean. This reflects a modest coverage as expected for systems of subsurface drip irrigation where the aim is to target the root zone of the crop effectively rather than the entire surface (Savva and Frenken, 2001). This pattern is typical for groundwater drainage systems, as water movement is mainly governed by capillary forces around each emitter rather than by uniform surface spreading, which results in concentrated wetting zones that are consistent with root distribution.

The expected wetting pattern is dominated by capillary flow, with water moving mainly vertically and remaining concentrated around the emitter rather than spreading out laterally across the soil profile. This behaviour is typical in coarse textured soils where the wetting front remains concentrated near the application site due to limited lateral distribution, which limits the expansion capacity of the wetted bulb. Conversely, lateral capillary redistribution is important for wetted volume (W) in the Kandelous and Šimůnek, 2010 model, which mechanistically assumes an axisymmetric infiltration under homogenous soil conditions. The irrigation depth obtained from the emitter spacing as implemented in the GSDI design tool Excel served as a basis for the estimation of wet soil parameters. This method introduces a number of potential biases which should be recognised, although it is more appropriate for planning and preliminary design than for the real-time management of irrigation. First, the technique assumes that the soil characteristics of the wetted zone are homogeneous and that water is applied evenly. Even at the field scale, the soil structure, bulk density and hydraulic conductivity often show significant spatial variability in practice (Alletto and Coquet, 2009). If wetting parameters are estimated only on the basis of the spacing of the emitters and the nominal irrigation depth, this diversity may result in asymmetric wetting fronts and variable infiltration rates that are not captured (Keller and Bliesner, 1990; Schwartzman and Zur, 1986). Depending on the local soil conditions, the actual volume of wetted area may therefore be overstated or underestimated. Secondly, the method does not take into account the dynamics of soil moisture over time. It does not specifically take account of the demand for evapotranspiration, the soil moisture conditions preceding irrigation or the redistribution processes after irrigation, such as deep percolation and lateral spreading, as this depends on the irrigation depth. Estimates of wetting depth and availability of water in the soil can be distorted by these simplifications, particularly in situations of changing weather patterns or in successive irrigation cycles. Thirdly, hydraulic variations in subsurface drip irrigation systems powered by gravity may introduce an additional bias. Even if the design requirements for uniformity of pressure are met, the actual application rates may be affected by friction losses, small emission discharge variations and small variations in pressure along the laterals and sub-mainlines. Therefore, the estimation of wetted soil parameters from the irrigation depth of the design may not accurately reflect the field conditions and presuppose optimum hydraulic efficiency. Finally, the chosen strategy lacks adaptive control mechanisms and real-time feedback from soil moisture sensors because of its design. In particular in soils with low infiltration capacity or in soils with limited and variable gravity heads, this constraint may lead to conservative or optimistic estimates of the extent of wetting and to deep percolation losses. These disadvantages highlight the potential benefits of combining predictive modelling techniques with sensor-based monitoring in the future optimisation of the system.

Overall, the sources of bias identified highlight the need for field validation and adaptive refinement in the transition from design to operational management, even though the methodology provides a consistent and useful framework for the design of GSDIs in constrained data scenarios.

3.2.3. *The total volume of water applied for mungbean*

The total volume of water used for mungbean was 90.00 litres per irrigation event (about 1.50 ml $\min^{-1}$ per emitter), reflecting the ability of the gravity-fed drip irrigation system to deliver a controlled amount of water directly into the root zone of the crop. Such precision in water delivery minimises evaporation and percolation losses from the surface, which are common problems in sandy soils with a coarse texture and low water retention capacity (Kandelous and Šimůnek 2010c; Phogat et al., 2017). By applying water below the surface of the soil, gravity-fed subsurface drip irrigation reduces the exposure to atmospheric pressure and ensures that a higher proportion of the water applied directly contributes to the renewal of the root zone.

The low and frequent water use is consistent with the finding that subsurface drip irrigation improves water efficiency by maintaining a favourable moisture balance in the root zone and not excessive deep percolation of water (Davis and Dukes, 2010; Lamm, 2014). This planning approach is consistent with the rapid infiltration rate of sandy soils, which require low volume, short duration irrigation to prevent percolation of water beyond the root zone and to stabilise the availability of moisture for the cultivation of crops.

In addition, for short-duration legumes such as mungbean, it is essential to match irrigation inputs to water demand in order to optimise yield and resource efficiency. Studies by Ambachew et al. (2014) and El-Nakhlawy et al. (2018) showed that moderate irrigation schedules, providing only the necessary volume to replenish the root zone, could maintain yields while saving water. Similarly, Tripathi et al. (2024) noted that improved scheduling and residue management in drip systems have significantly increased the water productivity of mungbean. These findings reinforce the rationale for the use of a controlled 90 L per irrigation event in this study, which ensures that the water used meets the demand for evaporation without causing stress or waste in gravity-fed subsurface drip irrigation systems operating under constrained conditions. This approach is particularly important for fast growing legumes whose shallow root systems are sensitive to both moisture deficiency and excess, which makes accurate matching of application depth to the evapotranspiration requirements necessary to maintain a constant physiological activity. In addition, controlled low pressure delivery helps to avoid excessive application, which is a common risk when relying on gravity-driven systems without automatic flow control.

3.2.4. *Implications for tropical sandy soil irrigation*

The results confirm that gravity-fed subsurface drip irrigation is a viable and effective method for tropical sandy soils, as the way water is applied is closely related to the high infiltration rate and the fast drainage characteristics of the soil (Kandelous and Šimůnek 2010b). However, the limited lateral distribution of moisture under these conditions underlines the importance of the appropriate design, discharge rate and location of the emitters to ensure uniform wetting and adequate coverage of the root zone (Phogat et al., 1984). This is because coarse-textured soils have a weak capillary pull, which limits horizontal redistribution and makes the spacing and depth of the emitters critical to avoid gaps in the wetted volume. The relatively high wetting percentage (63%) suggests that the system efficiently supplied water in the active root zone, which supports the finding that GSDI may increase water efficiency in light textured soils, if the spacing and frequency of irrigation is optimised (Singh, 2014). This shows that, despite the rapid drainage typical of sandy soils, well-designed GSDI systems can maintain sufficient moisture around the root zone by applying small, frequent doses that are consistent with the hydraulic behaviour of the soil.

In addition, adjustment of the spacing of the emitters or the frequency of irrigation according to the type of crop and the depth of the roots may further improve uniformity and avoid deep percolation losses (Ghumman et al., 2018; Silva et al., 2009). This is particularly important in sandy soils where water flows quickly down, which makes accurate alignment of the location of the emitter and the distribution of the roots necessary to avoid zones of insufficient or excessive irrigation. Overall, the results show that in sandy soils typical of many tropical areas, low-flow GSDI systems can achieve high irrigation efficiency, minimise water losses and better match water use with water requirements of crops, thus increasing the sustainability and resource efficiency of the system (Ghumman et al., 2018; Silva et al., 2009). By providing water in small, controlled volumes that correspond to both the hydraulic behaviour of the soil and the rate of crop uptake, subsurface drip irrigation reduces unnecessary losses and maintains a stable moisture environment favourable for efficient root function.

