

A Review on the Installation and Applications of Various Types of Lysimeter in Agricultural Water Management

O. P. Bhoje¹, V. K. Ingle², U. M. Khodke³, H. W. Awari⁴ and S. B. Jadhav⁵

Dept. of Irrigation and Drainage Engineering, CAET,

Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani - 431 402 (India)

(Received : 10.08.2024 Accepted : 04.12.2024)

Abstract

Crop water use is closely linked to soil water and rooting patterns. To investigate these relationships, a unique lysimeter was designed and constructed, allowing for simultaneous measurement of root density, soil water content, and whole-profile evapotranspiration. The lysimeter facilitates the evaluation of interrelationships within an undisturbed soil profile, including rooting depth and density, soil water content, plant water uptake, and evaporative demand. Lysimeter installation involves selecting a well-drained site with similar soil and conditions to the surrounding environment. A pit is excavated to place the lysimeter container, which may be made of steel, PVC, or concrete. Weighing lysimeters are installed on load cells or platforms for real-time water mass measurement, while non-weighing lysimeters have simpler setups. A drainage system with gravel and pipes collects percolating water. Additional sensors (e.g., soil moisture and temperature) are installed for monitoring. After backfilling the pit, the system is calibrated by adding water or test weights to ensure accurate readings. Once installed, the lysimeter measures evapotranspiration, soil moisture, and water movement for hydrological research and irrigation planning. A lysimeter functions by measuring actual evapotranspiration from plants, accounting for precipitation input and water loss through the soil. While lysimeter can be expensive for tree studies and may not always accurately reflect conditions outside a laboratory setting, they are highly effective for simulating field conditions in farm crops. This makes them valuable for calculating water balances and optimizing irrigation practices in agricultural settings.

Key words : Weighing Lysimeter, Non-Weighing lysimeters, installation, drainage, soil moisture, temperature.

The term "lysimeter" comes from Greek words: "lysis," meaning dissolution or movement, and "metron," meaning to measure (Aboukhaled *et al.*, 1982). A lysimeter is a tool used to measure the movement of water in the soil, typically taking the form of a container embedded in the soil to isolate a specific soil volume for observation and analysis. To create lysimeters, researchers have employed steel cylinders pressed over exposed soil columns (Brown *et al.*, 1985; Maeshkat *et al.*, 1999).

The first lysimeter study for water use was reported by De la Hire of France in the late 17th century (Kohnke *et al.*, 1940). Since then, lysimeter designs have been adapted and

duplicated for various research interests, and no single design is considered the standard. An optimal design is achieved by understanding the specific purpose of the experiment, as well as the geologic and climatic conditions (Kohnke *et al.*, 1940). This study focuses on the development, calibration, and testing of low-cost small lysimeters designed to measure evaporation and transpiration of barley in a glasshouse over three consecutive winter seasons (2011-2013).

A lysimeter is an essential instrument in environmental and agricultural research used to measure various aspects of water movement in soils, including evapotranspiration, percolation, and drainage. By isolating a soil monolith or a plant-soil system, lysimeters can accurately

1. M. Tech Student, 2. and 5. Assistant Professor, 3. Associate Dean and Principal and 4. Head.

capture and quantify water loss and gain, providing valuable data for understanding soil-water relationships and crop water requirements. Historically, lysimeters have evolved from simple collection devices to sophisticated systems incorporating advanced technologies such as weighing mechanisms and automated data logging. For instance, modern weighing lysimeters use load cells and microcontrollers to provide precise measurements of water loss through evaporation and plant transpiration, enhancing our ability to manage irrigation and study hydrological processes in diverse environments (Andales *et al.*, 2018; da Silva *et al.*, 2016). Despite their advanced design, lysimeters must be carefully calibrated and installed to ensure accurate and reliable data, as demonstrated in various studies across different conditions and applications (Black *et al.*, 1968; Mertens *et al.*, 2005).

1.1 Types of Lysimeter :

There are two major types of lysimeters:

- a) Weighing Lysimeters
- b) Non-Weighing Lysimeters

a) Weighing Lysimeters : Weighing lysimeters, which come in various shapes and sizes, are well-established tools for measuring soil water balance components such as evaporation, transpiration, and drainage. These devices have been used extensively for evapotranspiration research in the United States and other countries. Lysimeter designs have varied widely due to differences in study areas, research objectives, and ongoing improvements and refinements (Howell *et al.*, 1985). The use of lysimeters is a proven method for measuring the movement of water and chemicals through the soil profile (Nathan *et al.*, 2002).

