

The Relationship Between Climatic Conditions and Bamboo Water Potential in the Sandan Forest

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ABSTRACT

Bamboo is a fast-growing and ecologically significant plant that contributes to hydrological stability, soil conservation, and sustainable construction, particularly in tropical regions such as Bali. Beyond its mechanical and ecological importance, bamboo culms serve as natural water reservoirs capable of storing substantial volumes within their internodes. This hydrological function is strongly influenced by climatic factors such as rainfall, temperature, relative humidity, and wind speed, which regulate water absorption, storage, and transpiration processes within bamboo tissues. Understanding the relationship between climatic conditions and bamboo water potential is crucial for assessing its role in hydrological balance, ecosystem stability, and sustainable water resource management. However, limited research has explored how climate variability affects bamboo's internal water dynamics in humid tropical environments. This study aims to analyze the influence of climatic factors on the water potential of bamboo species in Sandan Forest, Baturiti District, Tabanan Regency. The research integrates ten years of climatic data (2014–2024) from NASA POWER with field measurements of bamboo water volume. The climatic parameters analyzed include rainfall (mm), temperature (°C), relative humidity (%), and wind speed (m/s). The findings from the Sandan Forest study demonstrate that climatic conditions, although relatively uniform across the observation period, significantly interact with the physiological characteristics of bamboo species to influence their water potential. The average annual climate—comprising rainfall of 5,441.94 mm, temperature of 25.47°C, relative humidity of 84.43%, and wind speed of 1.35 m/s—creates a humid environment favorable for bamboo growth and water retention. Results indicate that rainfall and relative humidity have a positive correlation with bamboo water potential, enhancing water absorption and retention, while temperature and wind speed show negative relationships by increasing evapotranspiration and water loss.

KEYWORDS:- Bamboo, water potential, climatic factors, hydrological balance, eco-hydrological

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I. INTRODUCTION

Bamboo is a fast-growing plant species with high ecological and hydrological importance, particularly in tropical regions such as Bali [1], [2], [3]. As a natural material, bamboo plays a crucial role in soil and water conservation, acting as a bioengineering agent that stabilizes slopes, reduces runoff, and enhances groundwater recharge [4], [5], [6]. Beyond its ecological functions, bamboo culms also serve as natural water reservoirs, capable of storing considerable volumes of water within their internodes. This hydrological property makes bamboo not only significant for environmental sustainability but also for its potential use in engineering applications, especially in green infrastructure and sustainable construction. However, the water potential within bamboo culms is highly dependent on climatic conditions, such as rainfall, air temperature, relative humidity, and wind speed, which collectively influence the bamboo's water absorption, storage, and transpiration dynamics.

Despite the known climatic sensitivity of bamboo, previous studies have primarily focused on bamboo's mechanical and structural properties—such as tensile strength, elasticity, and durability [7], [8], [9] while only a limited number of studies have examined how climatic variability affects the water potential and internal moisture content of bamboo species. This creates a knowledge gap in understanding the hydrological behavior of bamboo in response to environmental fluctuations, particularly within tropical monsoonal ecosystems.

Such information is vital because water potential directly influences bamboo's physiological health, mechanical performance, and its role in maintaining watershed stability.

Plant–climate interactions have demonstrated that climatic factors, such as precipitation and temperature, significantly affect the water balance of vegetation; yet, most of these studies have concentrated on crops and forest trees [10], [11]. The specific response of bamboo species to multi-year climatic variations remains underexplored, especially in the context of Southeast Asia's humid tropical environment. Recent advances in climate–vegetation modelling and hydrological monitoring offer opportunities to quantitatively assess these interactions, facilitating a deeper understanding of how bamboo adapts to changes in rainfall patterns, temperature regimes, and atmospheric moisture.

This study emphasizes the need to understand the relationship between climatic conditions and the water potential within bamboo culms. Changes in rainfall, temperature, humidity, and wind speed can significantly influence the physiological processes that regulate water absorption and storage in bamboo. Understanding these interactions is essential for assessing the role of bamboo in regional hydrological systems, particularly in relation to water resource sustainability, ecosystem stability, and adaptation to climate variability. Furthermore, as bamboo continues to be promoted as a sustainable material for construction and environmental engineering, knowledge of its water storage potential under different climatic conditions becomes increasingly important for optimizing its ecological and practical functions.