The following section presents results on hydraulic performance, including the distribution of the pressure head and the continuous losses along the line, since these parameters have a direct impact on the uniformity of emissions and on the overall efficiency of the system. This assessment should start with an analysis of the distribution of the pressure head and the continuous losses along the perimeter, as these parameters have a direct impact on the uniformity of emissions and on the overall efficiency of the system.

3.3. *Hydraulic performance of the gravity-fed subsurface drip irrigation system*

The results summarised in Table 4 show that the GSDI system developed for this study maintains a constant positive pressure head throughout the distribution network, with hydraulic gradients both on the main and secondary lines being within the acceptable limits for drip systems with low pressure. These gradients minimise frictional losses and confirm that the flow conditions are well-balanced over the design range (Chen and Baines, 1992; Williams, 1985). According to computational fluid dynamics modelling by Stovin, Bennett and Guymer, cited by Dündar et al. (2023), the maximum permissible head loss in irrigation canals should not exceed 0.8 m in order to maintain a uniform discharge throughout the entire pipeline (Stovin et al., 2013). Therefore, the results show that the emitters receive a uniform and reliable pressure, which promotes a consistent discharge along the line. Furthermore, the small tank plays a key role in dampening short-term hydraulic fluctuations, thus ensuring that the main pressure variations do not extend to the secondary pressures. This pressure stabilisation effect increases the stability of the pressure and helps to maintain the high uniformity of emissions throughout the system.

A gravity-fed subsurface drip irrigation system keeps a constant

Table 4
Hydraulic Head Distribution and Friction Losses in the Main pipe and Lateral of the GSDI System.

Parameters	Values
Head available to drive flow through the mainline (m)	0.50
Continuous friction loss in the mainline (m)	0.16
Local head losses in the mainline (fittings, bends) (m)	0.02
Total head losses in the mainline (m)	0.17
Net inlet pressure head at the small reservoir (m)	1.83
Hydraulic gradient in the mainline (m/m)	0.04
Head available to drive flow through the lateral (m)	1.40
Hydraulic gradient in the lateral pipe (m/m)	0.17
Continuous friction loss in the lateral (m)	0.01
Local head loss in the lateral (emitters, fittings) (m)	0.002
Total head losses in the lateral (m)	0.02
Net inlet pressure head at the lateral pipe (m)	1.38

positive pressure throughout the whole distribution network. This arrangement mechanically minimises frictional losses and ensures that all emitters operate under a uniform pressure, which results in a uniform flow rate along the entire length of the pipe (Chen and Baines, 1992; Williams, 1985). In this system, the gross head of 1.38 m, after taking into account the measured head losses of 0.17 m (primary) and 0.02 m (secondary), gives a working pressure of approximately 13.5 kPa, which is acceptable for low-pressure or pressure-compensating emitter systems (ASENSO et al., 2014; Mukesh Kumar et al., 2014a).

The small tank acts as a hydraulic reservoir, which reduces the short-term fluctuations in pressure and thus improves the uniformity of emissions. This buffering effect can be explained by a set of cause-effect relationships, namely the hydraulic gradient rule, the pressure-sensitivity rule and the emission-lateral construction rule (Keller and Bliesner 1990a). The Hydraulic gradient rule emphasises that the maintenance of a positive and continuous hydraulic gradient throughout the system is necessary to achieve a uniform distribution of flows. Lack of hydraulic gradient or presence of other local losses may lead to a loss of pressure in the downstream emitter, thereby reducing the uniformity of emissions and the overall performance of the system. The pressure sensitivity rule takes into account that low-head irrigation systems are very sensitive to small changes in elevation, hydraulic resistance and the production tolerances of the emitter. In gravity-driven conditions, even small changes in pressure may have a disproportionate effect on the discharge and flow uniformity of the emission (Pragna 2017a; Zhu et al., 2010). The Emitter-Lateral design rule emphasises the importance of short lateral lengths, appropriate pipe diameters and minimum number of fittings to reduce friction and local losses. These design considerations help to maintain a consistent pressure distribution along the laterals and to ensure consistent emission performance, thereby increasing the uniformity of emissions.

The budget for the hydraulic head is conservative: the gross head of 1.38 m gives an operating pressure of approximately 13.5 kPa for the emitters, after taking into account the total measured head losses of 0.17 m on the main line and 0.02 m on the secondary lines. This operating head is suitable for low pressure or pressure compensators, but requires precise choice of emitters, their lateral design and fitting configuration to ensure emission consistency (ASENSO et al., 2014; Mukesh Kumar et al., 2014a). These findings are in line with experimental observations by some researchers (Khedr, 2024; Mukesh Kumar et al., 2014a; b).

However, operating under such low pressures increases the sensitivity to local variations in height, tolerances of manufacture and small head losses in fittings or connections (London, 1970). Since the pressure difference is small, any additional resistance or minor elevation change may have a significant effect on the uniformity of the emission flow. Therefore, the choice of emitters should give priority to low pressure (pressure-compensating or partially-compensating) devices and the geometry of the lines should be optimised - short runs with a sufficient diameter and minimum fittings to reduce local losses (Perboni et al., 2015). This shows the need to integrate the Internet of Things (IoT) sensors which enables real-time monitoring of soil pressure and moisture at multiple points within the distribution network (Arvaree @ Alvar and Vijayasuria, 2025). When combined with predictive algorithms, these systems can: (i) detect local pressure drops or surges before they significantly impact emitter flow, and (ii) dynamically anticipate changes in crop water demand or irrigation schedules, even under low operating head conditions (Arjun and R 2024c; Arvaree @ Alvar and Vijayasuria, 2025; D. Srihar, 2025; Zhu et al., 2010).

In summary, the hydraulic analysis (Table 5) confirms that a GSDI system can provide satisfactory performance under very low operating head loads, provided that careful optimisation of the system layout, hydraulics and emitter selection is made. This optimisation is necessary to maintain uniform discharge rates and to ensure the long-term water efficiency of low-pressure irrigation systems.

Table 5
Statistical Analysis of Lateral Pipe Flow Rates for Multiple Reservoirs.

Parameters	First reservoir (flow rate, ml/minute)		
	Lateral pipe1	Lateral pipe 2	Lateral pipe 3
Average	1.55	1.64	1.52
Maximum	1.63	1.83	1.67
Minimum	1.40	1.43	1.25
Standard deviation	0.05	0.09	0.10
	Second reservoir (flow rate, ml/minute)		
	Lateral pipe1	Lateral pipe2	Lateral pipe 3
Average	1.54	1.41	1.52
Maximum	1.75	1.51	1.66
Minimum	1.34	1.36	1.32
Standard deviation	0.10	0.04	0.08
	Third reservoir (flow rate, ml/minute)		
	Lateral pipe1	Lateral pipe 2	Lateral pipe 3
Average	1.58	1.61	1.59
Maximum	1.71	1.63	1.59
Minimum	1.54	1.60	1.41
Standard deviation	0.03	0.01	0.07
	Fourth reservoir (flow rate, ml/minute)		
	Lateral pipe1	Lateral pipe2	Lateral pipe 3
Average	1.39	1.34	1.34
Maximum	1.44	1.36	1.43
Minimum	1.32	1.31	1.18
Standard deviation	0.03	0.01	0.06

The next section, summarised in Table 6, presents the statistical analysis of the lateral discharge measurements for each small reservoir.

