Scientific Note

Low-cost weighing lysimeter: development, calibration, and evaluation[1]

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ABSTRACT

Weighing lysimeters, which directly measure mass variations in the soil-plant system, provide high precision, but are typically costly, limiting their large-scale use. As an affordable alternative, six low-cost weighing lysimeters were developed, calibrated, and evaluated. The devices were built with low-cost materials and a modular design, integrating load cells with an Arduino microcontroller platform (ATmega 2560). The calibration with reference masses demonstrated excellent linearity, with determination coefficients (R^2) ranging from 0.9890 to 0.9987, confirming a high measurement accuracy. The error parameters were also rigorously assessed, including hysteresis (up to 6.33 % of the full scale - FS), non-linearity (up to 10.92 % of the FS), and repeatability (up to 14.57 % of the FS). Despite the calibration consistency, the analysis of these errors and the maximum absolute error (up to 10.77 % of the FS) revealed limitations in achieving the precision required for highly sensitive scientific applications.

KEYWORDS: Arduino platform, efficient irrigation, water management.

RESUMO

Lisímetro de pesagem de baixo custo: desenvolvimento, calibração e avaliação

Lisímetros de pesagem, que medem diretamente as variações de massa no sistema solo-planta, fornecem alta precisão, mas, geralmente, apresentam custo elevado, o que limita seu uso em larga escala. Como uma alternativa acessível, foram desenvolvidos, calibrados e avaliados seis lisímetros de pesagem de baixo custo. Os dispositivos foram construídos com materiais de baixo custo e um design modular, integrando células de carga a uma plataforma microcontroladora Arduino (ATmega 2560). A calibração com massas de referência demonstrou excelente linearidade, com coeficientes de determinação (R^2) variando de 0,9890 a 0,9987, confirmando alta precisão nas medições. Parâmetros de erro também foram rigorosamente avaliados, incluindo histerese (até 6,33 % do fundo de escala - FE), não linearidade (até 10,92 % do FE) e repetibilidade (até 14,57 % do FE). Apesar da consistência da calibração, a análise desses erros e do erro absoluto máximo (até 10,77 % do FE) revelou limitações na obtenção da precisão necessária para aplicações científicas altamente sensíveis.

PALAVRAS-CHAVE: Plataforma Arduino, irrigação eficiente, manejo de água.

The accurate evapotranspiration determination is fundamental to optimizing the water use in agricultural systems (Allen et al. 1998, Pereira et al. 2015). In this regard, lysimeters represent essential tools for quantifying the crop water demand and enabling a precise irrigation management. Among the various types, weighing lysimeters stand out for directly measuring changes in the mass of the soil-plant-atmosphere system, providing a high degree of accuracy (Fisher 2012). These instruments are particularly valuable for detailed monitoring of the soil water balance and for studying water and solute transport in unsaturated soils (Sołtysiak & Rakoczy 2019).

Despite their proven accuracy, traditional weighing lysimeters are expensive and complex to construct, limiting their large-scale use in contexts with financial constraints or limited technological

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access. The requirement for reliable data acquisition systems further increases both complexity and cost, affecting measurement precision (Bello & Van Rensburg 2017). Consequently, there remains a significant gap in the availability of affordable solutions, hindering the widespread adoption of precise water monitoring technologies in agriculture.

In this regard, microlysimeters have emerged as a promising and cost-effective alternative for measuring evapotranspiration. Their smaller dimensions and simplified weighing mechanisms make them practical, economical, and easily replicable, facilitating the integration into diverse agricultural systems while promoting efficient water management and the conservation of natural resources.

From this perspective, this study aimed to develop and evaluate a low-cost lysimetric system capable of providing accurate and reliable evapotranspiration measurements, with the goal of optimizing water use and reducing the production cost of monitoring equipment.

The study was conducted in two main stages, in the year 2023. The first involved designing the prototype in a virtual environment and constructing it at the Instituto Federal do Triângulo Mineiro (Paracatu, Minas Gerais state, Brazil). The second comprised laboratory calibration and performance testing at the Universidade Federal dos Vales do Jequitinhonha e Mucuri (Unaí, Minas Gerais state, Brazil).

Six weighing microlysimeter units were developed, each consisting of a cubic structure made of 6 mm medium density fiberboard (MDF). The parts were laser-cut from a CAD-generated vector file and assembled using a press-fit technique with instant adhesive. The structure was designed to accommodate 8-dm³ plastic pots and to ensure the stability of a centrally positioned 20 kg beam-type load cell at the base.

Support and finishing components were printed in polylactic acid (PLA) using a 3D printer. Structural and electronic parts were secured with screws, spacers, and custom-printed mounts. Positioning locks and wiring guides were incorporated to maintain internal organization and system integrity. Details of the construction process are presented in Figure 1.

