



Performance Evaluation of a Power-Operated Bamboo Drip Irrigation System Using *Schizostachyum pergracile* in South Gujarat, India

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Abstract: This study assesses the performance of a bamboo drip irrigation system at the Bambusetum, College of Forestry, NAU, Navsari, Gujarat, India. Parameters evaluated include the coefficient of uniformity, coefficient of variation, friction loss, pressure-discharge relationship, discharge rates, surface wetting patterns, and cost-effectiveness. The system utilized bamboo as a conveyance material, with medi-infusion tubes and bamboo microtubes of varying diameters serving as emitters. PVC pipes with drippers were used as the control at operating pressures of 1.3, 1.4, and 1.5 kg/cm². The bamboo-based system exhibited discharge rates ranging from 1.17 to 18.68 l/hr. CU ranged from 50.89 to 89.77%, and CV values from 0.04 to 0.65. Despite variability in some treatments, the results demonstrate that bamboo systems can deliver adequate uniformity with suitable emitter selection. Friction loss increased with rising pressure, while surface wetting patterns were influenced by microtube diameters. Though cost savings were marginal (₹370 per 122 m²), the system demonstrates economic viability when scaled and supported by local, low-cost materials. The bamboo systems showed slightly lower discharge uniformity, but remain a sustainable, affordable solution for subsistence farming and agroforestry in water-scarce regions where uniformity is less critical.

Keywords: Bamboo drip irrigation, Surface wetting patterns, Emission uniformity, Sustainable irrigation.

1. INTRODUCTION

Water scarcity is an escalating concern globally, affecting various sectors of human life and natural ecosystems (Rosegrant *et al.*, 2002). The rapid depletion of irrigation water resources is a significant contributor to this issue, compounded by growing populations and accelerated economic development in numerous nations. This challenge is particularly severe in arid and semi-arid regions, including India, where water resources are limited, and demand continues to rise (Biswas, 2001; Rosegrant *et al.*, 2002). Agriculture remains the sector with the highest water consumption globally. Consequently, the development and implementation of water-efficient and conservation-focused agricultural practices are vital for promoting sustainable development within the agricultural sector (Li *et al.*, 2023).

Among the water-efficient practices, drip irrigation has emerged as one of the most effective solutions to address water scarcity. Drip irrigation involves the efficient and

frequent delivery of water and nutrients directly to the crop root zone through emitters or drippers, significantly reducing water wastage (Ding *et al.*, 2019; Bajpai & Kaushal, 2020; Moursy *et al.*, 2023). The adoption of drip irrigation systems substantially improve water use efficiency by 60-200%, conserve water by 20-60%, and reduce fertilizer usage by 20-33%, enhances crop quality and increases crop yields by 7-25% compared to conventional irrigation methods (Guo & Li, 2024). Drip irrigation systems are particularly valued for their ability to deliver uniform water distribution across agricultural fields, ensuring reduced water loss from deep percolation, soil evaporation and runoff maintaining consistent moisture levels critical for healthy crop growth (Gil *et al.*, 2008; Guo & Li, 2024).

Despite these advantages, conventional drip irrigation systems rely on pipes primarily made of polyvinyl chloride (PVC). These materials are often imported, making them

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expensive and unaffordable for small-scale farmers (James, 1988; Fipps, 2003). Additionally, the production and disposal of PVC pipes pose environmental concerns due to their non-biodegradable nature. Given these challenges, the use of bamboo as an alternative material for constructing drip irrigation systems presents a promising solution. Bamboo is widely recognized as a "non-timber renewable forest product" and encompasses 1,575 species, which are used in a diverse range of applications (Paudyal et al., 2019).

