J. Bamboo Rattan (2026) 25(1): 1-11
https://doi.org/10.55899/09734449/jbr025101 www.jbronline.org
REVIEW ARTICLE

Bamboo as a sustainable alternative to plastic in a drip irrigation system

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Received: 16 October 2025/Accepted: 8 May 2026
Published 25 November 2026

Abstract: Bamboo's potential as an alternative to polyvinyl chloride (PVC) is primarily for use in pipes in drip irrigation systems. From a sustainability perspective, this research investigates the environmental benefits of bamboo relative to plastics. Compared with PVC, which causes contamination such as soil degradation and water pollution, bamboo can be an alternative; compared with other materials, it might be lighter, and its compressive strength is excellent. Therefore, it could become a sustainable material for various uses in the future, primarily in construction and farming, given its large market. Some countries, such as China, India, and Ghana, have been pushing its adoption globally. This study compares bamboo's performance with plastic and examines the technical traits that make bamboo suitable for irrigation systems. Several challenges appear during field trials, such as rough inner surfaces and uneven diameters. However, when pre-treatment and proper maintenance are emphasised, bamboo has been shown to hold its own in both urban and rural settings. During the field trial, leaks were discovered in most union accessories. On the other hand, in the laboratory, the bamboo tube achieved pressures around 30 PSI. While hydraulic performance was between 75 and 85 per cent, it was not far from PVC's. Bamboo presents an alternative in zones where it grows abundantly; it's an ecological choice with a reduced carbon footprint.

Keywords: Bio-based materials, Agricultural engineering, Circular economy, Sustainability, Bio substitutes.

Introduction

Worldwide, agriculture relies heavily on plastic materials, including irrigation pipes. This reliance creates serious environmental problems, such as water pollution, soil degradation, and even biodiversity loss. In addition, these plastics can affect long-term agricultural productivity and disrupt bacterial activity in the soil. Most irrigation systems currently use plastic materials, which may not be sustainable in the future.

On the other hand, bamboo appears as a more sustainable alternative. It is a natural and renewable material with excellent mechanical and structural properties. Moreover, bamboo offers benefits over other materials, such as a lower carbon footprint and lighter weight in construction. As a result of these advances, it could eventually replace plastic and serve as a sustainable alternative. In this context,

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bamboo has gained increasing attention as a sustainable material, particularly for construction and other engineering applications (Liese and Köhl, 2015; Sharma *et al*., 2015; Yadav and Mathur, 2021). In South America, bamboo cultivation covers approximately 11 million hectares, with Ecuador accounting for around 600,000 hectares. Recent studies have also characterized the physical and mechanical properties of Ecuadorian Guadua angustifolia, highlighting the variability of bamboo culms according to their characteristics and origin (Padilla *et al.*, 2024). This makes it a crucial source in the country and a growth area for sustainable resource development, such as bamboo, which has many native and cultivated species. Apart from that, bamboo is valued for its capacity to capture carbon dioxide, reduce soil erosion, and its applications in sustainable construction (Liese and Köhl, 2015; Yadav and Mathur, 2021).

With respect to PVC (polyvinyl chloride), pipes remain widely used in traditional and drip irrigation systems because they are strong, durable and relatively easy to install. However, the environmental persistence of PVC and concerns associated with its production, use and disposal have encouraged interest in natural and renewable materials. Bamboo, in contrast, is a rapidly renewable material with potential environmental benefits and could therefore represent a more sustainable alternative for irrigation applications (Yadav and Mathur, 2021).

Previous studies have shown that bamboo materials exhibit excellent mechanical properties and high structural capacity for use in engineering and construction (Sharma *et al.*, 2015; Rivera-Segura *et al.*, 2024). This is largely due to its unique anatomical structure: hollow internodes separated by solid nodes form natural tubular sections and confer high load-bearing capacity (Dixon and Gibson, 2014). In recent years, its use has been promoted in sustainable housing and eco-efficient construction systems (Yadav and Mathur, 2021). Studies indicate that bamboo stems offer sufficient mechanical strength for a variety of uses. Depending on species and the age of the bamboo culm, its bending strength ranges from 40 to 130 MPa, while its compressive strength ranges from 25 to 52 MPa (Liese and Köhl, 2015).