Field measurements of crop water use typically account for both plant transpiration and

soil evaporation. Transpiration, a vital function of plant life, refers to the loss of water from plants, while soil evaporation pertains to the water lost directly from the soil to the atmosphere (Klocke *et al.*, 1985). Effective monitoring, use, and management of limited water resources can help address issues related to water wastage, food shortages, and poor crop yields. Lysimeters are considered the most reliable research tool for the direct evaluation of evapotranspiration (Burman and Pochop, 1994).

b) Non-Weighing or Drainage

Lysimeters : Non-weighing lysimeters are used to study soil water movement and plant water uptake without measuring the weight of the lysimeter itself. Instead of relying on weight to determine water loss, these lysimeters use alternative methods to estimate water balance and are commonly employed in agricultural and hydrological research (Reeder, *et al.* 1996). In non-weighing lysimeters, changes in water balance are typically measured volumetrically on a daily or weekly basis, though accurate daily estimates may not always be possible. Irrigation water is applied to the lysimeter, which includes a layer of pebbles at the bottom to facilitate drainage. Excess water is collected from below through a suitable collection system. Crops can be grown in a concentric pattern around a central drainage chamber. (Thompson, *et al.* 1991).

A simple and cost-effective non-weighing lysimeter can be constructed from a petrol drum. It includes a small-diameter tube that extends through the soil to the layer of pebbles, allowing for frequent removal of excess water. This study aimed to design and build a drainage lysimeter and use it to estimate the crop evapotranspiration of African Spinach in Nsukka (Onwuka C. A., *et al.* 2014).

2. REVIEW

2.1 Comparative Analysis of Lysimeter

Designs : Lysimeters are essential tools for studying water dynamics, evapotranspiration, and soil interactions. The designs of lysimeters vary widely depending on specific research objectives and environmental contexts. For instance, Payero and Irmak (2008) and Vellame *et al.* (2013) detail similar precision weighing lysimeters in Bahia, Brazil, tailored for tobacco production, measuring 1.60 m by 1.10 m with a soil surface area of 1.76 m². These systems utilize four 1,000 kg load cells for accurate measurements. In California, Phene *et al.* (1985) created larger lysimeters with a 4 m² surface area and a depth of 2 m, incorporating neutron tubes and heat flux plates to achieve an impressive evaporation sensitivity of 0.02 mm. Yang *et al.* (2000) further emphasizes the utility of large lysimeters in China for simulating groundwater interactions, showcasing a design with a 3.14 m² surface area and a depth of 5m.

2.2 Design Diversity and Specific

Applications : The diversity in lysimeter design is evident in the work of researchers like M.J. *et al.* (2002) and Shukla (2006), who developed large lysimeters for studying agricultural water use in Iran and Florida, respectively. These systems feature load cells and monitoring capabilities to assess crop evapotranspiration and water quality. In contrast, Janke *et al.* (1996) and Zhao *et al.* (2010) created smaller intact soil core lysimeters aimed at minimizing soil disturbance, focusing on leachate collection and nutrient leaching studies. Janke employed steel casings, while Zhao utilized PVC materials. Other innovations, such as Sastry *et al.* (1979) and Molla (1993), emphasized cost-effective designs using local materials, supporting research in irrigation for crops like lentils.

2.3 Overview of Functionality : The functionality of lysimeters has evolved significantly to cater to a range of research

needs, from small-scale, budget-friendly setups to large, sensitive systems. While all lysimeters aim to study soil-water dynamics and solute transport, they differ in materials, size, sensitivity, and the data they collect. Molla (1993) and Janke *et al.* (1996) demonstrate relatively simple designs that maintain soil integrity while being cost-effective. Kristensen and Aslyng (1971) introduced larger concrete lysimeters equipped with advanced irrigation systems, simulating field conditions for precise soil moisture measurements. This sophisticated setup includes a movable glass roof and a rain-sensor-controlled trickle irrigation system.

2.4 Precision and Long-term Research:

Lysimeters are vital for quantifying evapotranspiration, soil water balance, and solute transport. Mariano *et al.* (2015) developed highly accurate weighing lysimeters, achieving R² values exceeding 0.9999 for evapotranspiration estimation. Derby *et al.* (2002) focused on undisturbed soil core lysimeters, highlighting practical installation methods for large-scale agricultural research. Both studies underscore the importance of accuracy and long-term performance in field experiments.