Each microlysimeter consisted of a cylindrical plastic pot with a total volume of 8 dm³, 21 cm in height, 24.5 cm in upper diameter, and 19 cm in base diameter, resulting in an evaporative surface area of approximately 0.047 m². The pots were filled with

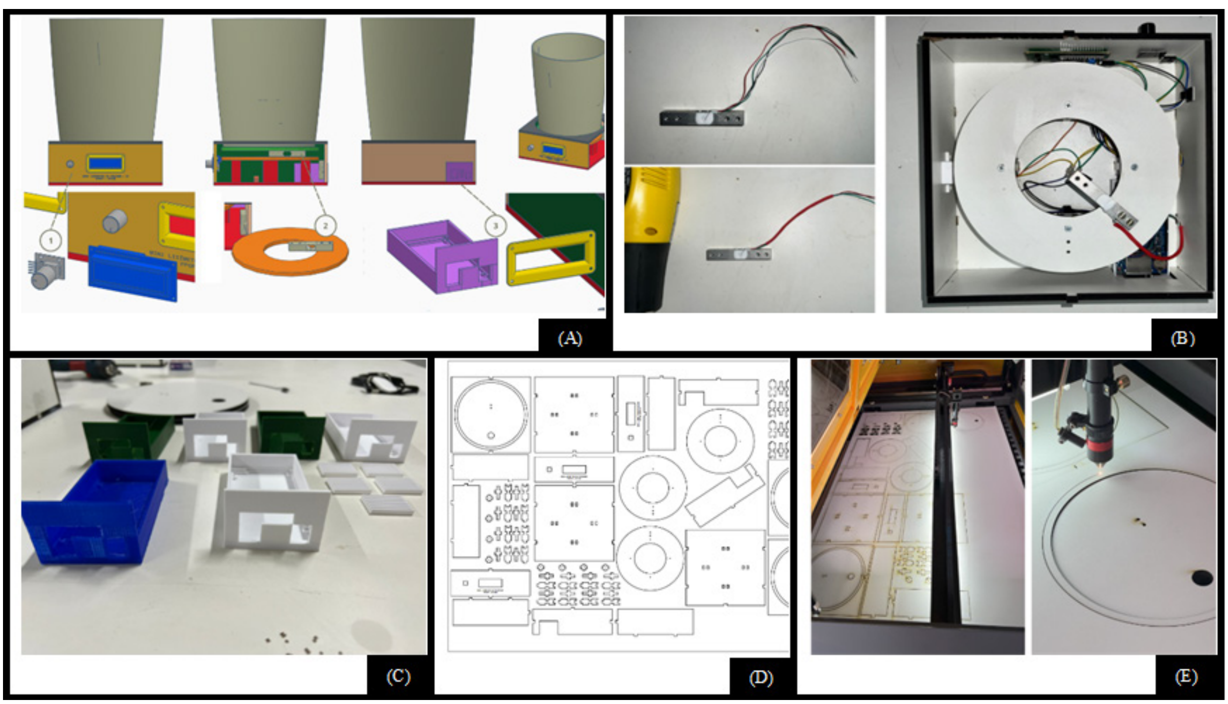

Figure 1. Lysimeter design and construction. A) General structure view; B) base cut with load cell; C) organized 3D-printed polylactic acid (PLA) parts; D) medium density fiberboard (MDF) cutting layout; E) laser cutting.

air-dried soil (sieved to < 2 mm), representing fine earth under laboratory conditions, with an apparent bulk density of 1.23 g cm^{-3} and a gravimetric water content of 3.2 % at calibration. It is important to note that the equipment was not tested under field conditions; all experiments were conducted under controlled laboratory conditions as a preliminary step for future lysimetric applications.

Data acquisition was managed by an Arduino Mega 2,560 microcontroller connected to a 16 × 2 LCD display via I²C, a rotary encoder for menu navigation, a real-time clock module with SD card storage (HW-169), and a temperature and humidity sensor (DHT11) (Figures 2A and 2B).

The load cell was integrated with the HX711 module (Figure 2C), widely used in weighing applications due to its high accuracy, low cost, and compatibility with prototyping platforms such as Arduino. The module amplifies the analog signal and enables digital communication with the microcontroller. All connections were organized using buses, a protoboard, and jumper terminals.

The system operates through an interactive menu displayed on the LCD screen. Available functions include scale calibration, acquisition interval configuration, datalogger initialization, stability testing, and real-time display of mass, temperature, and humidity (Figure 3). Navigation is performed by rotating or pressing the encoder, with feedback displayed on the LCD.

The calibration of each unit was performed using standard dry sand weights (250-1,000 g) contained in plastic bags. Reference masses were measured with an analytical scale (0.01 g accuracy), and readings from the HX711 module were correlated by linear regression. The calibration constant (CalFactor) was stored in the microcontroller's memory and recorded in a text file (*CALIB.txt*) on the SD card for traceability (Figure 4).