In addition to strength, other parameters should be considered when using bamboo. Among the most relevant factors for its use as drip-irrigation piping are diameter uniformity, surface roughness, pressure resistance, and durability. Thus, the present study aims to evaluate bamboo as an alternative material for drip irrigation, based on its hydraulic efficiency, durability, and economic viability compared with traditional PVC-based systems.

Materials and Methods

Study area

The study area was located at “Escuela Superior Politécnica Agropecuaria de Manabí Manuel Félix López”, in Calceta, Manabí, Ecuador, at 0° 49' 23” south latitude and 80° 11' 01” west longitude, at an elevation of approximately fifteen meters above sea level (see Fig. 1). The *Bambusa vulgaris* bamboo species was selected from nearby woods, with stems three to four years old, diameters between eight and twelve centimetres, and lengths between three and four meters. Appropriate wall thickness, consistent diameter, and the absence of obvious flaws—that is, a generally normal geometry—were among the selection criteria.

Bamboo preparation and processing

Selected bamboo culms were processed following standardized procedures (Fig. 2a and 2b):

- Cutting into 1-meter sections using appropriate tools
- Removal of nodes to create continuous tubes using manual perforation techniques
- Internal surface smoothing to reduce roughness
- Application of chemical preservation treatments to enhance durability
- Natural drying for 7 days under controlled conditions

Physical and mechanical testing

Physical characterization included measurements of external diameter, wall thickness, and internal roughness using precision instruments. Mechanical testing followed established protocols for bamboo evaluation:

- Pressure resistance tests using hydraulic testing equipment

- Flexural strength determination using three-point bending tests
- Compression testing of bamboo sections
- Hydraulic conductivity measurements under controlled flow conditions.

For the mechanical compression and bending tests, resistance tests were carried out on the selected bamboo. For the mechanical compression and bending tests, the Ecuadorian Technical Standard NTE INEN-ISO/DIS 22157 (INEN, 2004) was used, together with the Colombian technical standard NTC 5525 (ICONTEC, 2007).

Hydraulic performance evaluation

Comparative hydraulic performance analysis was conducted between bamboo and PVC pipes:

- Flow rate measurements under different pressure conditions
- Friction loss calculations using the Darcy-Weisbach equation (Atiyah *et al.*, 2025)
- Leakage testing under operational pressures
- Uniformity coefficient determination for drip irrigation applications.