The utilization of bamboo for water management is not a novel concept. In Meghalaya, a northeastern state of India, bamboo pipes have been used for water conveyance systems for over 200 years (Ryngnga, 2018). Sharma (2014) conducted an analysis of the physical properties of *Schizostachyum pergracile*, a bamboo species predominantly found in Manipur and extensively cultivated in Gujarat, revealing its suitability for use as pipes due to its favourable dimensions and structural characteristics. Subsequently, Agossou et al. (2017) highlighted the broader utility of bamboo, emphasizing its natural abundance, biodegradability, and cost-effectiveness as key attributes that position it as a sustainable and eco-friendly alternative to plastic components in drip irrigation systems, particularly in resource-limited contexts. Introducing bamboo as an alternative to conventional materials for drip irrigation systems offers significant benefits for small-scale farmers. Bamboo is cost-effective, environmentally friendly, and less polluting compared to PVC and asbestos-cement pipes.

The primary objective of this study is to evaluate the

performance of bamboo, particularly *Schizostachyum pergracile*, in a controlled low-pressure drip irrigation system, exploring its potential as a sustainable alternative for small-scale farming.

2. MATERIALS AND METHODS

The methodology involves a detailed sequence of analyses, beginning with an overview of the study area, followed by a description of the drip irrigation system. This includes the experimental setup and an evaluation of the system's hydraulic performance through the assessment of various uniformity parameters such as the coefficient of uniformity, coefficient of variation, friction loss, pressure-discharge relationship, emitter discharges, and surface wetting patterns. Finally, the economic aspects of laying the drip irrigation system are analysed to provide a comprehensive understanding of its feasibility and efficiency.

2.1. Study Area

The study was carried out at Bambusetum, College of Forestry (ACHF), Navsari Agricultural University located at 20°55'21.29" N latitudes, 75°54'16.00" E longitudes (Figure 1).

2.2. Bamboo Drip Irrigation Setup

Schizostachyum pergracile was chosen as the species for the construction of the bamboo drip irrigation system, taking into account its suitability owing to its straight culms, breakable internodes, hollowness, and degree of availability (Ryngnga, 2018). The irrigation system was evaluated in a subunit comprising a mainline (20 m in length) and six

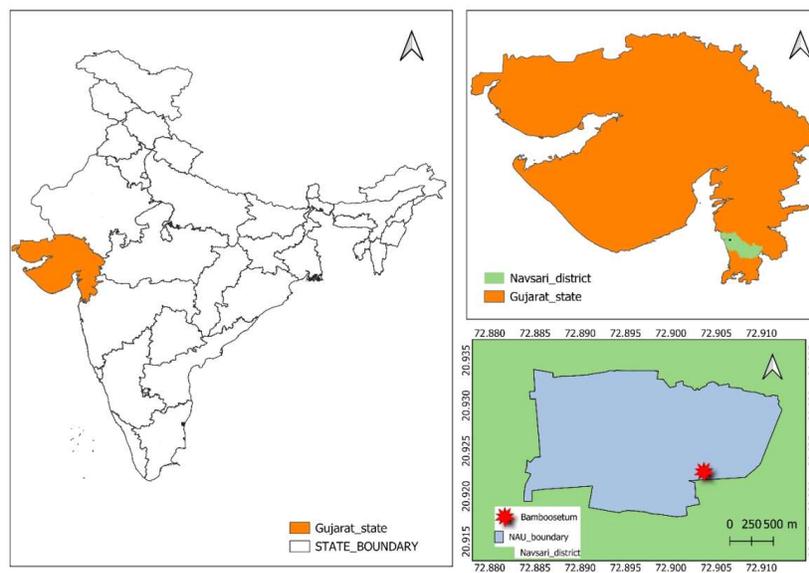


Figure 1. Location map of study area

lateral lines, each 6.1 m long and spaced 3 m apart, made of bamboo and set up on a flat surface. The septa of the nodes were removed using a metal rod and a hammer. Emitters were spaced 1 m apart on each lateral, with six drip points drilled using a sharp drill (Figure 2). The mainline and laterals were joined using a special adhesive blend of bamboo dust and Fevicol (serial no: 77345418) in equal proportions. For enhanced strength and waterproofing, an additional coating of Bondtite (parts A and B) was applied. The formal longevity testing was not conducted, similar composite bonding methods using wood adhesives have demonstrated adequate durability in short-term field use under low-pressure irrigation (Ella et al., 2013).