To ensure the metrological consistency of the calibration process, error parameters - hysteresis, non-linearity, and repeatability - were determined following standard static calibration procedures described by Wheeler & Ganji (2009) and Vilela et al. (2015). Hysteresis was defined as the maximum deviation between loading and unloading cycles for the same reference mass; non-linearity as the maximum deviation from the ideal calibration line;

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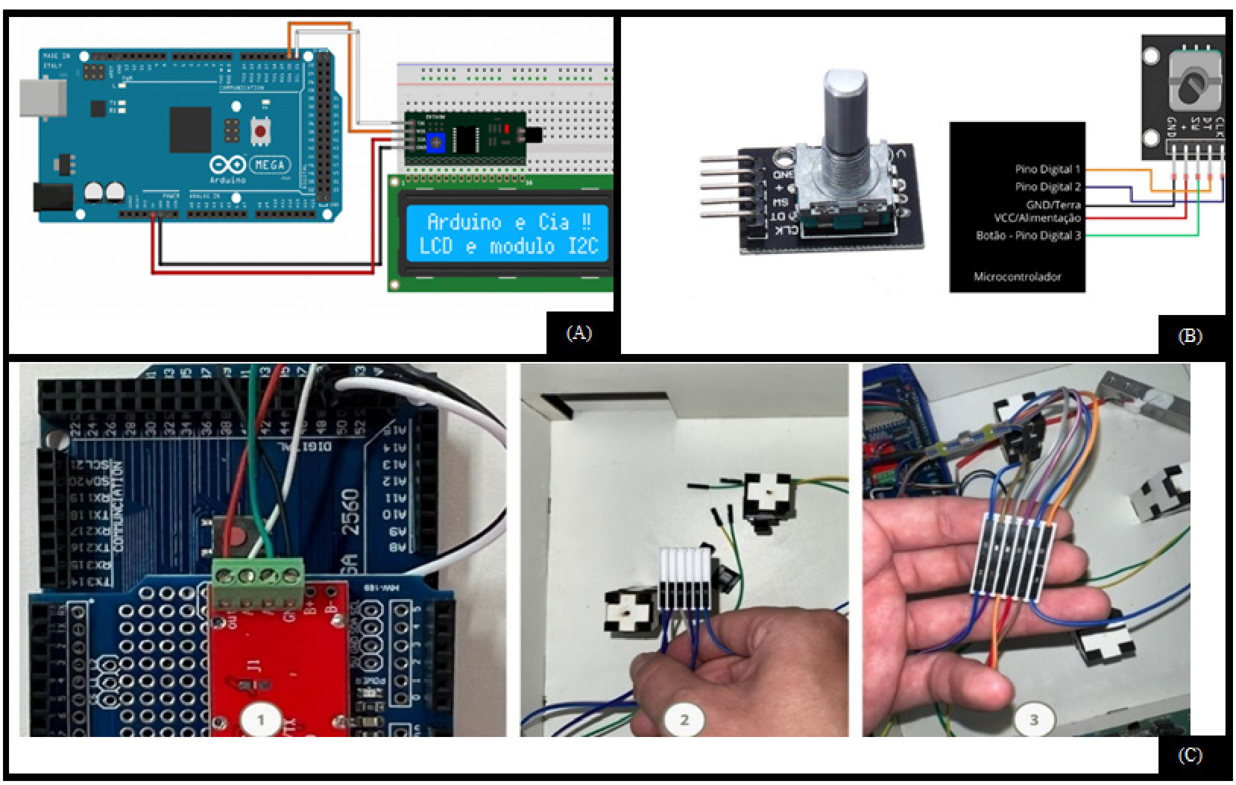

Figure 2. Embedded electronic architecture. A) Microcontroller; B) potentiometer; C) sensors and peripheral modules.

and repeatability as the highest deviation among repeated measurements under identical conditions. These parameters were calculated for all lysimeter units and expressed both in absolute terms (kg) and as a percentage of full scale (%FS).

Operational stability was assessed through a static load test using an 8 kg mass maintained for 30 min in a controlled environment (Figure 5A). During this period, continuous readings of mass, temperature, and humidity were recorded at 2-second intervals. The data were stored in the *ESTAB.txt* file and analyzed to quantify signal variability (Figure 5B).

System validation was performed by comparing lysimeter readings with known reference masses (100-1,000 g) distributed in sandbags placed on the pots. Accuracy was evaluated by linear regression between the actual mass and the values recorded by the HX711 module, using the coefficient of determination (R^2) and mean absolute error as performance indicators.

Calibration tests were conducted on the six low-cost weighing lysimeters to establish the linear relationship between the applied reference masses (kg) and the raw digital signals from

Figure 3. Interface and operation - navigation menu, functions, and variable readings.

Figure 4. System calibration - standard weights, HX711 readings, and LCD records.