This research lies in its integrative approach, combining multi-year climatic analysis (2014–2024) with direct field measurements of bamboo water potential. By linking meteorological parameters—rainfall, temperature, relative humidity, and wind speed—with the measured water volume within bamboo culms of different species (*Dendrocalamus asper*, *Bambusa jajang*, and *Bambusa tali*), this study provides a new quantitative perspective on the hydrological response of bamboo to climate variability.

The aim of this research is to analyze the influence of key climatic factors on the water potential of bamboo species in the Sandan Forest area. Specifically, the study seeks to (1) examine long-term climatic trends and their seasonal behavior, (2) evaluate how each climatic variable affects bamboo's internal water content, and (3) identify species-specific physiological adaptations that determine their capacity to store water. The outcomes of this research are expected to contribute to sustainable bamboo utilization strategies and the development of nature-based engineering solutions for watershed and ecosystem resilience under changing climatic conditions.

II. RESEARCH METHODS

Research Location

This research was conducted at Sandan Forest, Baturiti District, Tabanan Regency. The selection of these sites is based on the diversity of bamboo species growing in the area and the varying environmental conditions that may influence the quantity of water stored within bamboo culms. Sandan Village is situated at an elevation of approximately 1,200 meters above sea level, with an annual rainfall ranging from 2,000 to 3,000 mm, an average temperature of 18°C–25°C, and a relatively high humidity level of 80%–90%. The dominant soil type in this area is Andosol, which is rich in nutrients and supports the growth of various bamboo species such as *Dendrocalamus asper* (Petung bamboo), *Gigantochloa apus* (Tali bamboo), and *Gigantochloa atter* (Jajang bamboo). The moist tropical rainforest environment makes this area an ideal location for observing how high rainfall conditions influence the water content within bamboo stems.



Figure 1. Sandan Forest

Research Data and Tools

The data used in this study consist of climatic parameters and field measurements of bamboo water potential. Climatic data were obtained from the NASA POWER Data Access Viewer (<https://power.larc.nasa.gov/data-access-viewer/>) for the period 2014–2024, representing a ten-year climate record of the study area. The parameters collected include monthly and annual data on rainfall (mm), air temperature (°C), relative humidity (%), and wind speed (m/s). These variables were selected because they are key climatic factors influencing evapotranspiration, water balance, and plant–water interactions. The dataset was

downloaded in tabular format (CSV) and processed using Microsoft Excel to calculate annual averages, visualize temporal trends, and perform regression analyses between climate variables and bamboo water potential.

For field measurements, direct sampling of bamboo culms was carried out in the Sandan Forest, Baturiti District, Tabanan Regency, focusing on three bamboo species: *Dendrocalamus asper* (Petung), *Gigantochloa apus* (Tali), and *Gigantochloa atter* (Jajang). The volume of water contained within bamboo internodes was measured using a measuring cylinder (graduated glass) for volume quantification, a sharp knife for cutting and sectioning culms, and Microsoft Excel for data tabulation and analysis. The measurements were expressed in millilitres (ml) and averaged for each species.

Research Analysis Methods

This study employed a descriptive analytical approach to investigate the relationship between climatic factors and bamboo water potential, aiming to identify patterns, correlations, and variations between key climate parameters—namely rainfall, temperature, relative humidity, and wind speed—and the measured water volume within bamboo culms of different species.

Data collection integrated both secondary and primary sources. Climatic data were obtained from the NASA POWER database for the coordinates corresponding to Sandan Village, encompassing monthly and annual datasets from 2014 to 2024. These data provided a comprehensive overview of the local climatic trends over the past decade. Primary field data were gathered through direct measurement of the water volume stored in bamboo culms. Each bamboo specimen was cut at the internode section, and the released water was carefully collected in a graduated cylinder. The total volume of water for each bamboo species—Petung, Jajang, and Tali—was recorded and averaged to represent the species' water potential.

Data processing was conducted using Microsoft Excel. The climatic data were analyzed to determine annual averages and temporal patterns, with polynomial regression applied to identify increasing, decreasing, or stable trends over the observation period. Correlation analyses were then performed to determine the strength and direction of the relationships between each climatic factor and the bamboo water potential.