There were two types of emitters used in this study. The first comprised six medi-infusion tubes inserted into the first lateral (T1) (Mofoke et al., 2004; Awe & Ogedengbe, 2011). The second to fifth laterals (T2 to T5) employed bamboo microtubes with internal diameters of 0.3 cm, 0.4 cm, 0.5 cm, and 0.6 cm, respectively, as emitters. A PVC lateral with conventional emitters served as the control (T6). All emitters were inserted into pre-drilled drip points on the respective laterals. Water was supplied using a 1.0 HP centrifugal motor pump, commonly used in small-scale irrigation setups. Operating pressures were recorded at the mainline inlet using a pressure gauge and corresponded to stabilized levels of 1.3, 1.4, and 1.5 kg/cm² achieved by adjusting the pump output. These pressure levels were used to assess emitter discharge and hydraulic performance under controlled low-pressure

conditions representative of field-relevant scenarios. A test run was conducted prior to data collection to ensure proper functioning and to correct any leakage. The study was conducted for almost a period of 3 months. During the field assessment, catch cans were positioned beneath the emitters, and the system was operated for 5 minutes. The emitter discharge collected in the catch cans was then measured using a measuring cylinder based on volume. The discharge rate of the emitters was calculated through volumetric measurements over the specified time period.

2.3. Hydraulic Performance of Drip Irrigation System

The hydraulic performance of the drip irrigation system was evaluated using various uniformity parameters, including the coefficient of uniformity (CU), coefficient of variation (CV), friction loss (Hf), pressure-discharge relationship, emitter discharge, and surface wetting patterns. Discharge was recorded from each emitter under three pressure levels, resulting in 18 observations per treatment and 108 total observations across all treatments. These values were used to calculate mean discharge, CU, and CV and other parameters. In this study, coefficient of uniformity (CU) and coefficient of variation (CV) were used to evaluate the hydraulic performance of bamboo and PVC-based laterals. Additionally, the economics of installing the bamboo-based system was analysed and compared with a conventional PVC drip irrigation system.

2.4. Coefficient of Uniformity (CU)

The coefficient of uniformity (CU), defined by Christiansen (1942), measures the average deviation from the average depth of water application. It is influenced by factors such as operating pressure, emitter spacing, land slope, pipe size, and discharge variability. The formula for CU is (Eq. 1):

$$CU = 1 - \frac{\sum_{i=1}^n qi - \bar{q}}{N\bar{q}} \dots\dots\dots(1)$$

Where CU is the coefficient of uniformity, *qi* = emitter discharges in l hr⁻¹, *q* = average discharges in l/hr and N= total number of emitters in a lateral.

2.5. Coefficient of Variation (CV)

Flow variations among emitters of the same type can occur due to factors such as clogging from particulate matter, chemical precipitates, and organic growth, leading to non-uniform water application. Analysing these variations helps in the proper design of the drip system. The coefficient of variation (CV), a statistical parameter, was used to evaluate emitter discharge variations across laterals under different pressures. It was calculated using the formula defined by Keller and Karmeli (1974).

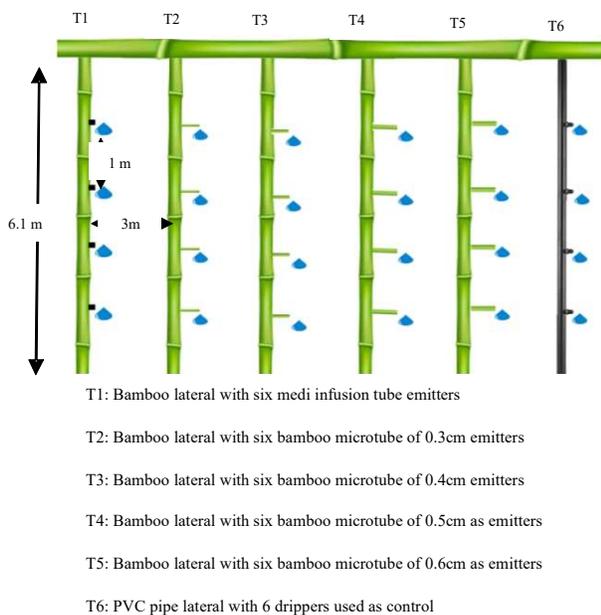


Figure 2. Layout of the drip irrigation system

$$CV = \frac{S}{\bar{q}} \dots\dots\dots (2)$$

Where CV stands for coefficient of variation, S stands for standard deviation of all emitters and q stands for average emitter discharges expressed in l/hr.