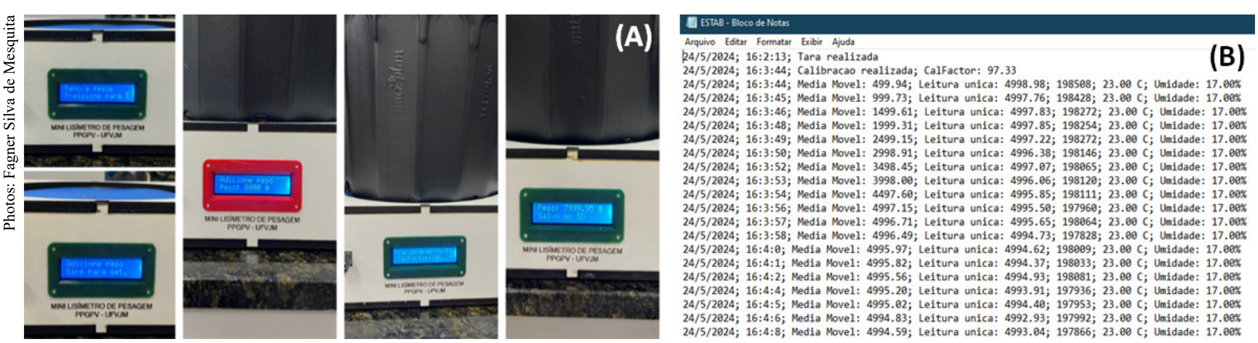

Figure 5. Stability test - continuous reading and sampling of the mass signal.

the HX711 amplifier. Linear regression analysis demonstrated an excellent linearity and a strong positive correlation in all lysimeter units. The coefficients of determination (R^2), slope and intercept values, as well as hysteresis, non-linearity, and repeatability parameters obtained in the initial calibration, are summarized in Table 1.

The coefficients of determination for the six lysimeter units ranged from 0.9890 to 0.9987 and were statistically significant ($p \leq 0.05$). These results demonstrated a high accuracy and reproducibility in the relationship between mass and sensor output, consistent with findings from previous studies reporting high R^2 values in weighing lysimeter calibrations. For example, Mariano et al. (2015) observed R^2 values above 0.9999, whereas Sanches et al. (2017) obtained an R^2 of 1 in four lysimeters.

However, as noted by Vilela et al. (2015) and Wheeler & Ganji (2009), R^2 alone does not fully represent the accuracy of a measurement system. Systematic errors - such as hysteresis and non-linearity - as well as random variability (repeatability), are fundamental to the total measurement uncertainty. The maximum deviations and relative uncertainties of each error component from the first calibration test are detailed in Table 2.

The maximum absolute error ranged from 0.51 kg (3.90 %) in the unit L02 to 1.42 kg (10.77 %) in L06. Although these represent the worst-case scenarios, they indicate systematic errors that may affect mass measurement accuracy. The relative measurement uncertainty (U) varied considerably, from 1.50 % (L03) to 10.37 % (L02).

Additionally, the functional validation of the system was carried out by comparing the actual reference masses with the values recorded by each lysimeter unit (Figure 6). This validation confirmed

Photos: Fagner Silva de Mesquita

Figure 6. Functional validation - comparison between actual mass and estimated readings.

Table 1. Calibration parameters and metrological performance (first test) of the low-cost weighing lysimeter units.

LU	SC	IC	R²	HS	NL	RE
L01	0.1879	0.6315	0.9900	4.99	9.30	8.41
L02	0.1776	0.4467	0.9987	4.77	4.14	7.65
L03	0.2280	1.2351	0.9972	2.40	6.11	5.25
L04	0.1954	-1.2564	0.9945	6.33	7.35	7.18
L05	0.2057	0.8068	0.9919	3.65	9.72	2.77
L06	0.2078	-0.5737	0.9890	4.00	10.61	4.12

LU: lysimeter unit; SC: slope coefficient (signal kg^{-1}); IC: intercept coefficient (signal); R^2: coefficient of determination; HS: hysteresis (% of the full scale - FS); NL: non-linearity (%FS); RE: repeatability (standard deviation; g).

Table 2. Summary of errors in the calibration process 1 (absolute values in kg and percentages relative to full scale).

Characteristic	L01 (kg/%)	L02 (kg/%)	L03 (kg/%)	L04 (kg/%)	L05 (kg/%)	L06 (kg/%)
MAE	1.25/9.50	0.51/3.90	0.82/6.24	0.94/7.12	1.30/9.88	1.42/10.77
HS	0.66/4.99	0.63/4.77	0.32/2.40	0.84/6.33	0.48/3.65	0.53/4.00
MU	-/5.61	-/10.37	-/1.50	-/2.35	-/2.38	-/3.72
RE	1.11/8.41	1.01/7.65	0.69/5.25	0.95/7.18	0.37/2.77	0.54/4.12
NL	1.23/9.30	0.55/4.14	0.81/6.11	0.97/7.35	1.28/9.72	1.40/10.61
RT	0.84/6.37	1.92/14.57	0.69/5.25	1.53/11.56	1.18/8.91	0.51/3.90
NN	1.28/9.69	0.66/5.02	0.84/6.37	0.91/6.90	1.32/10.03	1.44/10.92

MAE: maximum absolute error; HS: hysteresis; MU: measurement uncertainty; RE: repeatability (load); NL: non-linearity (load); RT: repeatability (unload); NN: non-linearity (unload).

the operational integrity of the system under practical load conditions and complemented the calibration and stability tests.