Results for emitter flow rates (Table 5) show a moderate variability of flow rates over distances, as measured by standard deviations. It should be noted that the average values of the emission flow rates per lateral are the average over three replicates as shown in Fig. 1. The slight variability of the flow rate observed in a gravity-fed subsurface drip irrigation system is due to inherent hydraulic constraints related to the distribution of the pressure along the manifold and the lateral sections. These variations show that pressure is not perfectly uniform throughout the network, mainly due to frictional and small (local) losses that accumulate as water flows through the pipes (Provenzano and Pumo, 2004). As the water moves along the manifold, friction losses progressively reduce the available pressure head, leading to different input pressures at the points of each passage.

Moderate standard deviations in emitter flow further indicate operation in the hydraulic range, where the discharge is still sensitive to variations in pressure. This is consistent with the relationship of pressure and discharge described by the generalised emission equation ($q = kH^x$), where even a small decrease in the pressure head reduces the flow if the exponents (x) are greater than zero (A. N. et al., 2024a; Pragna, 2017). Although pressure-compensating emitters may reduce this variability, many gravity-fed systems use non-compensating or partially compensated emitters whose performance is directly affected by the prevailing hydraulic conditions (Madramootoo, 1988).

Friction-induced loss of longitudinal pressure along individual lines contributes to intra-lateral variability. This pressure gradient affects the uniformity of water usage, which is a key consideration in the subsurface drip irrigation assessment. Studies in similar low pressure gravity-driven systems have shown that the uniformity tends to decrease as the lateral length increases and the input pressure decreases (ASENSO et al., 2014b; Enciso-Medina et al., 2011). Although the system assessed here is not hydraulically optimal, the slight variability observed indicates that it remains within acceptable operating range for practical farming - especially in resource-limited environments where pumping is not possible. The relatively low variability observed here may also be due to homogeneity of hydraulic properties of the soil (Ren et al., 2017). This shows that friction losses and external soil pressure were relatively consistent along the laterals, which makes it easier for emitters to operate under similar hydraulic conditions. However, under heterogeneous soils, the variability of flow may be increased due to interactions

Table 6

Flow Performance and Emission Uniformity of Lateral Valves in the GSDI System.

Lateral	Average discharge (qa)	Std Dev (Sq)	Coefficient of Variation (CV)	Uniformity Coefficient (UC) %	Emission Uniformity (EU) %	Distribution Uniformity (DU) %
First lateral valve (ml/min)	1.52	0.09	0.06	93.69	91.17	91.17
Second lateral valve (ml/min)	1.49	0.14	0.09	90.72	89.15	89.15
Third lateral valve (ml/min)	1.49	0.12	0.08	92.06	88.84	88.84

between the lateral hydraulic and soil properties. In such conditions, differences in soil compaction, moisture content and infiltration rate may cause uneven external pressure in the pipe, which in turn changes internal pressure and causes greater variability in the discharge. As pointed out by Nogueira et al., (2021b), even well designed subsurface drip irrigation systems may experience variations in emissions, mainly due to soil heterogeneity.

These findings have two main consequences for the efficiency of irrigation. Firstly, moderate variations in the flow rate may lead to an uneven wetting pattern, which affects the distribution of moisture in the root zone and may affect crop growth. Secondly, the results highlight the importance of careful design optimisation, including appropriate choice of pipe diameters, minimisation of gradient differences and appropriate manifold sizing to limit pressure losses. This is in line with the subsurface drip irrigation guidelines on Design, which emphasise the need for hydraulic balancing, particularly in gravity-fed assemblies (Hammami et al., 2013b; Sinobas and Gil Rodríguez, 2012).

This model is consistent with previous studies on subsurface drip irrigation where buried emitters and local soil pressure contributed to variability beyond the tolerances of the production process and hydraulic gradient (Gil et al., 2008; Nogueira et al., 2021a). Although the laterals were installed at the same height, a difference in flow was observed. This variability is due to differences in production and to soil over-pressurisation-effects which are negligible in sandy soils.

Overall, the results show that although the subsurface drip irrigation system with gravity is subject to measurable hydraulic variability, the degree of non-homogeneity is still low. This indicates that such systems can still provide reliable irrigation performance under low pressure conditions, if the key parameters of the design are optimised.

Compared to other low pressure irrigation methods, gravity-fed subsurface drip irrigation offers several advantages which make it particularly suitable for small-scale and resource-poor agricultural systems. Unlike pitcher and capillary-wick irrigation systems, which rely on porous or fibre materials which are susceptible to deterioration, clogging and loss of hydraulic function in field conditions, GSDI uses durable polyethylene dripline systems, which could be more reliable. In addition, GSDI systems do not require frequent manual refilling or repositioning, which reduces labour requirements and improves the consistency of water use. Another advantage of GSDI is its ability to precisely regulate the discharge of the emitters under low pressure conditions, which allows the irrigation supply to be closely aligned with the water requirements of the crops. This level of control allows for adaptation to a wide range of crops, soil structures and climatic conditions, while minimising losses due to evaporation and soil erosion (Sherpa et al., 2021). Subsurface gravity irrigation provides a scalable and reliable alternative to traditional low-pressure irrigation in environments where water and maintenance resources are scarce (Bhatnagar and Srivastava, 2003). Unlike surface irrigation methods such as bucket, basin or furrow irrigation, which are often labour-intensive and prone to uneven application, surface runoff and deep percolation, gravity-fed subsurface drip irrigation delivers water directly to the root zone, thus improving the uniformity of the irrigation process and reducing water wastage. Unlike micro-sprinklers or low-pressure sprayers, which are prone to evaporation, wind drift and surface-drying, subsurface spraying minimises evaporation, inhibits weed growth and reduces nutrient leaching.

Moreover, unlike tread-pumps or other low-cost pressure systems, which depend on continuous human or animal energy and frequent maintenance, gravity-fed subsurface drip irrigation is operated under low pressure conditions. This will eliminate pumping costs and reliability constraints, while ensuring a continuous and uniform supply of water. Gravity-fed subsurface drip irrigation can also be scaled up to larger fields with minimal additional work while maintaining the efficiency of the emitter and the uniformity of the soil moisture, a major limitation of pitcher and capillary systems, which are usually limited to small plots or micro-plants (Mahler, 2024; Sarangi et al., 2024).

The following subsection provides information on flow characteristics and emissions consistency of the lateral valves in gravity-fed subsurface drip irrigation systems.