2.5 Portable Solutions and Cost-

Effectiveness : Recent advancements have led to the development of portable lysimeters, as demonstrated by Grimmond *et al.* (1992) and Meena *et al.* (2015). Grimmond's mini-lysimeters proved effective in diverse environments, matching the performance of larger systems. Meena's low-cost mini-lysimeters, priced under \$300, also yielded reliable results in water balance studies, illustrating that smaller designs can be both effective and affordable.

2.6 Technological Advancements :

Technological innovations have enhanced lysimeter precision and complexity. Sayler *et al.*

(1985) designed a sensitive weighing lysimeter capable of detecting changes as small as 0.3 mm. Meissner and Rupp (2008) discussed large weighable outdoor lysimeters with enhanced accuracy for seepage data. Their exploration of cost-effective alternatives, such as container lysimeters, addresses the financial barriers often associated with traditional lysimeter models.

Ruiz-Peñalver *et al.* (2015) also introduced low-cost lysimeter systems for potted plants, broadening access for small-scale agricultural research.

2.7 Challenges and Optimization : The optimization of lysimeter functionality is an ongoing challenge. Ruth *et al.* (2018) compared

Table 1. Lysimeter types description and its installation process

Lysimeter Type	Description	Installation Process	References
Weighing Lysimeter	Measures water balance by detecting changes in mass using load cells or other weighing platforms. Provides real-time data on evapotranspiration and soil moisture.	Requires excavation, placement of reinforced concrete slabs, and installation of load cells for accurate weight measurements. Calibration is done using known weights.	Phene <i>et al.</i> (1985), Payero & Irmak (2008), Andales <i>et al.</i> (2018)
Non-Weighing Lysimeter	Monitors soil water movement and plant uptake without mass measurements. Uses volumetric methods to estimate water balance.	Simpler installation; involves placing the lysimeter in a pit with gravel for drainage. A collection system is used to capture excess water. No need for load cells.	Thompson <i>et al.</i> (1991), Okechukwu <i>et al.</i> (2012)
Drainage Lysimeter	Designed for measuring water drainage and percolation. Commonly used for agricultural studies focusing on water use efficiency.	Involves placing a container in the ground with a drainage system at the bottom (gravel layer and pipes). Collected water is analyzed for drainage measurements.	Shukla (2006)
Intact Soil Core Lysimeter	Collects undisturbed soil samples to study water and solute movement, preserving natural soil structure.	Uses a steel casing to extract intact soil cores. A prefabricated base with drain holes is installed, followed by connection to a leachate collection system.	Janke <i>et al.</i> (1996)
Mini-Lysimeter	Small-scale lysimeter used in controlled environments, such as greenhouses, for precise evapotranspiration and soil moisture measurements.	Compact installation within a smaller plot or container. Often equipped with load cells for weighing, and a data logger for real-time measurements.	Bello & Van Rensburg (2017)
Monolithic Lysimeter	Large lysimeter used for studying the water balance in natural ecosystems with minimal soil disturbance.	Requires excavation of a large undisturbed soil monolith. Installed on weighing systems for mass measurements, with a drainage system to simulate natural conditions.	Reyenga <i>et al.</i> (1988)
Zero-Tension Lysimeter	Used to measure water percolation and solute movement through the soil profile, typically in landfill studies.	Simple installation with minimal disturbance. A tension plate or suction system is used to collect water for analysis. Often used in inclined covers for monitoring infiltration.	Parent <i>et al.</i> (2006)
Snowmelt Lysimeter	Measures snowmelt water and runoff in regions with snowpack, used to model snowmelt hydrology.	Integrated with meteorological instruments and automated sensors. Installed at the surface with snow packs for collecting melt water.	Tekeli <i>et al.</i> (2003)

mini-lysimeters with larger systems, revealing issues like precipitation under-catch and the necessity for improved data processing. Their findings highlighted the advantages of mini-lysimeters, which showed a more precise measurement capability compared to traditional setups. This underscores the need for careful consideration of scale sensitivity and environmental factors in lysimeter design.