Hysteresis, caused by mechanical friction and structural deformation, ranged from 0.32 kg (2.40 %) in L03 to 0.84 kg (6.33 %) in L04. Mariano et al. (2015) and Bello & Van Rensburg (2017) reported minimal hysteresis values, indicative of high precision, whereas Vilela et al. (2015) found a value of 0.02 kg (0.057 %), significantly lower than those obtained in the present study. This difference underscores the disparity in accuracy and robustness between low-cost systems and more advanced solutions. It is important to emphasize that the hysteresis observed here is associated solely with the mechanical and electrical response of the load cell, as the air-dried soil substrate did not exhibit hydraulic hysteresis.

Repeatability errors ranged from 0.37 kg (2.77 %) to 1.92 kg (14.57 %) between loading and unloading cycles, indicating that random fluctuations contributed to overall measurement uncertainty. Non-linearity errors varied between 0.55 kg (4.14 %) and 1.44 kg (10.92 %), suggesting deviations from the ideal linear response expected for the load cell. The regression graphs (Figure 7) revealed a more pronounced dispersion at higher load ranges, displaying a heteroscedastic pattern. These deviations are primarily attributed to sensor saturation and minor calibration inconsistencies, which can reduce measurement accuracy near the upper limit of the cell's nominal capacity (Azadeh et al. 2018, Moosavi & Ghassabian 2018, Stano et al. 2020, Richiedei 2022).

To investigate and mitigate these distortions, a second calibration test was conducted, focusing on weight ranges not previously covered and within the load cell's capacity limit. Sand was placed directly in the pot to optimize the usable volume, and five repetitions were performed for each load point. The results, covering masses from 0 to 20 kg, are shown in Figure 8.

The second test confirmed a strong linear correlation, with R^2 values ranging from 0.9861 to 0.9954 (average = 0.9901). Although slightly lower than the first calibration (average = 0.9936), the error analysis (Table 4) revealed a significant reduction in maximum absolute error percentages, with decreases of up to 47.0 % and an overall average reduction of 4.75 %.

Hysteresis percentages ranged from 1.95 % (L02) to 4.77 % (L03), with a 28.5 % reduction in the unit L04, when compared to the first test. Similarly,

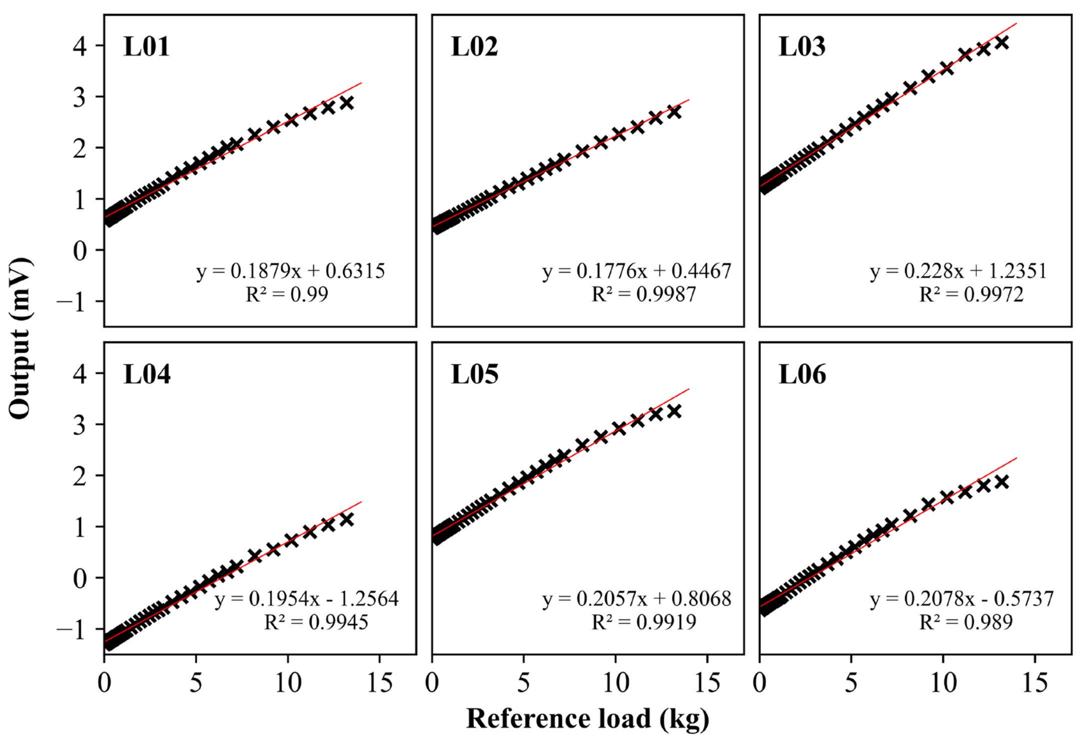

Figure 7. Calibration curves of the developed lysimeter units.