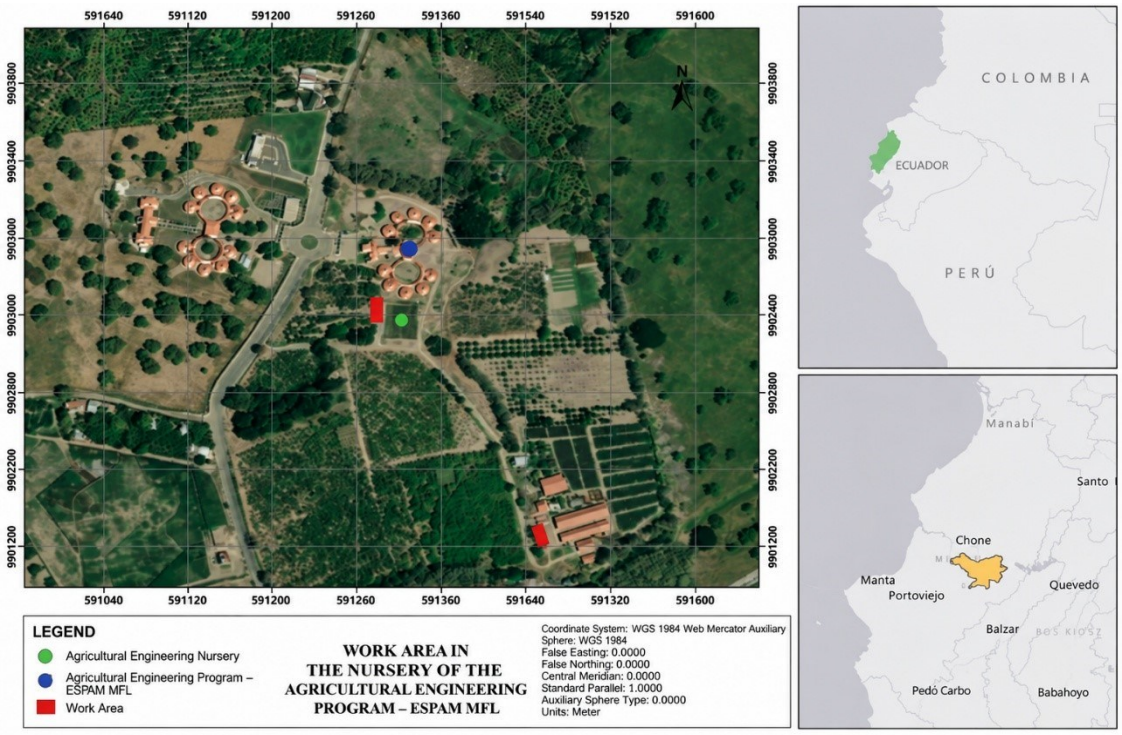


Fig 1. Study area (El Limón, Bolívar Canton, Manabí) at ESPAM MFL. Source: Authors

a) Calculation of the Reynolds number: Given the velocity flowing through the bamboo pipe, the diameter, and the temperature of the water, the Reynolds Number was calculated using the following expression as described by Zanoun *et al.* (2023)

$$Re = \frac{V * D}{\upsilon}$$

Where:

Re = Reynolds number.

V = Water velocity through the pipe (m/s).

D = Diameter of the bamboo (m).

υ = Kinematic viscosity (m^2/s).

The kinematic viscosity was calculated as a function of water temperature. The water temperature measured in the laboratory was 20°C, yielding a kinematic viscosity of 1.02×10^{-6} m^2/s, which was used in the corresponding calculations.

b) Calculation of pressure loss: Energy losses due to friction were calculated using the energy equation (Atiyah *et al.*, 2025). For a pipe section, the velocity terms in equation 2 are equal and can therefore be cancelled, yielding equation 3, which is

$$\frac{V1^2}{2g} + \frac{P1}{8} = \frac{V^2}{2g} + \frac{P2}{8} + hf(1-2)$$

$$\frac{P1}{8} = \frac{P2}{8} + hf(1-2)$$

pressure-dependent. Energy losses were calculated directly from the piezometer readings at the beginning and end of each pipe section.

c*) Calculation of the friction factor*: As described by Atiyah *et al.* (2025), the Darcy-Weisbach equation allowed the friction factor to be calculated based on the pipe's geometric data (length and diameter) and the flow conditions represented by water velocity and energy losses in the analyzed section. The friction factor was calculated using the following expression:

$$hf = f\frac{L * V^2}{D * 2g}$$

$$\Delta H = \frac{P1}{\delta} - \frac{P2}{\delta} = \mathrm{f}\frac{L * V^2}{D * 2g}$$