3.4. *Emitter flow performance and uniformity*

The results shown in Table 6 show that the developed gravity-fed subsurface drip irrigation system achieves high flow consistency and excellent consistency of emissions along the line despite its very small operating head (~1.38 m). Mean emitter discharge ranged from 1.49 to 1.52 ml min^{-1} with standard deviations of 0.09–0.14 ml min^{-1} and coefficients of variation (CV) ranged from 0.06 to 0.09. The observed discharge consistency at a gross operating head of about 1.38 m reflects the correct application of the basic hydraulic principles governing the gravity-driven flow of the fluid. At such low head, emission is mainly controlled by the balance between the available gravitational potential and the cumulative losses of frictional and local head along the line. If these losses are kept within acceptable limits, the pressure variation along the axis is low enough to allow the emitters to operate within their nominal discharge and pressure range. This behaviour is governed by the principle of pressure continuity in low loss conduit flow, where frictional losses and local losses are small in relation to the available head, and where a positive and almost homogeneous hydraulic gradient is maintained. In these conditions, the variations in pressure are below the threshold where the emission of the emitter becomes sensitive to head differences. This interpretation is supported by the measured hydraulic gradients (Table 4) which confirm that the cumulative head losses are below the permissible range of the pressure change for a uniform emission performance.

The results of CV confirm the excellent consistency across all laterals, with CV < 0.10 (Keller and Bliesner, 1990a; Mansour et al., 2010), and confirms that the variations of the pressure in the pipes are well controlled. Low CV values (0.06–0.09) and narrow discharge range (1.49–1.52 ml min^{-}) indicate that the hydraulic gradient along the line is shallow and stable. This confirms that the choice of pipe diameters, length of the pipe and spacing of the emitters were suitably matched to the available head. In addition, in subsurface systems, the soil acts as a hydraulic buffer, reducing the variability of short-term discharge and further increasing efficiency of uniformity compared with surface irrigation methods. This buffering effect explains why the uniformity of the emission discharge from subsurface drip irrigation systems is often higher than that of surface drip or furrow systems, especially in homogenous sandy soils with stable infiltration characteristics.

The uniformity indices derived from emitter discharge measurements further confirm the stable hydraulic performance of the system. The Christiansen uniformity coefficient (CU) ranged from 90.72% to 93.69%, while emission uniformity (EU) and distribution uniformity (DU) varied between 88.84% and 91.17%. These values exceed the 85 % threshold commonly recommended for well-designed drip irrigation systems (Keller and Bliesner 1990a) and are consistent with reported performance levels of gravity-fed subsurface drip irrigation systems optimized for low-pressure operation (Sarker et al., 2019).

From a hydraulic point of view, these results suggest that the hydraulic grade line along the laterals is maintained in a nearly homogeneous pattern, so that the pressure variations are kept within the permissible emission limits. Low frictional losses, short lateral lengths and appropriate pipe diameters limit head losses and prevent the development of significant spatial pressure gradients along the distribution network. From a mechanical cause-effect point of view, a single pressure environment ensures that the flow of the emitter is controlled by the intrinsic emission-pressure characteristics of the emitter and not by external hydraulic disturbances. From a mechanical point of view, the available head provides sufficient thrust to overcome the internal emitter resistance, while avoiding excessive sensitivity to minor changes in elevation, fitting or production tolerances. Consequently, local perturbations do not translate into a measurable imbalance of emissions, which leads to a consistent emission and a maintenance of high CU, EU and DU values even under very low operating head conditions.

The findings suggest that slight modifications of the length of the conduit, the emitter spacing or the height of the tank could further increase the uniformity to a level of more than 92 %, bringing the system performance closer to that of pressure-controlled configurations, while maintaining the energy-efficiency of gravity-fed operation. These results support the recent evidence that well-balanced subsurface drip irrigation systems fed by gravity can be comparable to conventional pressure systems (Yang et al., 2025).

The same table summarises CU, EU and DU, all of which have an above-85 %. Values above 90 % are excellent uniformity (Christiansen, 1942;Keller and Bliesner, 1990b), while values of 80–90 % are good uniformity (Sarker et al., 2019). DU > 85 % is also classified as excellent (alsalami et al., 2024; Sharu, 2021), which means that the emitters have been operating consistently over the network and ensuring efficient water supply. Together, these indicators confirm that the emitters operated consistently under the pressure head available, which allowed for an efficient and uniform supply of water throughout the network in spite of low pressure and gravity conditions.

Mechanically, the reason for the high uniformity observed in this system can be traced to the interaction between gravity-induced pressure distribution, emitter hydraulic systems and soil-water dynamics. At the operating head of ~1.38 m, the pressure losses along the laterals were low enough to avoid significant degradation of the discharge at the downstream end. This is confirmed by the measured hydraulic gradients (Table 7) which confirm that the loss of friction has remained within the design limits reported in comparable experimental studies.

The uniformity of water distribution is crucial for the effectiveness of micro-irrigation (Al-Saadi et al., 2024). In homogenous soils, the uniformity of emission discharge (ED) in the gravity-fed subsurface drip irrigation is generally higher than in surface runoff, as water movement is buffered by the soil matrix. However, in field conditions variations are due not only to production tolerances but also to spatial variations in soil characteristics, in particular soil bulk density (SBD), soil humidity and average flow rate, which have a direct impact on the lateral hydraulic performance.

Recent findings by Martinez et al. (2022) similarly showed that low-cost gravity-fed kits achieved very high CUs (97.5 %-98.5 %) and EU values (95.9%-97.7%) when the key design parameters - in particular the lateral length and permissible head loss - were well controlled. The high uniformity achieved in this study therefore confirms that hydraulic accuracy, emitter selection and compatibility of the soil with the GSDI are key factors for success in sandy soils with limited pressure availability.

The combination of low CV values and high CU, EU, and DU coefficients demonstrates that the hydraulic design and emitter selection are well adapted to gravity-fed operation.

While hydraulic results show that a developed gravity-fed subsurface drip irrigation system can reliably perform under very low pressure, the integration of Internet of Things (IoT) technologies and machine learning frameworks can further improve the monitoring, diagnostics and adaptive control of the system (Pragna, 2017a). In gravity-fed systems where pressure ranges are limited and design tolerances are tight, it is of particular importance to detect early deviations from the nominal hydraulic behaviour. Low-cost IoT sensors - such as pressure sensors at the outlet and the lateral side of the tank, soil moisture sensors in the root zone, and flow or water level sensors in the delivery tank - can provide continuous, real-time feedback about the functioning of the system (Arvaree @ Alvar and Vijayasuria, 2025; D. Srihar, 2025; Syahputra and Andriani, 2025). These measurements allow detection of small pressure losses, partial blockages or emitter faults before they propagate to significant non-compliance. In the current system, where the uniformity indices are above 90 % at a gross head of approximately 1.38 m, the monitoring by the Internet of Things would help to keep friction losses and emissions within the narrow operating range required for gravity-fed power. Machine learning models provide an additional layer of analysis by learning the relationships between hydraulic inputs (e.g. gravity head, lateral pressure gradients, emission discharge), soil conditions (e.g. moisture content, bulk density), and agronomic results.

For Subsurface drip irrigation fed by gravity, the inclusion of uniformity metrics (CV, EU, DU) as explanatory variables allows quantifying the marginal contribution of increasing hydraulic uniformity - by changing the tank height, the lateral length or the emitter spacing. Deep learning techniques further enhance this capability by linking spatial irrigation patterns to responses at the level of the plants. Convolutional neural networks (CNNs), widely used for detection of plant diseases and stress based on RGB or multispectral imaging, can identify areas of decreased vigour or early signs of disease associated with localised low or high irrigation intensity (Vishnoi et al., 2023). When CNN stress maps are overlaid by hydraulic indicators such as measured head loss or emission variability, a causal relationship between the non-uniformity of the hydraulic data and the crop response can be established. In subsurface drip irrigation systems driven by gravity, this integration allows for targeted maintenance actions such as flushing specific laterals or adjusting the operating head, rather than uniform system-wide interventions.