Descriptive analysis provided a comparative interpretation of how each climatic variable influences the hydrological behavior of bamboo. The relationship between rainfall and bamboo water potential highlighted the impact of water availability within the root zone. Temperature analysis emphasized the role of thermal energy in controlling transpiration and evaporation rates, while relative humidity analysis revealed how atmospheric moisture affects the bamboo's ability to retain water within its culms. The influence of wind speed was also evaluated to understand how air movement accelerates water loss from bamboo tissues through enhanced evapotranspiration.

Through this comprehensive descriptive approach, the study synthesized climatic data trends with field observations to elucidate the adaptive capacity of each bamboo species under specific climatic conditions. The findings demonstrate that environmental variability significantly affects bamboo's internal water balance, thereby influencing its hydrological properties and overall resilience. These insights are crucial for eco-hydrological management, sustainable bamboo utilization, and the formulation of climate adaptation strategies in regions where bamboo ecosystems play a vital role in water conservation and environmental stability.

III. RESULT AND DISCUSSION

Precipitation

Based on Figure 2, the monthly precipitation pattern shows that rainfall is highest from December to February, with monthly totals exceeding 300 mm, indicating the dominance of the northwest monsoon that brings moist air masses from the Indian Ocean. During this period, the atmosphere is saturated with humidity, leading to frequent heavy rainfall events and overcast conditions. Conversely, from June to September, rainfall drops drastically to below 50 mm/month, marking the dry season under the influence of the southeast monsoon, which carries dry air from the Australian continent. The transitional months, particularly April–May and October–November, act as shoulder seasons, with moderate rainfall marking the shift between the wet and dry phases. This clear rainfall seasonality suggests that water availability and river discharge in the area are highly dependent on the monsoonal cycle.

The annual precipitation trend (2014–2024) indicates notable interannual variability, with alternating wet and dry years. Rainfall peaks occurred in 2016–2017 and 2021–2022, with annual totals surpassing 2000 mm, while minimum values around 2019 dropped to approximately 1100 mm/year. The high R^2 value (0.9815) of the polynomial regression demonstrates a strong cyclical pattern, implying that rainfall variability may be influenced by large-scale climatic oscillations such as the El Niño–Southern Oscillation (ENSO). During El Niño years, rainfall tends to decrease, often leading to drought, while La Niña phases contribute to above-average precipitation and possible flooding.

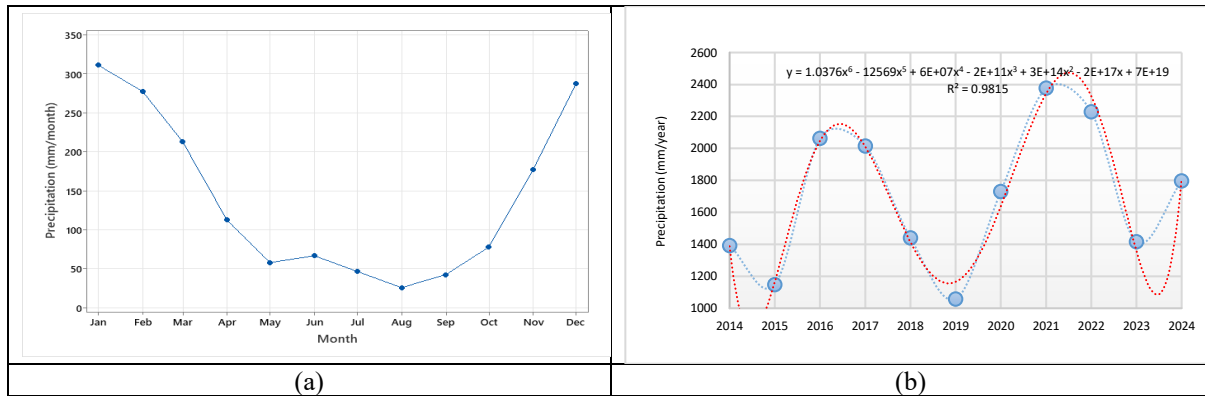


Figure 2. Precipitation Trend

Wind Speed

Based on Figure 3, the wind speed data show an inverse relationship to rainfall. On a monthly scale, wind speeds are lowest during February–March (around 1.5 m/s) and increase steadily toward the dry season, reaching a peak of nearly 3.0 m/s in August. This pattern suggests that the dry season is typically windier, which can enhance evaporation rates, lower humidity, and increase fire risk in vegetation-dominated landscapes. The higher wind activity during mid-year months may also be associated with the stronger southeast trade winds, which are a defining feature of the dry monsoon.