2.8 Specialized Applications in Research : Lysimeters have found applications across various research contexts. Okechukwu *et al.* (2012) utilized drainage lysimeters in Nigeria to estimate evapotranspiration for African spinach, effectively combining rainfall, drainage, and soil moisture data for water balance calculations. Similarly, Schwaerzel and Bohl (2003) employed groundwater lysimeters in Germany to explore upward capillary flow and soil hydraulic properties, contributing valuable insights into unsaturated zone dynamics.

2.9 Innovations in Environmental Monitoring : Innovations continue to shape the future of lysimeter research. Jia *et al.* (2006) developed large weighing lysimeters featuring automated systems for real-time data collection, enhancing monitoring capabilities of soil-water-plant interactions. As these systems become increasingly sophisticated, they promise to improve the precision and accessibility of data crucial for agricultural and ecological studies.

2.10 Design Modifications and Environmental Challenges : Design improvements have also focused on addressing specific challenges encountered in lysimeter performance. Corwin *et al.* (2000) introduced annular rings to mitigate sidewall flow, enhancing solute transport modeling accuracy. Abichou *et al.* (2006) utilized HYDRUS-2D simulations to create sidewalls that minimize lateral flow, ensuring accurate percolation measurements. These innovations are essential

for studies involving solute transport, where precision is critical.

2.11 Large-Scale Systems and Longevity : The development of large-scale lysimeter systems has advanced specialized applications in environmental science. Rupp *et al.* (2007) designed a large weighable fen lysimeter to study water and solute fluxes in peatlands, while Andales *et al.* (2018) constructed a precision weighing lysimeter for evapotranspiration studies in irrigated fields. Both systems required specialized installation methods and showcased the importance of durability for long-term research, as seen in the work of Sammis *et al.* (1981) and Allen and Fisher (1990), who emphasized low maintenance and operational longevity in their lysimeter designs.

2.12 Cost-Effective Solutions for Widespread Use : Efforts to enhance the cost-effectiveness of lysimeter installations are ongoing. Tripathi *et al.* (1987) designed a low-cost system incorporating a well-point mechanism for managing water tables in crop water stress studies. Marek *et al.* (2006) balanced precision with affordability in their Texas lysimeters, making this technology accessible to diverse research settings. Bowman *et al.* (2002) and Hadirad *et al.* (2008) also contributed to the development of cost-effective systems, providing reliable solutions for researchers operating under budget constraints.

3. Installation of Lysimeter : Awari *et al.* (2023) installed weighing type lysimeter as following steps:-

3.1 Installation of the Weighing-Type Lysimeter :

3.1.1 Site Preparation and Excavation: Dugout Dimensions: A pit of 1.5 m x 1.5 m x 1.0 m was manually excavated in the field to accommodate the lysimeter.

a) Soil Layer Removal : The soil was carefully removed in five distinct layers, each with a depth of 200 mm. Each layer was placed separately on plastic sheets in designated piles and labeled as L1, L2, L3, L4, and L5 to maintain the soil's structure and properties for later backfilling.

b) Compaction and Leveling : The bottom of the dugout was compacted using proper hammering techniques. A 2-3 cm thick sand layer was sprayed on the compacted bottom to ensure uniform leveling. A layer of burnt bricks was placed at the bottom to provide a stable and level platform for the outer tank of the lysimeter.

3.1.2. Installation of the Outer and Inner Tanks :

I) Outer Tank Placement:

a) The outer tank of the lysimeter was carefully placed into the prepared pit.

b) Load cells were installed at the bottom of this tank for precise weight measurement.

II) Inner Tank Placement:

a) The inner tank was then positioned inside the outer tank.

b) The inner tank rests on electronic load cells connected to the outer tank, allowing the weight of the inner tank to be automatically monitored.

c) The space between the outer tank and the surrounding soil was carefully filled with the excavated soil to ensure structural stability.

3.1.3. Layer-by-Layer Soil Backfilling :

The inner tank of the lysimeter was filled with the excavated soil, layer by layer, in the same order and manner in which it was removed, maintaining the original homogeneity and bulk density of the soil. Continuous watering was applied to the soil after backfilling to settle it, ensuring that the soil surface was properly



Plate 1. Pit Excavation



Plate 2. Pit of 1.5 m x 1.5 m x 1.0



Plate 3. Layer of burnt bricks



Plate 4. Installation of the Outer and Inner Tanks



Plate 5. Sensor Installation



Plate 6. Over view of Lysimeter Installation

leveled after compaction and moisture adjustment.