Recent reviews highlight the significant improvement in reliability and interpretability of Machine Learning models for irrigation when physically meaningful hydraulic and soil parameters are explicitly included such as emission discharge coefficients, infiltration rates and head loss distribution (Parashar et al., 2024). The high hydraulic uniformity demonstrated in this study provides a stable and well-characterised basis, which makes the system particularly suitable for integrating with data-driven approaches, without introducing distracting hydraulic noise. Overall, the combination of high hydraulic uniformity, energy efficiency from gravity and compatibility with the Internet of Things and Machine Learning -based monitoring positions the developed gravity-fed sub-surface drip irrigation system as a technically advanced and future-proof solution for irrigation.

Table 7
Hydraulic Assessment of Emitter Discharge Relative to Soil Infiltration Capacity.

Parameters	Values	Units
Emitter flow rate	0.09	L/h
Infiltration rate	365	mm/h
Wetted area	600	(cm^2)
Irrigation depth from emitter flow rate	1.64	mm/h
Final Decision	No risk for runoff or percolation	

The following section presents the consequences of the design for predominantly sandy soils, with particular reference to the potential for surface runoff or deep percolation under the irrigation scheme proposed. Table 7 summarises the decision criteria for the likelihood of runoff or percolation based on the calculated irrigation depth and soil infiltration properties of the irrigated area. The results show that the risk of surface runoff is minimal under the current design parameters, especially in the absence of other natural inputs such as precipitation.

3.5. Soil–Emitter compatibility assessment

Table 7 presents a comparative assessment of emission discharge and soil infiltration properties for the assessment of the potential for surface runoff or deep percolation losses. The emission rate of 0.09 L h^{-1} is equivalent to an irrigation depth of approximately 1.64 mm h^{-1} , which is considerably less than the measured infiltration rate in Tshilenge sand. The resulting infiltration-to-application ratio (>200:1) clearly shows that the soil can absorb the applied water easily without surface ponding or lateral expansion beyond the wetted area of the emitter. In addition, the measured wetted area ($\approx$ 600 cm^2) is in line with the reported wetting patterns of sandy soils under low-flow subsurface emitters (Lamm and Trooien, 2003; Skaggs et al., 2004), which confirm the effective vertical redistribution with a minimum risk of surface encroachment or preferential flow.

The calculated infiltration capacity is well above the rate of emitter use, which does not imply any risk of runoff or deep percolation losses, as summarised in Table 7. The results of the soil-water interaction analysis show that the calculated infiltration capacity significantly exceeds the emission rate, which confirms that the soil can absorb the applied water easily without surface runoff or excessive downward movement. This hydraulic equilibrium is essential for subsurface drip irrigation, where matching the emission and absorption characteristics of the soil ensures an effective wetting of the root zone while avoiding undesired losses. As the infiltration capacity is higher than the application rate, the system operates well within the intake limits of the soil, which means that there is no risk of surface runoff and no risk of deep root erosion. Similar findings in the subsurface drip irrigation studies highlight that if the discharge of emissions remains below the soil infiltration limit, water distribution is optimised and irrigation efficiency maximised (Keller and Bliesner, 1990; Lamm and Trooien, 2003). These results therefore confirm that the selected emitter flow rate is hydraulically compatible with the characteristics of the soil and ensures both high application efficiency and minimum water loss in a gravity fed configuration. These findings are consistent with previous assessments of the subsurface drip irrigation which show that low flow emitters (<1 L h^{-}) in coarse-textured soils maintain high infiltration efficiency and prevent percolation below the root zone, if the irrigation duration and frequency are appropriately adapted to the water requirements of the crop (Ajdary et al., 2007). This confirms that the design of hydraulic system is compatible with the soil infiltration characteristics of the site, ensuring efficient interaction between soil and water and high overall irrigation efficiency.

Table 8
Germinate rate of Mungbean.

Treatments	Germination rate	
	Dry season	
	3DAS	5DAS
T1 (25 %)	94	100
T2 (Rainfed)	0	0
T3 (50 %)	95.5	100
T4 (100)	97	100

3.6. Agronomic performance

Table 8 presents the agronomic performance of mungbean during dry season, with emphasis on the germination rate under different irrigation treatments. The first treatment corresponds to 25% of crop evapotranspiration (ETc), the second treatment represents the control, the third treatment applies 50% of ETc, and the fourth treatment corresponds to 100% of ETc (full crop evapotranspiration).

Table 8 confirms that gravity-fed subsurface drip irrigation provides strong and consistent agronomic performance, as reflected by the rapid and uniform mungbean germination under all irrigation regimes. All irrigation regimes showed high germination rates at 3 DAS (94–97%), while at 3 or 5 DAS under rain-fed conditions there was no germination at all. These results provide clear agronomic confirmation of the hydraulic efficiency of the GSDI. The rapid and synchronous emergence is a reflection of the system's ability to maintain a stable and constant humidity regime in the seed environment. This finding underlines the effectiveness of deficit irrigation strategies.

Although observed crop heights, biomass and yields were not directly measured in this study, the observed emergence patterns indicate that GSDI has a strong potential for promoting positive agronomic outcomes, especially in environments characterised by variability in rainfall and limited access to inputs. Uniform and timely emergence of seedlings is strongly correlated with better crop formation, canopy development and stability of yields. Those results can be scaled from plot to field.

The high hydraulic uniformity achieved in this study establishes a stable and hydraulically predictable baseline, which makes the developed gravity-fed subsurface drip irrigation (GSDI) system particularly suitable for integration with IoT- and machine-learning-based decision-support tools, without compromising its low-energy operating characteristics.

3.7. System design application at field scale

Results related to the number of emitters, length of the drip line, volume per block, pressure head and maintenance of gravity drip irrigation are presented under this section.

The Table 9 presents the details related to the upscaled of gravity-fed subsurface drip irrigation at the area of 0.25ha, where the details are provided as below:

3.7.1. System upscaling and field layout

The gravity-fed subsurface drip irrigation system has been increased to a total command area of 2500 m^2 (0.25 ha) with a spacing between

Table 9
Agronomic and layout inputs (FAO-based).

Total Area (m^2)	2500
Crop water requirement (mm/day)	2.3
Crop water requirement (mm/season)	**172.4**
Application efficiency (Ea)	0.95
Daily net irrigation depth (mm/day)	2.42
Lateral spacing S_l (m)	0.3
Emitter spacing Se (m)	0.3
Emitter discharge qe (L/h)	0.09
Number of emittters	27,778
Number of emitters per lateral	333
Total system discharge (m^3/h)	2.5
Wetted area fraction	0.63
Wetted area (m^2)	1575
Daily irrigation volume (m^3/day)	3.62
Daily irrigation volume (m^3/season)	271.69
Irrigation time (h/day)	1.45
Application efficiency (Ea)	0.95
Total lateral length (m)	8333
Total of laterals	83
Number of plants	27,778

the lateral (S) and the emitter (Se) spacing of 0.30 m. This dense spacing is suitable for sandy soils where lateral water movement is limited and frequent watering is necessary to ensure adequate moisture availability in the crop root area. The scaled-up design resulted in a total of 27,778 emitters serving 27,778 plants. This arrangement improves the uniformity of soil moisture and reduces the risk of localized water stress, especially in low pressure gravity-fed conditions.