2.6. Friction Loss (Hf)

Friction loss or head loss (Hf) occurs due to the materials used in the drip irrigation system and the insertion of laterals and emitters. In bamboo drip systems, it is attributed to the bamboo material and the insertion of components. The Darcy-Weisbach equation (Michael, 2009), which is effective for small-diameter laterals, was used to calculate friction loss for average emitter discharges under pressure values of 1.3, 1.4, and 1.5 kg/cm². The equation 3 is as follows:

$$Hf = \frac{fL}{D} \frac{V^2}{2g} \dots\dots\dots (3)$$

Where Hf stands for head loss expressed in meters, f stands for friction factor which is 0.02 for bamboo (Merriam & Keller, 1978), L stands for length of the pipe expressed in meter, D stands for diameter of the pipe expressed in meter, V represents fluid flow velocity expressed in m/s and g represents acceleration due to gravity (9.8m/s).

2.7. Pressure Discharge Relationship

Pressure-discharge models were developed to optimize emitter selection and operating pressures. Data for pressures (1.3, 1.4, and 1.5 kg/cm²) were measured, and emitter volumes were recorded. Using Microsoft Excel, an exponential function was fitted, and R² values were calculated to assess the correlation between pressure and discharge. Dripper flow rate is expressed as a function of pressure in the following manner (Eq. 4):

$$Q = Kp^X \dots\dots(4) \text{ (Keller \& Karmeli, 1974)}$$

Where Q stands for dripper discharge expressed in l hr⁻¹, K stands for coefficient of proportionality, P stands for operating pressure expressed as kg/cm² and X stands for emitter discharge exponent.

2.8. Discharge of Emitters

The discharge rate of each emitter was measured by collecting water in catch cans for 5 minutes, recording the volume in millilitres using a measuring cylinder, and repeating the process three times for accuracy. The values, converted to litres per hour, were averaged and calculated for pressures of 1.3, 1.4, and 1.5 kg/cm² (Michael, 2009), with pressure measured using a gauge connected to the main valve with the following equation 5:

$$Q = \frac{\text{volume of water collected}}{\text{time}} \dots\dots (5)$$

2.9. Surface Wetting Pattern

The surface wetting pattern was evaluated by measuring the horizontal wetted diameter at 10, 20, and 30 minutes after irrigation using a standard measuring tape. The wetted area was approximated as an ellipse using the formula A = πAB (Keller & Bliesner, 1990), where A and B represent half of the measured horizontal diameters along two axes (Eq.6).

$$A = \pi * A * B \dots\dots(6)$$

Where, π (pi) value is 3.14, A stands for half of the horizontal diameter and B stands for half of vertical diameter.

2.10. Economics of Laying the System

The economics of the bamboo drip irrigation system was compared to a hypothetical conventional system using identical area, pipe length, lateral length, and number of emitters. Feasibility was assessed based on costs for cutting, assembling, and installation to determine its practicality for the forested watershed of South Gujarat.