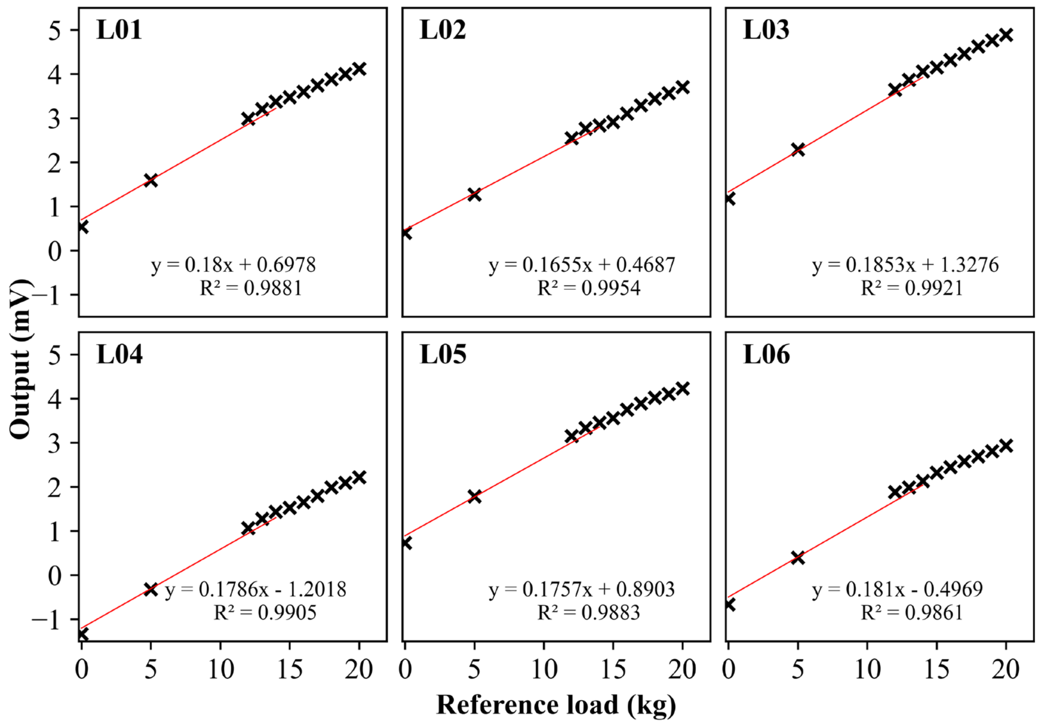

Figure 8. Calibration curves of the lysimeters in the test with reference values from 0 to 20 kg.

Table 4. Summary of errors in calibration process 2 (absolute values in kg and percentages relative to full scale).

Characteristic	L01 (kg/%)	L02 (kg/%)	L03 (kg/%)	L04 (kg/%)	L05 (kg/%)	L06 (kg/%)
MAE	1.00/4.98	0.86/4.30	0.81/4.07	0.87/4.35	1.02/5.08	1.14/5.71
HS	0.54/2.69	0.93/1.95	0.95/4.77	0.79/3.97	0.42/2.09	0.79/3.94
MU	-/0.69	-/0.98	-/0.84	-/0.97	-/1.14	-/0.86
RE	1.26/6.28	0.77/3.85	1.12/5.62	0.90/4.52	3.39/16.95	1.10/5.50
NL	0.98/4.89	0.73/3.65	0.82/4.09	0.84/4.22	1.01/5.05	1.06/5.32
RT	0.85/4.25	1.20/6.02	1.14/5.70	1.50/7.50	3.39/16.95	1.36/6.79
NN	1.14/5.71	0.99/4.95	1.02/5.11	1.27/6.34	1.02/5.11	1.48/7.39

MAE: maximum absolute error; HS: hysteresis; MU: measurement uncertainty; RE: repeatability (load); NL: non-linearity (load); RT: repeatability (unload); NN: non-linearity (unload).

maximum non-linearity decreased by 50.2 % in the unit L06.

The improvement observed in the second calibration test can be attributed to both mechanical and procedural factors. First, the calibration range was extended to the upper limit of the load cell's nominal capacity, reducing extrapolation effects and improving regression linearity. Second, the direct addition of sand into the pot eliminated internal voids, resulting in more uniform load distribution and minimizing deformation and friction in the sensor assembly. Third, the increased number of repetitions per load point enhanced statistical robustness and reduced random variability. Collectively, these adjustments contributed to lower hysteresis and non-linearity values and to a more consistent calibration response across all lysimeter units.