The daily volume of irrigation required for the system is 3620 litres. The tank used in this study has a capacity of 1 000 litres, which is sufficient to meet only part of the daily demand for irrigation. Therefore, in order to meet the full daily water needs of crops, it would be necessary to use either several tanks or to refill the tank repeatedly during the day. This underlines the importance of appropriate storage tank size in relation to irrigation volume in gravity-fed subsurface drip irrigation systems.

3.7.2. *Hydraulic implications of upscaling*

The selected discharge of 0.09 L h^{-1} reflects the hydraulic constraints inherent in gravity-fed subsurface drip irrigation systems, which usually operate under low pressure heads, usually less than 5 m, which are well suited to this type of conditions, as they reduce pressure requirements and help to limit the loss of deep percolation in soils with a high infiltration rate. However, their use also increases the sensitivity of the system to pressure variations and friction losses, which makes hydraulic control an essential consideration in the construction of the building.

For the irrigated area, the system consists of 83 lateral sections, each approximately 100 m long, resulting in a cumulative lateral length of 8333 m. In order to reduce hydraulic impacts, the system may be subdivided into block sections. Under basic hydraulic principles, friction losses increase with the length of the pipe and the discharge, which generates gradients in pressure along the laterals which, if not properly controlled, may adversely affect the uniformity of the emission discharge. Pressure variations along the line are a critical factor in maintaining uniform emissions in drip irrigation systems. Excessive head losses reduce the flow at the downstream end of the laterals, especially in conditions of low pressure and gravity. These results highlight the need for zoning, control of the lateral length and careful design of hydraulic parameters to ensure consistent water use in gravity-fed sub-surface drip irrigation systems.

3.7.3. *Zoning (Block Irrigation) as a hydraulic control strategy*

The calculated required system flow rate (Qr) of 1.56 m^3 h^{-1} compared to a total system discharge capacity of 2.5 m^3 h^{-1} indicates that, while the source can meet demand, simultaneous operation of the entire field would exacerbate friction losses and pressure non-uniformity along long laterals.

To address this limitation, the system was divided into irrigation blocks (zones), each operating independently. Zoning is a fundamental design principle in drip irrigation systems where water supply, pressure head, or pipe hydraulics limit full-field operation.

Zoning in the upscaled subsurface drip irrigation (SDI) system must be guided by four key hydraulic principles: pressure uniformity, flow matching, friction loss reduction, and operational flexibility.

First, pressure uniformity is a primary design criterion. Each irrigation zone was designed to operate within a narrow pressure range to ensure uniform emitter discharge along laterals. Maintaining limited pressure variation is essential for achieving acceptable application uniformity, particularly in gravity-fed systems where available pressure head is low and highly sensitive to hydraulic losses.

Second, flow matching is applied by aligning the discharge demand of each zone with the available gravity-fed water supply. This approach prevents excessive head losses in the conveyance network and avoids unstable flow conditions that could compromise emitter performance. Flow matching ensures that the system operates within its hydraulic capacity while maintaining reliable water delivery to all emitters within a zone.

Third, friction loss reduction is addressed through zoning by limiting the number of laterals operating simultaneously. Reducing simultaneous flow in the mainline and submains lowers friction losses, thereby preserving pressure at the lateral inlets and improving overall system hydraulic performance. This principle is particularly critical in systems with long pipe networks and small-diameter laterals.

Finally, operational flexibility is enhanced through zoning. The division of the irrigation system into independent zones allows for sequential irrigation and facilitates adjustments in irrigation scheduling without requiring structural modifications to the system. This requires the multi-stage tanks, float valve systems and controlled zoning, which can significantly enhance the uniformity of low-pressure systems (El-Mansy et al., 2024b; J.alsalami et al., 2024). This flexibility is advantageous for accommodating variations in crop water demand, system maintenance activities, and fluctuations in water availability.

The net irrigation depth of 2.42 mm day^{-1} closely matches the crop water requirement (ETc = 2.3 mm day^{-1}), demonstrating effective alignment between crop demand and system supply. The slight increase accounts for application efficiency (Ea = 0.95) and minor system losses. An irrigation time was 1.45 h day^{-1} was found to be sufficient to meet daily crop water requirements. This relatively short duration is operationally advantageous for gravity-fed systems, as it reduces evaporation losses, limits prolonged low-pressure operation, and allows flexibility in daily irrigation scheduling.

3.7.4. *Maintenance Implications of Zoning and Low-Discharge Emitters*

While zoning enhances hydraulic performance in subsurface drip irrigation (SDI) systems, it also has important maintenance implications, particularly when very low discharge emitters are employed. Key maintenance considerations include clogging risk, flushing and filtration requirements, and system longevity.

Clogging risk is a critical concern in systems using emitters with discharge rates as low as 0.09 L h^{-1} . Such emitters are highly susceptible to clogging caused by suspended sediments, biological growth (biofilms), and chemical precipitation of dissolved salts. Zoning enables the isolation of individual sections of the system, allowing targeted inspection, diagnosis, and corrective actions without disrupting the operation of the entire irrigation network.

With respect to flushing and filtration, zoning allows each irrigation block to be flushed independently, thereby improving maintenance efficiency and reducing water losses during cleaning operations. Independent flushing is particularly beneficial in gravity-fed systems, where available pressure is limited and flushing velocities must be carefully managed. Adequate filtration is therefore essential to protect low-flow emitters and maintain system performance.

System longevity is also positively influenced by zoning. Reduced operating pressures and controlled flow rates within individual zones minimize mechanical stress on pipes, fittings, and emitters. This reduction in hydraulic stress decreases the likelihood of material fatigue and leakage, thereby extending the operational lifespan of the irrigation system.

These maintenance considerations are especially relevant in rural and energy-limited environments, where technical support, spare parts, and replacement components may be difficult to access. In such contexts, zoning not only improves hydraulic reliability but also enhances system resilience and long-term sustainability.

3.7.5. *Overall System Performance and Practical Implications*

The upscaled GSDI system demonstrates that gravity-fed subsurface drip irrigation can be effectively implemented at the quarter-hectare scale, provided that hydraulic limitations are addressed through zoning and careful system design. The combination of low emitter discharge, dense spacing, high application efficiency, and block irrigation ensures that crop water requirements are met while minimizing water losses and energy inputs. However, the results also emphasize that hydraulic design and maintenance planning are inseparable in low-pressure subsurface drip irrigation systems. Without appropriate zoning and regular maintenance, long laterals and low-flow emitters could lead to unacceptable levels of non-uniformity and system failure.

The following table focus on the hydraulic calculation of the upscaled results

Table 10 summarises the hydraulic characteristics of a 100 m lateral equipped with 333 emitters spaced at 0.3 m, each delivering 0.09 L/h (2.5×10^{-8} m^3/s). The pipe diameter is 0.016 m, typical for low-discharge subsurface drip irrigation laterals.