The annual wind speed trend (2014–2024) exhibits less pronounced variability compared to precipitation, ranging between 2.0–2.4 m/s with an R^2 of 0.6628, indicating moderate predictability. The observed oscillations suggest that while annual averages are relatively stable, short-term fluctuations are common due to local atmospheric dynamics, topography, and land–sea interactions.

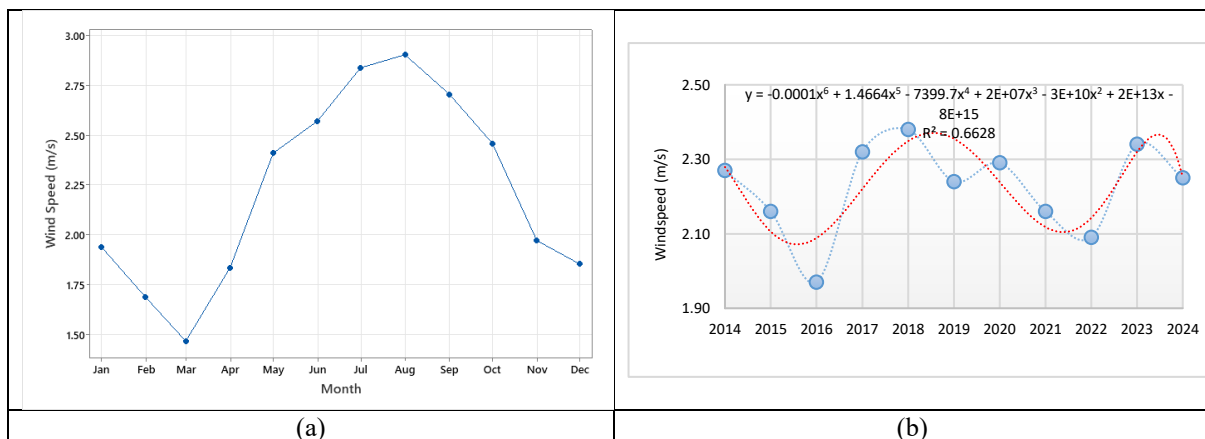


Figure 3. Windspeed Trend

Temperature

Based on Figure 4, the monthly temperature pattern shows that the average temperature fluctuates between approximately 23.9°C and 26.5°C throughout the year. The highest temperature is observed around November, while the lowest occurs in July and August, indicating a clear seasonal cycle between the dry and wet seasons. From an engineering and hydrological perspective, this variation has a significant influence on evapotranspiration processes within the watershed. Higher temperatures during the dry season increase evaporation from soil and transpiration from bamboo leaves, thereby reducing available soil moisture and water content within bamboo tissues. Conversely, cooler months promote lower evapotranspiration rates, allowing the soil to retain more water and enabling bamboo culms to absorb and store more moisture. This relationship implies that bamboo growing during the cooler, wetter months maintains a higher internal water quantity, enhancing its flexibility and mechanical stability — an important consideration in the use of bamboo as a sustainable construction material. The yearly temperature trend from 2014 to 2024 shows moderate fluctuations between 25°C and 26°C, with a polynomial regression indicating a slight increase toward recent years. The regression coefficient ($R^2 = 0.4635$) suggests that temperature changes are moderately correlated with time, implying potential climatic warming tendencies. In engineering terms, such long-term temperature changes affect the hydrological balance of the watershed and the thermal behavior of vegetation, such as bamboo. A gradual increase in temperature may lead to higher long-term evapotranspiration rates, which can deplete soil moisture reserves and reduce the amount

of water available for bamboo uptake. This has implications for bamboo's water content stability and overall resilience under climate change scenarios. Monitoring these temperature trends becomes essential for sustainable watershed and vegetation management, especially in areas like the Tukad Mati watershed where bamboo plays a vital role in soil and water conservation.