$$\mathrm{f} = \frac{Hf}{\frac{L * V^2}{D * 2g}}$$

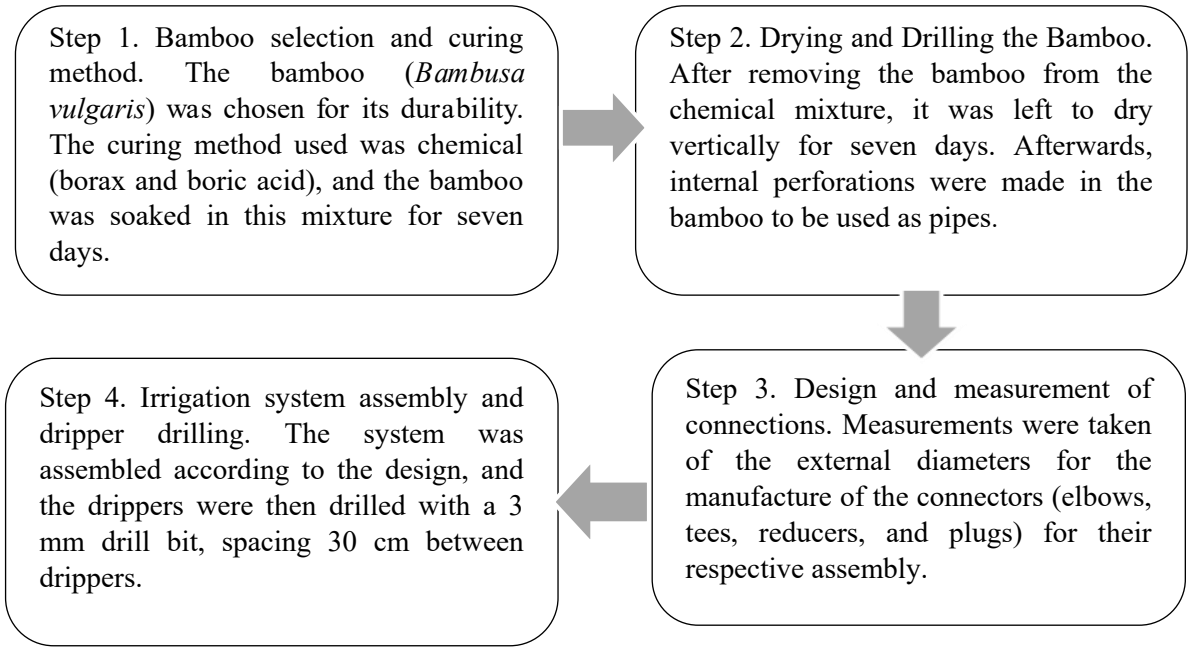


Fig 2a. Bamboo Preparation and Processing at ESPAM. Source: Authors

Economic analysis

Cost-benefit analysis included:

- Material costs comparison between bamboo and PVC systems
- Installation time and labor requirements
- Maintenance costs and frequency
- System longevity and replacement considerations
- Environmental impact assessment using life cycle analysis principles

Results and Discussion

Physical characteristics of bamboo pipes

Regarding Phase I, in the non-experimental analysis, bamboo culms with diameters between 7 cm and 10 cm were selected to ensure material homogeneity and to achieve dimensions comparable to those of PVC pipes. Eighty-seven percent (87 %) of the bamboo stems were found to be suitable and undamaged for use as pipes; however, the procedure had to be repeated for the remaining stems, as they did not dry properly. To evaluate this difficulty that occurred during the natural drying process, it was



Fig 2b. Pictures of bamboo preparation and Processing at ESPAM. Source: Authors

noted that ambient humidity had a direct negative effect on the curing quality. The influence of moisture content on the mechanical performance of bamboo, particularly its tensile strength, has also been reported by Ribeiro *et al.* (2019). The natural drying method used generated internal stresses that reduced the material's uniformity. The tests were conducted in accordance with the Ecuadorian Technical Standard NTE INEN-ISO/DIS 22157 (INEN, 2004). Previous research has shown that bamboo treatment can influence dimensional stability and other physical properties (Li *et al.*, 2022).

Mechanical properties and pressure resistance

In Phase II, the compressive strength of *Bambusa vulgaris* used as piping was evaluated. This ranged from 31.76 to 130.52 kN/cm², with an average slightly lower than that of PVC pipes of similar commercial diameters. Among the samples, the highest wall thickness was observed in sample number six, indicating greater resistance to pipe crushing. These findings are consistent with previous research demonstrating that the cellular structure and fibre organization of bamboo contribute to its mechanical performance and high strength-to-weight ratio (Dixon and Gibson, 2014; Sharma *et al.*, 2015; Osorio *et al.*, 2018). As various studies have demonstrated, when processes such as preservation and drying are performed correctly, with sufficient experience and standardized execution, bamboo can compete with other materials, such as polymeric materials, in uses such as structural applications or hydraulic and irrigation, despite inherent differences in diameter and internal roughness (Sharma *et al.*, 2015; Zhang *et al.*, 2024).

Laboratory pressure tests indicate that bamboo pipes can withstand up to 30 PSI (2.07 bar) before failure. This is sufficient for most drip irrigation systems, which typically operate at pressures of 10 to 15 PSI. However, field tests have shown that, to prevent leaks at knot and processed joints, practical operating pressures should be limited to 7 PSI (Fig. 3).

The results of this study demonstrated that the age of the cane, moisture content, and processing quality are key determinants of strength variation. According to Zhang *et al.* (2024), compression tests yielded strengths of 32–48 MPa, supporting the mechanical potential of bamboo for applications subjected to installation loads (Fig. 4).

Hydraulic performance comparison

Flow rate measurements under identical pressure conditions showed that the bamboo pipes achieved 75% to 85% of the flow capacity of equivalent PVC pipes. Increased internal roughness and diameter irregularities were perhaps the main contributors to this reduction. It is important to note that the treated bamboo pipes exhibited a Hazen-Williams roughness coefficient of 120-140, whereas the new PVC pipes had a coefficient of 150 (Fig. 5).