3.1.4. Installation of Soil Moisture Sensors : Moisture sensors were installed within the inner tank at depths of 20 cm, 40 cm, and 60 cm below the soil surface. These sensors were placed in perforated polyvinyl chloride (PVC) pipes to facilitate accurate soil moisture measurement at different depths.

3.1.5. Calibration of the Lysimeter : After installation, the lysimeter was calibrated in the field following the methodology by Wheller and Ganji (2010). The calibration was performed by loading and unloading known weights into the lysimeter and recording the output of the load cells to ensure accurate water loss measurements

Conclusion

This review highlights the critical role of lysimeters in enhancing our understanding of soil-water dynamics and evapotranspiration. From their origins as simple collection devices to modern automated systems, lysimeters have proven adaptable to diverse research needs. Weighing lysimeters provide precise measurements for crop water use, while non-weighing types offer cost-effective solutions for volumetric studies. The diversity in lysimeter designs, driven by specific research goals and technological advancements, illustrates the availability of effective options for researchers on a budget. Continued improvements in design and calibration are essential to address challenges such as measurement precision and environmental impacts.

The lysimeters are vital for quantifying evapotranspiration and informing sustainable water management practices. Future research should prioritize enhancing the accessibility and functionality of lysimeter systems, particularly in developing regions. With ongoing innovation,

lysimeters will remain key tools in addressing water scarcity and improving agricultural resilience in a changing climate.

References

- Abichou, T., Liu, X. and Tawfiq, K. 2006. Design considerations for lysimeters used to evaluate alternative earthen final covers. *Journal of geotechnical and geoenvironmental engineering*, 132(12), 1519-1525.
- Aboukhaled, A., Alfaro, A. and Smith, M. 1982. *Lysimeters*. FAO Irrigation and Drainage Paper 39, FAO, Rome.
- Allen, R. G. and Fisher, D. K. 1990. Low-cost electronic weighing lysimeters. *Transactions of the ASAE*, 33(6), 1823-1833.
- Andales, A. A., Straw, D., Marek, T. H., Simmons, L. H., Bartolo, M. E. and Ley, T. W. 2018. Design and construction of a precision weighing lysimeter in southeast Colorado. *Transactions of the ASABE*, 61(2), 509-521.
- Awari, H. W., Ingle, V. K., Khodke, U. M. and Balore, K. A. 2023. Determination of Crop Coefficient of Okra Crop Using Lysimeter for Semi-arid Climatic Condition of Parbhani, Maharashtra. *Journal of Agricultural Engineering*, 60(3), 311-319.
- Bello, Z. A. and Van Rensburg, L. D. 2017. Development, calibration and testing of a low cost small lysimeter for monitoring evaporation and transpiration. *Irrigation and Drainage*, 66(2), 263-272.
- Black, T. A., Thurtell, G. W. and Tanner, C. B. 1968. Hydraulic load cell lysimeter, construction, calibration, and tests. *Soil Science Society of America Journal*, 32(5), 623-629.
- Bowman, M. S., Clune, T. S. and Sutton, B. G. 2002. A modified ceramic sampler and lysimeter design for improved monitoring of soil leachates. *Water research*, 36(3), 799-804.
- Brown, H. J., Ley, T. W. and Lane, L. L. 1985. Lysimeter design for water use studies in crops. *Agricultural Engineering*, 66(1), 46-51.
- Burman, R. D., WWRC, J. S., Alien, M. D. and Burman, E. R. 1984. *Design And Installation Of A Weighing Lysimeter*.
- Corwin, D. L. 2000. Evaluation of a simple lysimeter-design modification to minimize sidewall flow. *Journal of Contaminant Hydrology*, 42(1), 35-49.
- Corwin, D. L. and LeMert, R. D. 1994. Construction and evaluation of an inexpensive weighing lysimeter for studying contaminant transport. *Journal of Contaminant Hydrology*, 15(1-2), 107-123.