Most units exhibited a stable performance throughout the test. Mean deviations from the reference value ranged from 0.26 g (L01) to 4.69 g (L04). Although the unit L04 showed the highest mean deviation, its standard deviation was relatively low (25.49 g, or 0.5 % of the mean), suggesting that the initial discrepancy likely resulted from a transient mechanical disturbance at the start of the test.

The operational stability of the devices was assessed by subjecting six units to a constant static load of 5 kg for at least 90 hours, simulating field conditions under a steady mass. This procedure allowed isolating system-induced variations from actual changes in load. The histogram in Figure 9 presents the distribution of measured values relative to the reference mass (5,000 g), whereas the time series in Figure 10 shows stabilization after the initial fluctuation.

The stability test, combined with uncertainty analysis, demonstrated that the devices produce consistent measurements and have potential for practical use under constant load conditions. However, the maximum absolute error values and uncertainties observed during calibration indicate significant limitations in overall accuracy. For highly sensitive applications - such as determining crop evapotranspiration, where minute mass changes (on the order of a few grams, equivalent to 0.1 mm of water layer) are critical - these uncertainties may considerably compromise result reliability.

In practical terms, converting the maximum observed mass deviation (~1.0 kg) into an equivalent water depth using the pot surface area (0.008 m²), according to the equation ET = Δm/A, where ET is the evapotranspiration, Δm the mass variation, and A the area, yields an estimated uncertainty of approximately 125 mm month^{-1}. This magnitude

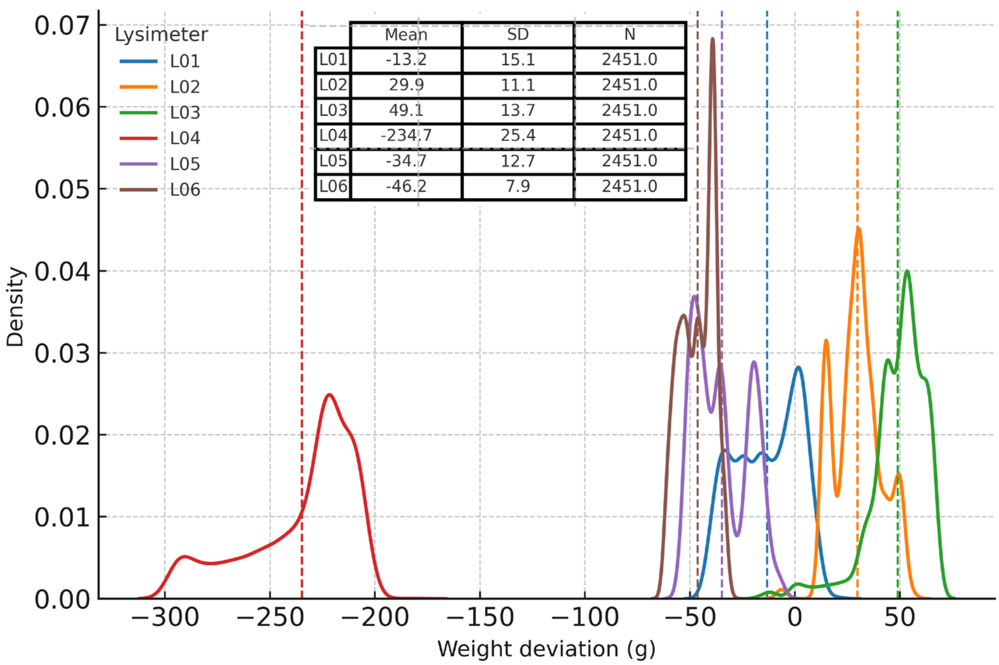

Figure 9. Distribution of values relative to the reference value.

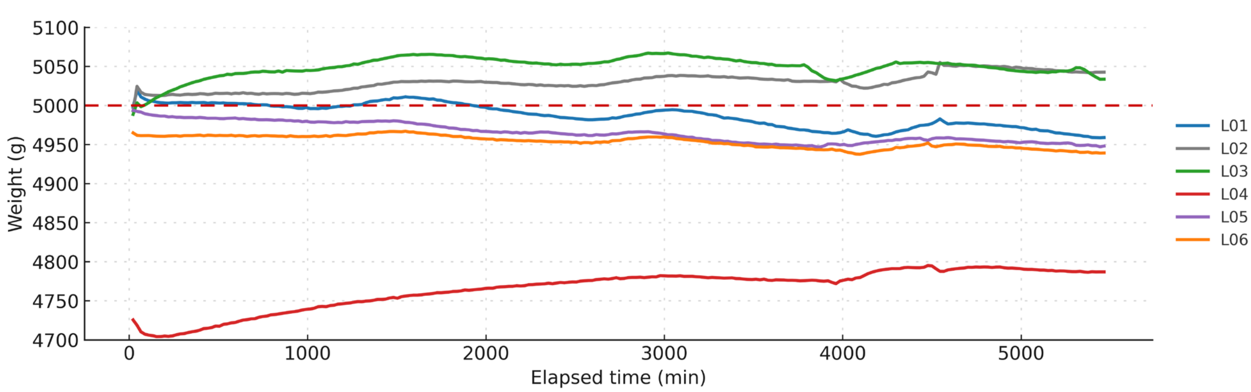

Figure 10. Weight over elapsed time.