Calculations of friction losses showed that, under identical flow conditions, bamboo systems incurred 15 to 25% higher losses than PVC systems. However, these losses can be offset through proper system design, including larger-diameter sections, pressure control, and custom-fitted fittings for each pipe section.

The results of this study are consistent with those of Demir *et al.* (2007), who noted that surface roughness increases friction and pressure losses in fluid systems, which is a disadvantage for bamboo when used as piping. However, when other factors are considered, such as lower environmental impact, low production costs, and the material’s ability to withstand pressures of 20–30 PSI, bamboo can be considered technically viable. This is particularly true for small irrigation projects, provided that the curing and drying processes are properly controlled to minimize operational junction defects (Fig. 6).

Leakage and connection performance

The main challenge in the methodology and field tests was achieving an airtight seal at the joints. Under operating conditions, traditional joining techniques result in leakage rates of between 2% and 8%. Therefore, improvements were sought through mechanical accessories and natural sealants. This reduced leakage to 1-3%, which is close to acceptable levels for irrigation applications. In addition, due to variations in bamboo diameter, the joint solutions were made to measure, increasing the complexity of the installation. In contrast, in standardized PVC systems, the joints are standardized and designed for commercial diameters.

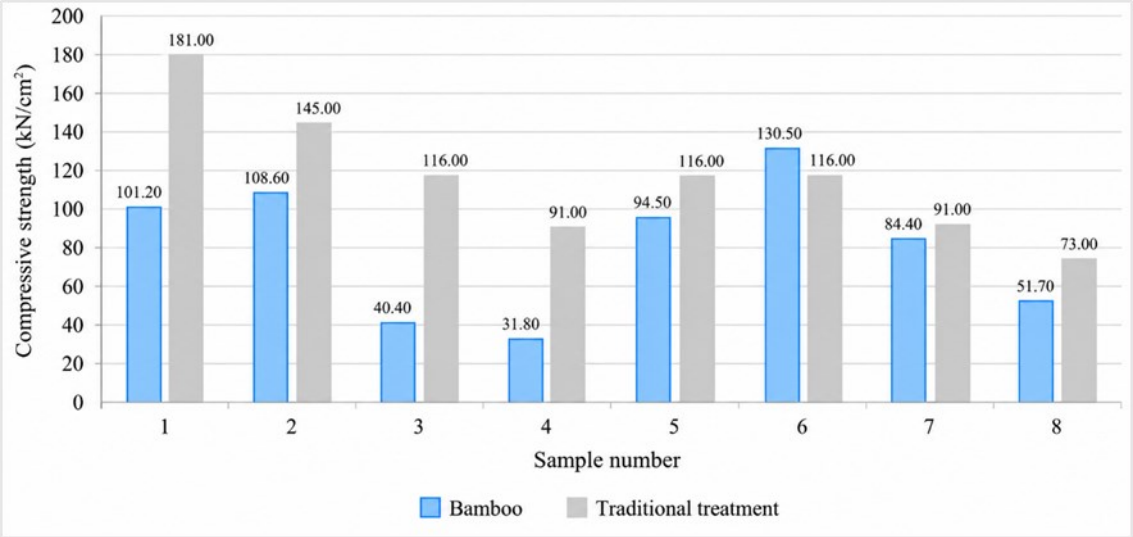


Fig 3. Compressive strength of bamboo (*Bambusa vulgaris*). Source: Authors

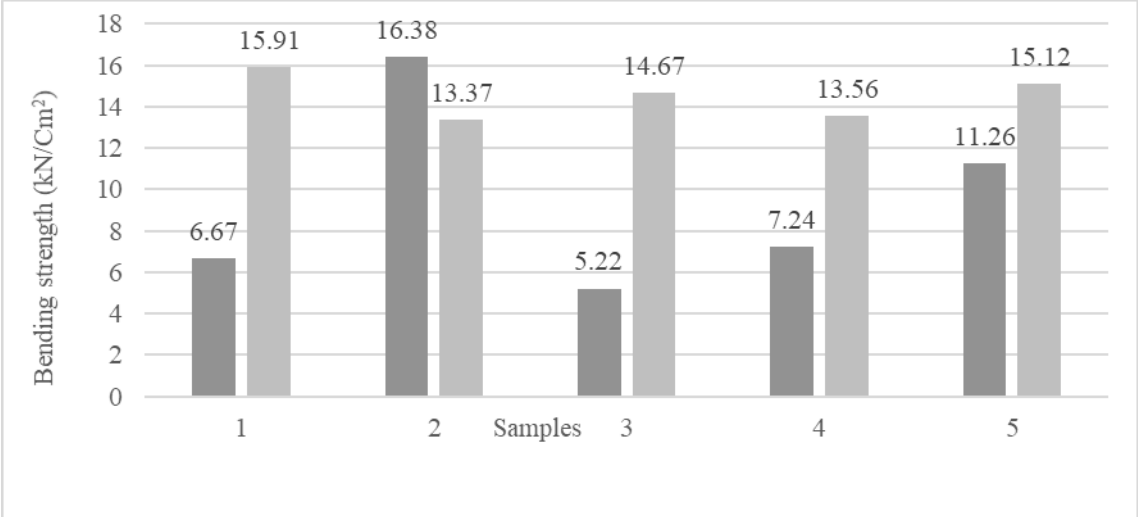


Fig 4. Bending strength testing of *Bambusa vulgaris* culms.

However, thanks to local manufacturing, with the support of artisans, effective joining techniques adapted to irrigation applications were successfully developed.

Economic analysis

In terms of system cost analysis, bamboo offers significant economic advantages in regions where the material is readily available. Compared with similar PVC installations, the initial material costs of bamboo systems were 60%–75% lower. These savings are partially offset by higher labour costs, particularly for processing and installing each gasket in a bamboo system (Liese and Köhl, 2015).

It is important to note that in rural areas, drip irrigation using bamboo pipes is 35% to 45% cheaper than PVC systems (including materials, manufacturing, and installation). Regarding maintenance, requirements are relatively higher; material replacement costs will be lower due to local availability and renewability (Fig. 7).

Durability and maintenance requirements

Over 18 months, we conducted field tests involving the harvesting and curing of bamboo pipes. Every 6 to 8 months, the system underwent routine maintenance, including inspecting joints, resealing them as needed, and replacing any damaged pieces.