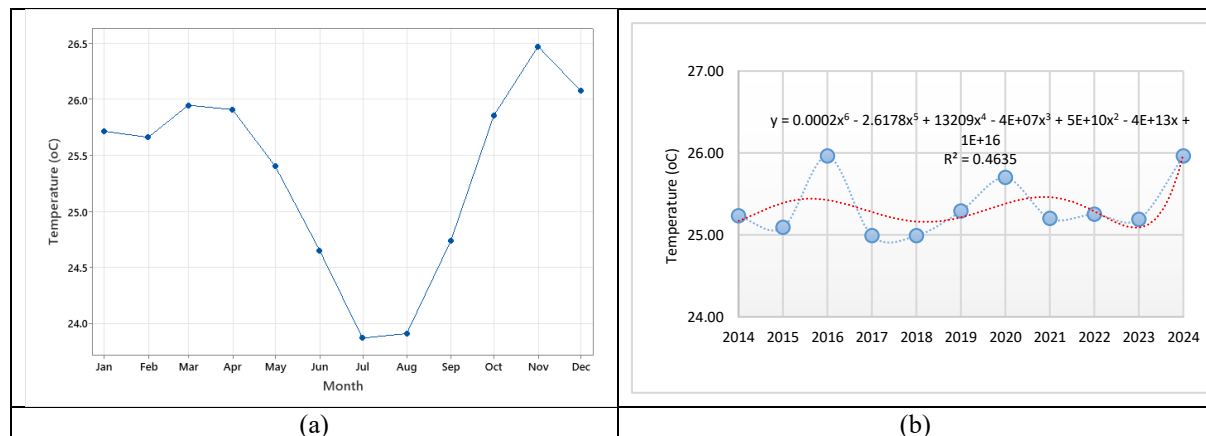


Figure 4. Temperature Trend

Relative Humidity

Based on Figure 5, the monthly variation in relative humidity (RH) reveals that humidity is highest between January and June, reaching values around 85–86%, and lowest between September and October, dropping to about 79–81%. This inverse relationship with temperature reflects the regional climatic pattern, where the rainy season supports higher moisture content in the air and the dry season brings lower humidity. From an engineering hydrology perspective, relative humidity strongly affects the vapor pressure deficit (VPD), which governs the rate of water loss from plant surfaces. Low humidity during high-temperature months increases the VPD, causing faster transpiration and dehydration of bamboo tissues, which in turn lowers bamboo water quantity. On the other hand, high humidity conditions during cooler months slow down water loss, allowing bamboo culms to maintain higher internal moisture. This mechanism highlights how microclimatic conditions directly influence bamboo's physiological water balance, impacting its structural integrity and suitability for use in engineering applications such as green building materials and slope stabilization. Over the 2014–2024 period, relative humidity shows a strong cyclical trend, with significant peaks around 2016–2017 and 2021–2022, and a high correlation coefficient ($R^2 = 0.9311$) indicating a consistent seasonal rhythm. These oscillations likely correspond to monsoon activity and regional climate cycles that regulate atmospheric moisture. From an engineering standpoint, the stability of relative humidity trends suggests predictable patterns in soil moisture availability and plant-water interactions. For bamboo ecosystems, high-humidity years favor greater water retention in the plant's cellular structure, supporting optimal growth and mechanical strength. Conversely, years with lower average humidity can lead to stress conditions that reduce bamboo water content and may affect the material's dimensional stability when used in structural applications.