equals or exceeds typical monthly evapotranspiration values in tropical climates (80-150 mm month^{-1}), meaning that such cumulative error could obscure the actual evapotranspiration dynamics over long integration periods. Nevertheless, the device remains suitable for short-term (daily or hourly) measurements, for which the proportional error is substantially lower.

Although load cells are expected to exhibit linear responses and low variability for high accuracy (Wheeler & Ganji 2009), this study deliberately employed low-cost sensors in equipment requiring high precision for the intended application. The reduced cost of components inherently limits material quality and sensor robustness, resulting in higher variability and susceptibility to systematic errors. These constraints may necessitate compensation adjustments and more frequent calibrations to maintain an acceptable field performance.

In conclusion, while the device demonstrates a consistent operation under constant load and reliable data collection, its current accuracy does not yet meet the requirements of more demanding applications, such as evapotranspiration estimation in scientific research. To enhance accuracy without compromising cost efficiency, project modifications or advanced signal-processing techniques should be considered.

The non-linear behavior and hysteresis observed during calibration indicate that conventional linear regressions may inadequately represent sensor response. Several strategies have been proposed in the literature to mitigate measurement uncertainty. Non-linear regression models, such as polynomial (Moosavi & Ghassabian 2018) and Bouc-Wen (Rakotondrabe 2010), better accommodate systematic error-induced variations and capture the non-linear relationship between load and sensor response. When integrated with adaptive filtering techniques, such as the Kalman filter (Halimic & Balachandran 1995), these methods enable a dynamic estimation and correction of hysteresis and noise effects. Moreover, machine learning approaches - particularly neural networks - have been successfully applied to load-cell calibration, yielding notable improvements in precision and robustness (Céspedes 2002).

Despite their proven effectiveness, such computational approaches require additional processing capacity and technical expertise. Therefore, their implementation should be carefully evaluated in light of the low-cost nature of the proposed system, whose affordability remains as one of its principal advantages over conventional lysimeters. To illustrate the economic feasibility of the design, Table 5 presents the costs associated with constructing a single microlysimeter unit.

The total cost estimated in this study (US$ 60.10 per unit) is substantially lower than those reported for other lysimeter and weighing-system projects in the literature. Carvalho et al. (2024), for instance, reported a total cost of US$ 81.82 for a system of comparable scale and materials, whereas Capri et al. (2021) reported US$ 210.64. In contrast, high-performance weighing lysimeters may range from US$ 6,440.00 (Flumignan 2011) to US$ 21,171.00 (Bello & Van Rensburg 2017) per unit. This cost analysis reinforces the affordability and economic feasibility of the proposed design.

Although software-based strategies to mitigate hysteresis and other sources of uncertainty are viable, the most direct and effective improvement involves replacing the current load cells with higher-precision equipment, preferably from certified manufacturers, and increasing calibration frequency. While such sensors are more expensive, the total lysimeter cost would still align with the low-cost proposal, especially when compared with commercial evaporation tanks or other high-precision water-monitoring devices. Investing in higher-quality sensors is therefore justified by the need for greater accuracy in evapotranspiration research.

Uncertainty can also be reduced by increasing the number of sensors per lysimeter, depending on container volume, to improve load distribution and provide measurement redundancy. This enhancement can be readily implemented by grouping load cells or using the second channel of the HX711 amplifier,

Table 5. Production cost of the microlysimeter (per unit).

Equipment	Price (US$)
Arduino Mega	21.78
HX711 Amplifier	4.52
LCD with I²C	5.15
SW-169 Module	7.24
Rotary Encoder	1.98
Load Cell	7.79
9V DC Power Supply	4.54
MDF Structure	4.38
Miscellaneous	2.72
Total	60.10

without introducing significant complexity or cost increases.

The integration of these strategies - software optimization, sensor replacement, and/or multiple-sensor configurations - offers a robust solution to the main challenges identified. Systematically combining these approaches could yield more reliable results in the short term while establishing a flexible and adaptable platform for future applications in irrigation research and management.

The combination of low-cost design principles with technological innovation highlights the feasibility of developing accessible lysimeters as economically viable alternatives to high-cost systems. This outcome underscores the potential of open-source technologies, such as Arduino, to democratize water-monitoring tools and foster more sustainable and informed irrigation practices.

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