The upstream lateral flow is the cumulative discharge of all emitters along the lateral, calculated as 8.33×10^{-6} m^3 /s. This corresponds to a flow velocity of 0.0414 m/s, resulting in a Reynolds number of 662, confirming that the flow is laminar. Accordingly, the friction factor was calculated using ($f = 64$ / Re), yielding 0.0967.

Using the Darcy–Weisbach equation, the total head loss along the 100 m lateral was determined to be approximately 0.0528 m (5.3 cm), with an average head loss per emitter of 0.16 mm. These values are extremely small, indicating that pressure variation along the lateral is negligible, and therefore emitter discharge uniformity is effectively maintained under gravity-fed conditions.

Overall, the analysis confirms that the proposed lateral design is hydraulically feasible, with minimal risk of non-uniform irrigation. The flow regime, friction factor, and head loss values are consistent with theoretical predictions for low-flow, laminar, gravity-fed SDI systems. This validates the design assumptions and supports its implementation for the target agroecological area.

There is a strong potential for integrating machine learning and the Internet of Things (IoT) technologies to these findings. IoT-based soil moisture sensors, pressure sensors and flow meters can generate continuous, high-resolution field data capturing spatial and temporal variations in the dynamics of soil and water, the performance of emitters and the pressure of the system (Eze et al., 2025; Monchusi et al., 2024; Padiya et al., 2023; Singh et al., 2019; Sivakumar et al., 2022). These data sets can then feed ML models that can predict the behaviour of the system under different field configurations, soil types or gradients, allowing data-driven optimisation of emitter spacing, irrigation schedules and water allocation at farm level (Gupta et al., 2023; N. Mohana Priya, 2024). These approaches are increasingly being used to improve micro-irrigation management by improving the prediction of uniformity, the prediction of water needs for crops and the detection of hydraulic anomalies in real time. Therefore, future research should integrate dynamic hydraulic modelling, multi-seasonal field testing and detailed economic evaluations to validate the long-term performance of GSDI systems powered by gravity. A holistic framework combining hydraulic design principles with ML-based decision support and IoT-based monitoring will be crucial to develop a farmer-suitable system (Mahdhi et al., 2019), energy-independent SDI solutions in regions with limited access to energy.

Table 10
Summary of the hydraulic analysis for a full 100 m lateral with 333 emitters GSDI system.

Parameters	Value	Units	Notes
Pipe diameter, (D)	0.016	m	SDI lateral diameter
Pipe length, (L)	100	m	Lateral length
Number of emitters per lateral, (Ne)	333	–	Based on 0.3 m emitter spacing
Flow per emitter, (qe)	2.5×10^{-8}	m^3 / s	0.09 L/h
Upstream lateral flow, ($Q_{upstream}$)	8.33×10^{-6}	m^3 / s	Sum of all emitter flows
Flow velocity, (V)	0.0414	m/s	At upstream end
Reynolds number, (Re)	662	–	Laminar flow
Friction factor, (f)	0.0967	–	Laminar: $f = 64/Re$
Total head loss along lateral, (hf)	0.0528	m	≈ 5.3 cm
Head loss per emitter, ($h_{emitter}$)	0.00016	m	≈ 0.16 mm
Flow regime	Laminar	–	Confirmed Re < 2000
Hydraulic impact	Negligible	–	Emitter uniformity maintained

3.7.6. *Limitations of the hydraulic analysis*

It should be noted that the hydraulic evaluation presented here assumes steady-state flow conditions, uniform emitter discharge, and clean water supply. Temporal variations in discharge due to partial clogging, sediment accumulation, or biological growth were not explicitly modeled. Additionally, head losses associated with fittings, connectors, and emitter insertion points were neglected, as they are expected to be small relative to mainline and submain losses under laminar flow conditions. Future studies could incorporate field-based pressure measurements and long-term performance monitoring to further validate the hydraulic assumptions and assess system behaviour under operational variability.

The following subsequent section provides the preliminary cost estimate for implementing the gravity-fed subsurface drip irrigation upscaled at the surface area of 0.25ha. Table 11 presents a preliminary cost estimate for a 0.25 ha gravity-fed subsurface drip irrigation system. Costs are indicative and reflect local market prices at the time of system design. Labor and maintenance costs are approximate and intended to provide order-of-magnitude estimates rather than detailed life-cycle costing.

Table 11 presents a preliminary financial assessment of a 0.25 ha gravity-fed subsurface drip irrigation system, designed for smallholder farmers in water-limited settings. The system includes driplines with emitters, submains, mainline, storage tank with elevated stand, fittings and valves, labor, and maintenance. The total estimated cost is USD 12,561.812. The dripline with integrated emitters remains the dominant cost component (≈63% of total system cost). This is consistent with gravity-fed subsurface drip irrigation systems designed with dense emitter spacing (0.30 × 0.30 m) and very low emitter discharge (0.09 L h^{-1}), which require a large number of emitters to ensure uniform soil wetting in sandy soils.

Installation labor is also significant due to the careful placement of dripline length, emitter alignment, and positioning of storage tanks at the required elevation to generate sufficient gravity head. Maintenance costs, approximately 10 % of total investment, cover filtration, flushing, and emitter inspection, which are particularly important in low-pressure systems to prevent clogging and maintain long-term emission uniformity.

The costs of laterals, submains, and mainline pipes are relatively modest, reflecting the use of small-diameter (16 mm) polyethylene pipes suitable for low-pressure gravity-fed operation. Their combined contribution (<7% of total cost) confirms that materials costs are driven more by emitter density than by conveyance infrastructure, a pattern commonly reported in micro-irrigation systems.

Table 11
Preliminary cost estimate for a 0.25 ha Gravity-fed subsurface drip irrigation system.

Component	Quantity	Unit Cost (USD)	Total Cost (USD)
Dripline length with emitters of 100 m	83	95	7885
Submains 16 mm 100 m	3	70	210
Mainline 16 mm 100 m	5	70	350
1000 L tank	1	450	450
Elevated stand (1000 L)	1	350	350
Fittings & valves	Lump sum	442.5	442.5
Labor (installation)	Lump sum	2664.522	2664.5
Maintenance (initial/annual)	Lump sum	1256.2022	1256.2
TOTAL			12,561.812

The lump-sum allocation for fittings and valves (USD 442.50) covers essential hydraulic and control components required to ensure proper system operation, zoning, and maintenance. These typically include the components such as control valves for one isolation and sequential irrigation, ball or gate valves for mainline and submain regulation, end caps and flush valves for lateral flushing, tees, elbows, reducers, and connectors for pipes junctions, basic filtration unit (screen or disc filter) appropriate for low-flow emitters, and air release valves.

The aggregated as a lump sum cost represents approximately 3.5% of total system investment. The inclusion of adequate fittings and valves is particularly critical for GSDI, as they enable targeted flushing, pressure control, and isolation of zones, thereby reducing clogging risk and improving long-term reliability.