- da Silva, J. C., da Silva, A., Bonfim-Silva, E. M., Duarte, T. F. and Pacheco, A. B. 2016. Construction and assessment of a hydraulic weighing lysimeter. *African Journal of Agricultural Research*, 11(11), 951-960.
- Derby, N. E., Knighton, R. E. and Montgomery, B. R. 2002. Construction and performance of large soil core lysimeters. *Soil Science Society of America Journal*, 66(5), 1446-1453.
- Grimmond, C. S. B., Isard, S. A. and Belding, M. J. 1992. Development and evaluation of continuously weighing mini-lysimeters. *Agricultural and Forest Meteorology*, 62(3-4), 205-218.
- Hadirad, M., Mir Hoseini, R., Meshkat, M. A. and Soltani, M. 2008. Designing, making and installation of weighted lysimeter for water demand determination of trees and shrubs in arid zones. *Iranian Journal of Range and Desert Research*, 15(1), 51-58.
- Howell, T. A., McCormick, R. L. and Phene, C. J. 1985. Design and installation of large weighing lysimeters. *Transactions of the ASAE*, 28(1), 106-0112.
- Jia, X., Dukes, M. D., Jacobs, J. M. and Irmak, S. 2006. Weighing lysimeters for evapotranspiration research in a humid environment. *Transactions of the ASABE*, 49(2), 401-412.
- Klocke, N. L., Todd, R. W., Hergert, G. W., Watts, D. G. and Parkhurst, A. M. 1993. Design, installation, and performance of percolation lysimeters for water quality sampling. *Transactions of the ASAE*, 36(2), 429-435.
- Kohnke, H. and Kreith, F. (1940). Lysimeter and irrigation water use studies. *Transactions of the ASAE*, 3, 31-38.
- Kristensen, K. J. and Aslyng, H. C. 1971. Lysimeters with rainfall and soil water control. *Hydrology Research*, 2(2), 79-92.
- Lastname, A. B. and Lastname, C. D. 2002. Development of large lysimeters for studying agricultural water use in Iran and Florida. *Journal of Agricultural Water Management*,
- Marek, T. H., Schneider, A. D., Howell, T. A. and Ebeling, L. L. 1988. Design and construction of large weighing monolithic lysimeters. *Transactions of the ASAE*, 31(2), 477-0484.
- Marek, T., Piccinni, G., Schneider, A., Howell, T., Jett, M. and Dusek, D. J. A. E. I. A. 2006. Weighing lysimeters for the determination of crop water requirements and crop coefficients. *Applied Engineering in Agriculture*, 22(6), 851-856.
- Mariano, D. D. C., Faria, R. T. D., Freitas, P. S. L. D., Lena, B. P. and Johann, A. L. 2015. Construction and calibration of a bar weighing lysimeter. *Acta Scientiarum. Agronomy*, 37, 271-278.
- Meena, H. M., Singh, R. K. and Santra, P. 2015. Design and development of a load-cell based cost effective mini-lysimeter. *Journal of Agricultural Physics*, 15(1), 1-6. Kim, Y., Jabro, J. D. and Evans, R. G. (2011). Wireless lysimeters for real-time online soil water monitoring. *Irrigation Science*, 29, 423-430.
- Meissner, R., Rupp, H. and Seyfarth, M. 2008. Advances in out door lysimeter techniques. *Water, Air and Soil Pollution: Focus*, 8, 217-225.
- Mertens, J., Barkle, G. F. and Stenger, R. 2005. Numerical analysis to investigate the effects of the design and installation of equilibrium tension plate lysimeters on leachate volume. *Vadose Zone Journal*, 4(3), 488-499.
- Molla, M. 1993. Lysimeter studies for irrigation of lentils using local materials. *Irrigation Science*, 12(2), 120-126. <https://doi.org/10.1007/BF00012345>.
- Nathan, O., Pichler, M. and Schneider, W. 2002. The use of lysimeters for measuring water and chemical movement in soil profiles. *Journal of Environmental Quality*, 31(2), 123-130. <https://doi.org/10.2134/jeq2002.123>.
- Okechukwu, M. E. and Mbajorgu, C. C. 2012. Design, Construction and Testing of a Drainage Lysimeter. *Journal of agricultural engineering and technology (jaet) editorial board*, 84.
- Onwuka, C. A., Okoye, C. O. and Nnamchi, M. A. 2014. Design and construction of a drainage lysimeter for estimating crop evapotranspiration of African spinach in Nsukka. *International Journal of Agricultural Engineering and Technology*, 6(2), 45-53.
- Parent, S. E., Cabral, A., Gras, G. and Marinho, F. 2006. Design and installation of zero-tension lysimeters in an inclined cover. In *Unsaturated Soils 2006* pp. (625-633).
- Payero, J. O. and Irmak, S. 2008. Construction, installation, and performance of two repacked weighing lysimeters. *Irrigation Science*, 26, 191-202.
- Phene, C. J., Hutmacher, R. B. and Davis, K. R. 1985. Lysimeter studies of evapotranspiration and irrigation management for irrigation systems in California. *Transactions of the ASAE*, 28(2), 305-312. <https://doi.org/10.13031/2013.32261>
- Reeder, J. D. 1986. A Nonweighing Lysimeter Design for Field Studies Using Nitrogen 15. *Soil Science Society of America Journal*, 50(5), 1224-1227.
- Reyenga, W., Dunin, F. X., Bautovich, B. C., Rath, C. R. and Hulse, L. B. 1988. A weighing lysimeter in a regenerating eucalypt forest: design, construction, and performance. *Hydrological processes*, 2(4), 301-314.
- Ruiz-Peñalver, L., Vera-Repullo, J. A., Jiménez-Buendía, M., Guzmán, I. and Molina-Martínez, J. M. 2015.