3. RESULTS AND DISCUSSION

3.1. Coefficient of Uniformity (CU) and Coefficient of Variation (CV)

The PVC control (T6) exhibited the highest uniformity (CU ≥ 96.24%) and lowest variation (CV ≤ 0.05), (Table 1)

Table 1. Coefficient of uniformity and coefficient of variation in different treatments

Treatment	Coefficient of uniformity (%)			Coefficient of variation		
	Pressure range (kg/cm ²)					
	1.3	1.4	1.5	1.3	1.4	1.5
T1	89.77	88.40	87.99	0.1	0.15	0.14
T2	54.63	52.29	56.15	0.52	0.59	0.65
T3	51.21	51.21	50.89	0.52	0.63	0.59
T4	58.89	58.89	56.35	0.62	0.48	0.25
T5	81.59	81.59	56.35	0.36	0.25	0.55
T6	96.24	96.24	90.38	0.05	0.05	0.04

consistent with global standards for efficient micro-irrigation (Bralts et al., 1981; Solomon, 1985). Among the bamboo treatments, T5 (0.6 cm bamboo microtubes) performed best (CU: 81.59%, CV: 0.25–0.55), likely due to reduced internal friction and smoother discharge paths. These findings align with earlier observations that larger emitter diameters improve flow stability and uniformity in low-cost systems (Ella et al., 2013; Sokol et al., 2019). T1 (medi-infusion tubes) also performed reliably, with CU > 87%, showing potential for hybrid applications using commercial components in traditional materials. T2 and T3, which used smaller diameter bamboo emitters (0.3 and 0.4 cm, respectively), demonstrated the poorest performance. This may be attributed to higher head losses and clogging susceptibility due to narrower internal paths—issues well-documented in uniformity studies of non-compensating emitters (Gil et al., 2008).

Overall, while bamboo systems cannot yet match the uniformity of standard PVC setups, treatments like T5 and T1 show promising performance, especially under controlled pressure conditions. Moreover, these systems offer a sustainable and low-cost alternative, particularly for smallholder or hill farming regions (Jeeva et al., 2006; Maurya & Singh, 2021).

3.2. Flow Dynamics and Efficiency

The T6 (PVC lateral) had the lowest friction loss (0.0015–0.00168 m), highest discharge coefficient (6.606), and a stable pressure–discharge exponent of 0.886 (Table 2). Exponents between 0.4 and 1.0 indicate predictable and hydraulically stable flow. In contrast, bamboo microtubes—especially T2 (0.3 cm)—had higher friction losses and unstable exponents (>10), reflecting pressure-sensitive discharge (Kirnak et al., 2004). T5 (0.6 cm) performed better, with lower friction loss (0.0202–0.0344 m) and a moderate exponent (6.169), consistent with findings that

larger diameters and smoother surfaces improve uniformity (Obio et al., 2013; Chen et al., 2022). Modifications like bore standardization, internal polishing, or resin/wax coatings can reduce resistance and improve flow stability (Awe & Ogedengbe, 2011). Although tested under moderate pressure (1.3–1.5 kg/cm²), the high CV in bamboo treatments reflects discharge inconsistency more than pressure effect. Prior studies confirm that optimized bamboo systems can function efficiently under low-pressure, gravity-fed conditions, making them suitable for smallholder use (Awe & Ogedengbe, 2011; Obio et al., 2013).

3.3. Discharge of Emitters

There were significant differences in emitter discharge across treatments (Table 3). The PVC pipe drippers (T6), with a rated discharge of approximately 8 l/hr, maintained consistent output across pressures (7.94–8.42 l/hr). This stability can be attributed to low friction loss, high manufacturing precision, and pressure-regulated discharge, typical of commercial emitters (Bralts et al., 1981; Keller &

Table 3. Average discharge of emitters (l/hr) with pressure (kg/cm²)

Treatment	Average discharge of emitters (l/hr) with pressure (kg/cm ²)		
	1.3	1.4	1.5
T1	1.17	1.56	1.28
T2	3.15	2.61	0.52
T3	5.81	2.95	12.34
T4	11.48	7.84	18.68
T5	14.21	8.01	18.54
T6	7.94	8.28	8.42
CD (p=0.05)	4.56	2.78	7.13
C.V. (%)	52.54	44.91	60.21