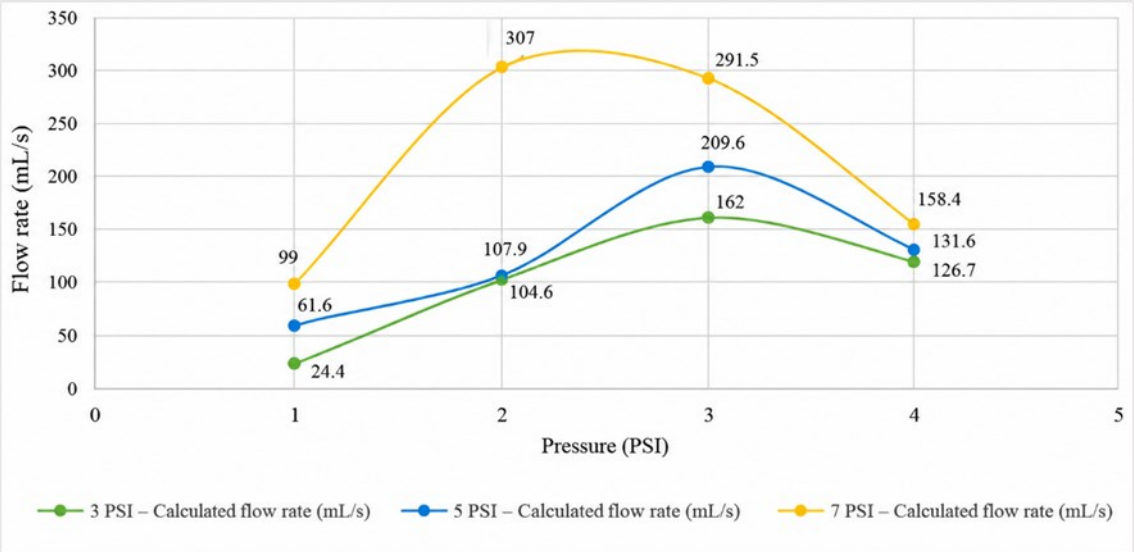


Fig 5. Flow in bamboo pipes (*Bambusa vulgaris*). Source: Authors

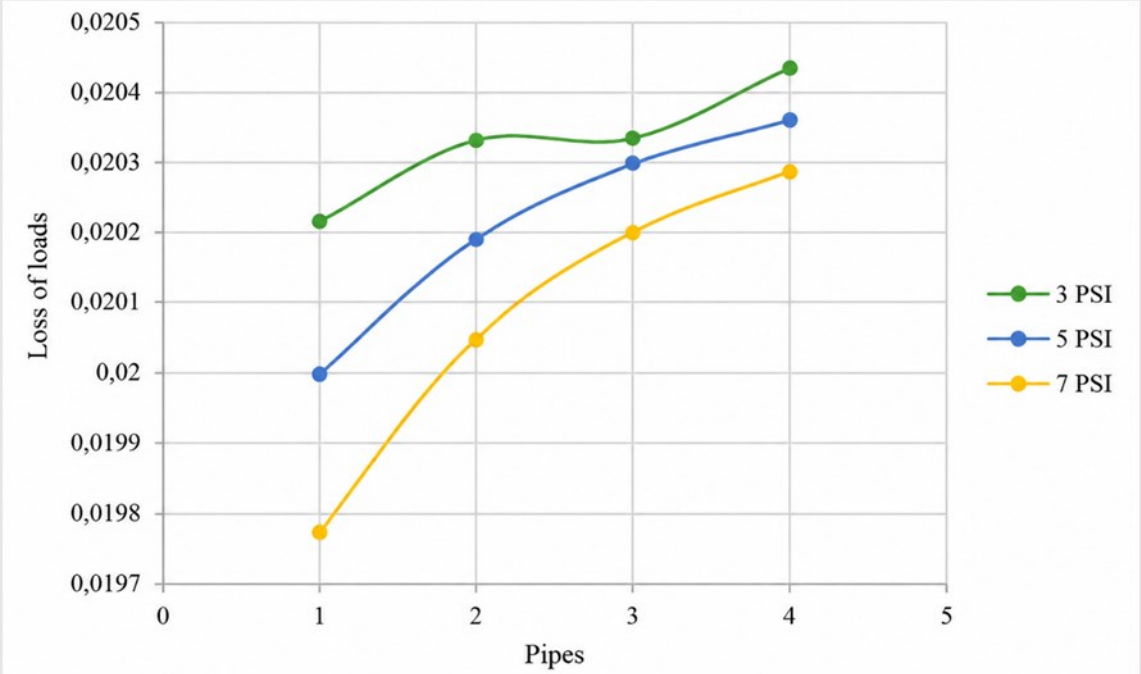


Fig 6. Loss of loads in bamboo pipe systems. Source: Authors

Treatments designed to preserve bamboo can improve its durability and dimensional stability. In the present study, the treated bamboo pipes were estimated to have a service life of approximately 3 to 5 years. In the local context evaluated in this study, bamboo pipes showed economic advantages compared with PVC, particularly in terms of initial and installation costs. In addition, bamboo offers potential environmental benefits associated with its renewable and biodegradable nature (Yadav and Mathur, 2021). Moreover, bamboo grows back quickly and is readily available nearby (Yadav and Mathur, 2021).

Environmental impact assessment

Previous life cycle assessments have identified potential environmental benefits associated with bamboo-based materials, although these benefits