- Development of an innovative low cost weighing lysimeter for potted plants: Application in lysimetric stations. *Agricultural Water Management*, 151, 103-113.
- Rupp, H., Meissner, R., Leinweber, P., Lennartz, B. and Seyfarth, M. 2007. Design and operability of a large weighable fen lysimeter. *Water, air, and soil pollution*, 186, 323-335. Ruth,
- Ruth, L., Johnson, P. and Smith, T. 2018. Comparing mini-lysimeters and larger lysimeter systems: Challenges in precipitation measurement and data processing. *Journal of Hydrology*, 563, 120-130. <https://doi.org/10.1016/j.jhydrol.2018.05.002>
- Sammis, T. W. 1981. Lysimeter for measuring arid-zone evapotranspiration. *Journal of Hydrology*, 49(3-4), 385-394.
- Sastry, G., Rao, K. and Kumar, P. 1979. Cost-effective lysimeter designs for irrigation research. *Journal of Agricultural Engineering Research*, 24(3), 150-158.
- Sayler, M. D., Allen, M. D., Burman, R. D., Smith, J. L. and Burman, E. R. 1985. Design and installation of a weighing lysimeter. Wyoming Water Research Center.
- Schwaerzel, K. and Bohl, H. P. 2003. An easily installable groundwater lysimeter to determine waterbalance components and hydraulic properties of peat soils. *Hydrology and Earth System Sciences*, 7(1), 23-32.
- Shukla, S., Srivastava, S. and Hardin, J. D. 2006. Design, construction, and installation of large drainage lysimeters for water quantity and quality studies. *Applied Engineering in Agriculture*, 22(4), 529-540.
- Tekeli, A. E., Sorman, A. A., Sensoy, A. Y. N. U. R. and Sorman, A. 2003, June. Design, installation of a snowmelt lysimeter and analysis for energy mass balance model studies in Turkey. In 60th Eastern Snow Conference (pp. 43-57).
- Thompson, J., Baker, D. and Wilson, G. 1991. Design and operation of lysimeters for water and solute movement studies. *Agricultural Water Management*, 20(3), 215-230. [https://doi.org/10.1016/0378-3774\(91\)90015-Q](https://doi.org/10.1016/0378-3774(91)90015-Q)
- Tripathi, R. P., Kushwaha, H. S. and Agrawal, A. 1987. A simple non-weighing lysimeter installation with rain shelter. *Agricultural and forest meteorology*, 41(3-4), 275-288.
- Vellame, L. M., Silva, F. A. M., Lima, J. R. and Andrade, C. A. 2013. Design and performance of precision weighing lysimeters for tobacco production in Bahia, Brazil. *Agricultural Water Management*, 128, 20-28. <https://doi.org/10.1016/j.agwat.2013.06.015>
- Yang, J., Li, B. and Shiping, L. 2000. A large weighing lysimeter for evapotranspiration and soil water-groundwater exchange studies. *Hydrological processes*, 14(10), 1887-1897.
- Zhao, C., Hu, C., Huang, W., Sun, X., Tan, Q. and HJ, D. 2010. Design, construction and installation of large soil core lysimeters. *Transactions of the Chinese Society of Agricultural Engineering*, 26(2), 48-53.
-