Table 2. Friction loss and pressure discharge relationship of the emitters

Treatment	Friction loss (mm)			Developed model	Pressure discharge		
	Pressure range (kg/cm ²)				Discharge Coefficient	Exponent	R ²
	1.3	1.4	1.5				
T1	0.03327	0.05915	0.03982	Q=0.654P ^{2.030}	0.654	2.030	0.95
T2	0.03176	0.02180	0.00087	Q=0.018P ^{12.88}	0.018	12.88	0.84
T3	0.02564	0.00661	0.11567	Q=0.186P ^{10.12}	0.186	10.12	0.99
T4	0.03280	0.01530	0.08685	Q=1.366P ^{6.039}	1.366	6.039	0.88
T5	0.02020	0.00642	0.03438	Q=1.640P ^{6.169}	1.640	6.169	0.96
T6	0.00150	0.00163	0.00168	Q=6.606P ^{0.886}	6.606	0.886	0.99

Bliesner, 1990). T6 delivered uniform wetting, aligning with its low CV and high CU observed earlier. In contrast, bamboo microtubes showed greater variability. For instance, T2 (0.3 cm) experienced a sharp discharge decline from 3.15 to 0.52 l/hr with increasing pressure. This may be due to increased head loss, localized clogging, or flow turbulence in the narrow lumen at higher velocities, phenomena well-documented in drip systems using unrefined or small-diameter materials (Kirnak et al., 2004, Gil et al., 2008). Similarly, the sharp increase in discharge observed in T3 and T4 under rising pressure may result from sudden shifts from laminar to transitional or turbulent flow in inconsistently polished bamboo tubes. Minor changes in surface roughness or lumen shape can dramatically alter flow behavior, leading to the observed non-linearity-especially in naturally variable materials like bamboo. On the other hand, T5 (0.6 cm) exhibited the highest discharge (14.21–18.54 l/hr), indicating that larger internal diameters reduce resistance and enhance flow capacity (Chen et al., 2022). Skaggs et al. (2004, 2010) demonstrated that wider emitters promote greater horizontal soil wetting, which complements findings that bamboo microtubes, when properly dimensioned and polished, can mimic the performance of PVC systems (Bidondo et al., 2010; Awe & Ogedengbe, 2011)

3.4. Surface Wetting Pattern

Surface wetting patterns differed markedly across treatments (Table 4). T5 (0.6 cm bamboo) produced the widest horizontal spread-up to 6032 cm² at 1.5 kg/cm² in 30 min-while T2 (0.3 cm) managed only ~1948 cm², reflecting its lower discharge and higher flow resistance. These findings align with studies showing that higher emitter discharge leads to increased lateral spread, especially in sandy loam soils where infiltration capacity is high and vertical penetration exceeds lateral expansion (CGWB, 2013; Naglic et al., 2014; Onwuegbunam et al.,

2019). The wetted diameters observed in sandy loam setups ranged from 15 to 23 cm in 30-75 min, with limited depth spread supporting the trends (Table 4). The study measured only horizontal wetted area as vertical infiltration data were not collected. This methodological limitation will be addressed in future investigations. The high discharge can risk surface ponding in slower soils, no ponding was observed, suggesting that the sandy loam in this trial accommodated the flow without exceeding its infiltration capacity. From an agronomic standpoint, a broader wetted surface improves moisture availability in the root zone, benefiting shallow-rooted crops and enhancing nutrient uptake efficiency (Kandelous & Simunek, 2010). Hence, emitter selection and spacing must be tailored not only for hydraulic performance but also for crop-specific rooting depth and water requirements to maximize irrigation efficiency (Bozkurt et al., 2006). Optimizing bamboo microtubes by increasing diameter and reducing internal roughness has clear benefits, delivering wider and more uniform surface coverage. However, future validation should include vertical infiltration behaviour and soil-specific performance, especially when considering irrigation in different soil textures.