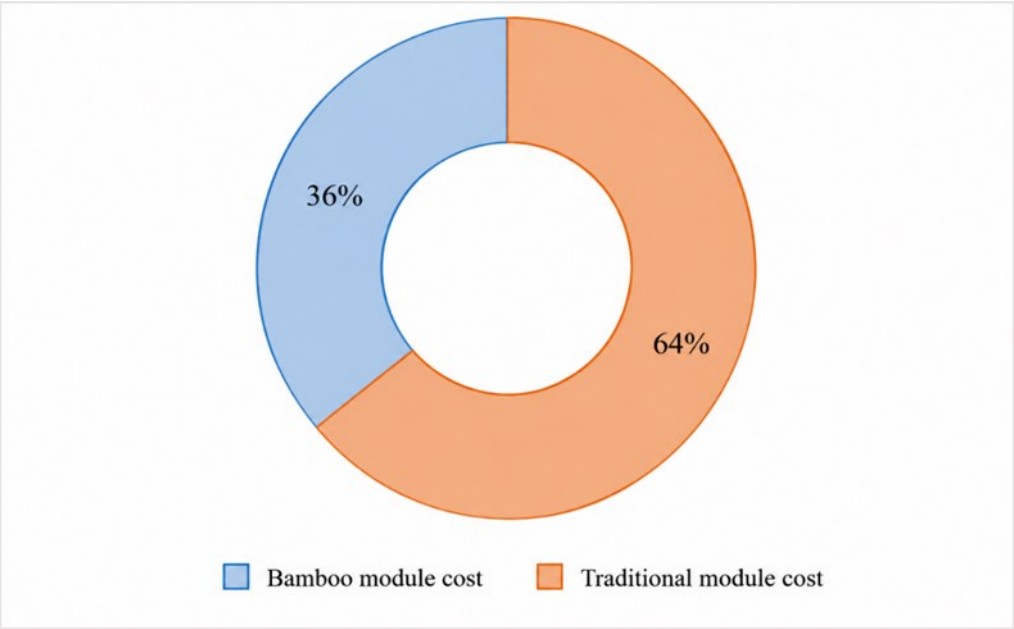


Fig 7. Cost materials analysis, Bamboo vs PVC. Source: Authors

depend on production, processing, transportation and end-of-life conditions (Zea Escamilla and Habert, 2014). Other environmental advantages are associated with bamboo's rapid growth and its capacity to sequester carbon during growth. In addition, bamboo's biodegradability may reduce the long-term persistence of waste compared with synthetic materials (Yadav and Mathur, 2021). Bamboo systems did not adversely affect the chemical composition of the irrigation water under the conditions evaluated in this study.

Technical recommendations and system optimization

Several technological recommendations have been developed to enhance bamboo irrigation systems based on the results of this research. Uniform diameter and selection techniques for bamboo culms are recommended to avoid variation and heterogeneity in their geometry (Liese and Köhl, 2015; Zhang *et al.*, 2024). By reducing internal roughness, surface treatment techniques may enhance hydraulic performance. To improve the connection system and increase durability and operational dependability, best practices and a preventive maintenance procedure are required. Summarizing this recommendation has:

1. Uniformity in inner diameter
2. Surface treatment
3. Connection systems
4. Pressure management
5. Maintenance protocols

Conclusions

Bamboo might be a viable alternative to PVC in drip irrigation systems, particularly in countries such as Ecuador, which has rural areas with abundant resources and a limited economy. There are some technical challenges, including variations in diameter, rougher surfaces, and more complex connections, but these can be addressed if the right processes and bamboo treatments are used in accordance with normative and international regulations. Furthermore, bamboo systems could reduce initial costs by 35% to 45% compared to PVC systems. This represents an important advantage, especially in areas where bamboo is available in large quantities. Biodegradability and the potential for a lower environmental footprint are among the benefits of bamboo, making it a promising material for sustainable irrigation (Liese and Köhl, 2015; Yadav and Mathur, 2021).

On the other hand, the key conclusions are that the

results are excellent for small projects, with hydraulic performance ranging from 75% to 85% of PVC efficiency. It is important to note that, under general conditions, cost-effectiveness was favorable, with pressure resistance up to 30 PSI in laboratory conditions and up to 7 PSI in field applications. In areas with abundant bamboo, it is a recommended option due to its rapid growth, potential environmental benefits, and diverse uses, making it a promising sustainable material (Liese and Köhl, 2015; Yadav and Mathur, 2021).

To improve the effectiveness of bamboo and increase its use in irrigation systems, future research should focus on developing standardized processing methods, improved connection systems, and treatments to extend durability (Li *et al.*, 2022). Additionally, extending field research across diverse regions would provide important information for system design under different climatic conditions, soil types, topographic settings, and irrigation practices.

Finally, the synergies between traditional knowledge and modern technical concepts offer promising prospects for developing irrigation solutions that boost agricultural production and for protecting the environment. It can therefore be said that bamboo irrigation systems are a good example of how natural materials can contribute to sustainable practices while reducing dependence on synthetic materials.

Acknowledgements

All authors appreciate Escuela Superior Politécnica Agropecuaria de Manabí MFL for providing laboratory facilities and technical support for this research.

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