Installation labor accounts for approximately 21% of total system cost, reflecting the labor-intensive nature of GSDI installation. Activities include trenching or shallow burial of driplines, careful alignment of laterals, installation of the elevated tank stand, and system testing. This proportion aligns with findings from smallholder irrigation projects in Sub-Saharan Africa, where labor often represents 15–30% of total micro-irrigation investment. While the maintenance cost (USD 1256.20, ~10% of total cost) represents initial or annual operation and maintenance (O&M) requirements, including: (i) routine flushing of laterals and submains, (ii) filter cleaning or replacement, (iii) and minor repairs and replacement of clogged emitters or fittings.

When normalized per hectare, the investment corresponds to approximately USD 50,248.088 ha^{-1} , which is higher than surface or sprinkler irrigation but within the range reported for high-density subsurface drip systems. In contrast:

- Surface irrigation systems typically require much lower capital investment but suffer from low application efficiency and high labor demand.
- Sprinkler systems present moderate costs and efficiencies but depend on energy inputs and are sensitive to wind and evaporation losses.
- GSDI, despite higher upfront cost, offers superior water-use efficiency, minimal energy dependence, and improved yield stability, making it attractive in water-scarce and energy-limited environments.

Furthermore, compared to the pitcher applied on acre, it initial cost was estimated 4500 (nearly $48), about 80 % cheaper than drip and sprinkler irrigation in India (Adhikary and Pal, 2020b). The yield per acre is around 60 % higher than with furrow and flood irrigation, which many farmers continue to use. A farmer can save 90 % of water as compared to flood irrigation. Fertilizers can also be mixed along with the water and poured into the pot. Weed growth is very minimal because water delivery is limited to the roots. Many farmers in the coastal districts are following this method. Some authors (Hatungimana et al., 2023) stated that clay pot irrigation can be a viable option for water scarce areas, especially for small-scale farmers searching to enhance their productivity with their small-scale farmers to enhance their productivity.

Although the capital costs of an optimised gravity-fed subsurface drip irrigation system remain high, low-cost IoT technologies offer a way to reduce the effective costs of the system without increasing them significantly. Basic sensor-based tools such as soil moisture sensors, low pressure sensors and simple automatic valves can improve the timing of irrigation, allow early detection of pressure losses or clots, and reduce manual intervention (Meriç 2025; Vandôme et al., 2023a; b). For gravity-fed subsurface drip irrigation systems, the monitoring enabled by the Internet of Things can partially compensate for the lack of uniformity of the emissions by adaptive scheduling and zonal control, thus maintaining acceptable yield at lower design levels in the EU (El-Sheshny et al., 2025; Ferrarezi and Peng, 2021). Studies report 20–50 % savings in maintenance and reduced repair costs due to better fault detection and avoidance of excessive irrigation (Cardenas et al., 2021; Dukes, 2020). If implemented at the level of cooperatives or systems, the marginal costs of deploying the Internet of Things are small compared to the gains in reliability, water productivity and system life. Chigerwe et al. (2004) presented the investment cost as a big barriers to micro-irrigation adoption.

Despite the higher upfront costs compared to surface-drip systems, subsurface drip irrigation offers several structural advantages which are particularly important in energy-limited and climate-sensitive environments. Furthermore, the gravity-fed configuration avoids recurrent energy costs, which is a key advantage in regions where access to energy is limited. When assessed over the life of the system and not just the initial investment, these characteristics partly compensate for higher capital costs, especially in the case of high value crops or collectively managed systems.

Despite the optimisation, direct acceptance of individual smallholder farmers on a hectare scale remains unlikely without financial or institutional support. The feasibility of the adoption is significantly improved if the systems are introduced gradually on small plots (0.1–0.25 ha), managed collectively by groups of farmers or cooperatives, targeting high value or water-sensitive crops, and supported by simplified operating and monitoring tools, including the Internet of Things. From a policy perspective, the findings call into question design paradigms that favour maximum hydraulic power over affordability and robustness. Rather than maximizing emissions uniformity, design standards should emphasise modularity, cost containment, and institutional adequacy. Public investment can increase adoption by subsidizing the initial capital costs, promoting shared infrastructure and cooperative ownership models, and promoting locally adapted designs of SDIs rather than imported commercial systems. Adoption studies consistently show that the marginal gains in technical efficiency in the decision-making of smallholders are outweighed by the simplicity, reduced risks and perceived reliability. Therefore, the alignment of hydraulic design objectives with economic constraints is crucial for the scaling-up of SDI technologies in small-scale agricultural systems.

4. Conclusion

This study evaluated the design and hydraulic performance of a gravity-fed subsurface drip irrigation (SDI) system implemented on predominantly tropical sandy soils in a context where electricity supply is unreliable. Under these conditions, gravity-fed subsurface drip irrigation represents a potentially cost-effective and energy-independent irrigation solution. Despite constraints related to limited storage capacity, low operating pressure, and simplified network configuration, the system achieved high emission uniformity and effective delivery of water to the crop root zone. The integration of soil hydraulic characterisation with measured emitter discharge enabled a reliable prediction of system behaviour and supported informed design decisions. However, it is acknowledged that semi-empirical soil–water models may not fully capture preferential flow paths or transient soil moisture dynamics, particularly in coarse-textured soils. Nevertheless, the results demonstrate that gravity-fed subsurface drip irrigation can substantially improve water-use efficiency, reduce dependence on external energy sources, and enhance resilience to rainfall variability in smallholder farming systems. The present analysis did not consider alternative hydraulic configurations, such as the use of larger-diameter conveyance pipes (e.g., >16 mm), multiple water entry points, variable field slopes, or more complex network layouts. These factors may significantly influence hydraulic performance and system cost, and therefore require further site-specific hydraulic and economic evaluation prior to large-scale deployment. Although gravity-fed subsurface drip irrigation offers clear technical and promising agronomic advantages over other low-technology irrigation options, the relatively high initial investment remains a significant barrier for smallholder farmers. In this context, two complementary pathways merit further consideration: (i) promoting cooperative or collective investment models to reduce individual financial burden, and (ii) systematically evaluating the efficiency and cost-effectiveness of alternative low-pressure irrigation methods under comparable conditions. Future research should also incorporate socio-economic assessments, including structured questionnaires, to capture farmer perceptions, acceptance, and practical constraints, thereby supporting more inclusive and scalable irrigation development strategies. In addition, field measurements should be conducted to develop empirical, semi-empirical, or physically based models for simulating wetting patterns in this agroecological region. Wider adoption would benefit from increased storage capacity or modular storage solutions to enhance available hydraulic head, as well as farmer training and simplified maintenance guidelines to ensure long-term system functionality.

CRediT authorship contribution statement

Eric Kakanda Tshitende: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Pierre M. Kabuya:** Writing – review & editing, Project administration. **Paul Malumba:** Writing – review & editing, Project administration, Funding acquisition. **Joost Wellens:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the author(s) used the ChatGPT, a generative artificial intelligence tool, to correct the spelling. The use of artificial intelligence-assisted techniques was limited to language refinement and did not affect the scientific content, interpretation of data or conclusions of the study.

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 manuscript. The research was financially supported by the Académie de Recherche et d'Enseignement Supérieur (ARES) et le Partenariat Pour le développement du Congo.

Acknowledgment

We thank the Academie de Recherche et d'Enseignement Supérieur (ARES) and the Partenariat pour le développement du Congo for their Financial support.

Data availability

Data will be made available on request.

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