3.5. Economics of Laying the System

The cost analysis indicates that bamboo drip irrigation is marginally more economical than conventional systems, with a total cost of ₹17,280 per 122 m² compared to ₹17,650 for conventional drip (Table 5). The slightly lower initial investment (₹16,530 vs. ₹16,720) and maintenance costs (₹331 vs. ₹349) contribute to this difference, while water and labour expenses remain constant. Although the immediate financial savings are modest, bamboo offers certain practical advantages such as local availability, biodegradability, and reduced material dependence on plastics. In regions where bamboo is abundant and locally treated to enhance

Table 4. Surface wetting pattern across different treatments

Treatment	Area (cm ²) covered under the surface wetting pattern of 1.3kg/cm ²			Area (cm ²) covered under the surface wetting pattern of 1.4kg/cm ²			Area (cm ²) covered under the surface wetting pattern of 1.5kg/cm ²		
	10 min	20 min	30 min	10 min	20 min	30 min	10 min	20 min	30 min
T1	461.58	659.40	967.12	372.87	631.92	1001.66	439.60	678.24	879.20
T2	760.05	1285.27	1832.57	888.54	1639.90	1889.99	607.96	1113.15	1948.19
T3	854.08	1601.63	2136.00	795.36	1236.35	1609.25	907.36	1848.45	2431.44
T4	1732.25	2748.15	2092.38	505.54	1287.85	1880.88	1002.34	2431.44	3590.93
T5	1753.29	3047.03	4039.61	1810.83	2776.02	3202.70	1298.79	3360.12	6032.14
T6	961.62	1103.71	1318.80	827.39	1103.71	1350.20	753.60	960.84	1193.20

Table 5. Comparative statement of cost of bamboo drip and conventional drip

Particulars	Bamboo drip irrigation	Conventional drip irrigation
Initial investment (Rs/122m ²)	16,530	16,720
Maintenance cost (Rs/122m ²)	331	349
Water cost (Rs)	230	230
Labour cost (Rs)	700	700
Total cost (Rs)	17280	17650

durability, components may be reused across short-term cycles-particularly in gravity-fed systems where pipes are aboveground-leading to lower per-season costs. PVC systems are more durable and standardized, bamboo-based systems may still serve as a low-cost, transitional alternative for smallholder or resource-constrained contexts with access to bamboo. Previous studies have highlighted its application in traditional irrigation in such regions, supporting its use with appropriate design and handling practices (Swami, 2021, Pan et al., 2023). However, the environmental sustainability of bamboo-based systems must be weighed against their limited lifespan under field conditions. Studies indicate that untreated bamboo is susceptible to biodegradation and fungal attack, often deteriorating within 6–24 months (Kaur et al., 2016 and Liu, 2023). The preservative treatments using crude lake salt and borax-boric acid have been shown to significantly extend the service life of bamboo under fungal exposure (Mwanja et al., 2024), making such systems more viable for repeated seasonal use. These findings highlight the need for proper treatment and maintenance protocols if bamboo-based drip systems are to be considered for wider adoption.

4. CONCLUSION

This study evaluated the hydraulic performance, surface wetting patterns, and cost effectiveness of bamboo microtube-based drip irrigation systems under varying lateral diameters. The bamboo systems are capable of delivering water, they currently fall short of standard performance benchmarks. The high discharge rates, poor emission uniformity, and high variability were observed, especially in treatments with smaller diameters. These inconsistencies limit the reliability of the system under variable pressure conditions. Although larger-diameter bamboo laterals showed improvements in discharge rate and lateral wetting area, these gains were not sufficient to achieve acceptable uniformity or flow stability. Furthermore, only the horizontal spread of moisture and

absence of vertical infiltration restricts the completeness of the wetting pattern analysis. Additionally, the high discharge rates may risk surface ponding, which runs counter to the principles of efficient drip irrigation. There was some potential for economic benefit in bamboo-abundant regions, the savings alone do not justify widespread adoption given the hydraulic limitations.

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Authors' Contributions

Haripriya S: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing the original draft. P.K. Shrivastava: Conceptualization, Supervision, Validation, Writing – review & editing. Nirav Pampaniya: Data analysis and tabulation. Dileshwar Nayak: Technical support, Instrumentation. Jayendra Chawda: Field experimentation, Data collection. Jayesh Pathak: Supervision, Project administration

Conflict of 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 paper.

Declaration of Generative AI and AI-assisted technologies

The authors declare that no generative AI tools were used in the preparation of this manuscript.

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