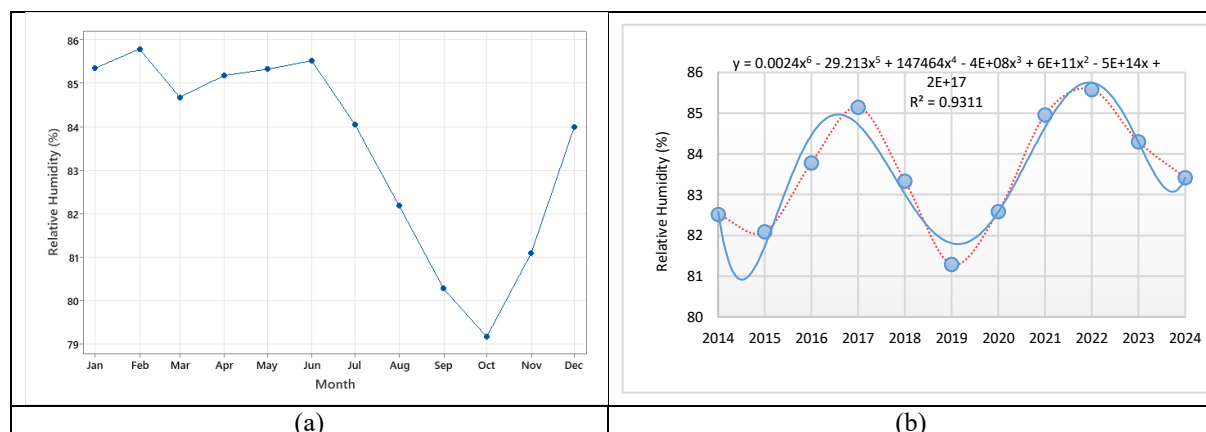


Figure 5. Relative Humidity Trend

The Influence of Climatic Factor on the Water Potential in Bamboo

The water potential within bamboo culms is strongly influenced by surrounding climatic conditions, particularly rainfall, air temperature, relative humidity, and wind speed. These four factors collectively determine the bamboo's water balance — the equilibrium between water absorbed through the roots and water lost through transpiration and evaporation from the surface of the culms and leaves.

Rainfall serves as the primary source of water available for absorption by the bamboo root system [12]. Higher rainfall intensity and frequency increase soil moisture availability in the root zone [13], thereby enhancing water uptake and storage within the culm tissues. Conversely, during dry seasons with low rainfall, groundwater availability decreases, resulting in reduced internal water pressure within bamboo tissues. This condition can significantly lower the water volume stored in the culm, particularly for bamboo species with low water retention capacity. Therefore, rainfall has a positive correlation with the bamboo's water potential, as it increases the water supply available to the plant system.

Air temperature plays a crucial role in regulating the rate of transpiration and evaporation from bamboo culms [14]. At higher temperatures, the increased thermal energy in the atmosphere accelerates the evaporation of water from leaf and culm surfaces. Consequently, the internal water content decreases if root water uptake cannot compensate for the loss. In contrast, under lower temperature conditions, transpiration rates decline, allowing more water to be retained within the culm tissues. Hence, temperature has a negative relationship with the water potential of bamboo — the higher the air temperature, the lower the water content that can be maintained within the culm.

Relative humidity of the air also influences the bamboo's water balance. When relative humidity is high, the air contains more water vapor, reducing the vapor pressure gradient between the plant surface and the atmosphere [15], [16]. This condition suppresses transpiration and evaporation rates, enabling bamboo to retain more water within its culms. Conversely, at low relative humidity, the humidity gradient increases, leading to faster evaporation of water from plant tissues into the air.

Wind speed also plays a significant role in influencing the water potential within bamboo culms. Wind enhances the movement of air around the plant surface, which increases the rate of water vapor removal from the leaf and culm boundary layers. When wind speed is high, this continuous removal of moist air promotes faster transpiration and evaporation, accelerating water loss from the plant tissues [17]. As a result, if the rate of water absorption through the roots cannot keep up with the rate of water loss, the internal water content in the bamboo culm will decrease. In contrast, under low wind speed conditions, the air layer surrounding the bamboo remains more stable and humid, slowing down the diffusion of water vapor and allowing the culm to retain more moisture. Therefore, wind speed typically shows a negative correlation with the water potential of bamboo — the stronger the wind, the greater the rate of water loss and the lower the volume of water that can be stored in the culm.

The Relationship Between Climatic Conditions and Bamboo Water Potential in the Sandan Forest



Figure 6. Bamboo Water Potential Measurement

Figure 6 shows the field activity of measuring water potential in bamboo. The measurement results are supported by climatic data recorded over the past three years, corresponding to the growth period of the bamboo samples. Based on the data presented in the table, the climatic conditions at the study site are relatively uniform, with an average annual rainfall of 5,441.94 mm, an average air temperature of 25.47°C, a relative humidity of 84.43%, and a wind speed of 1.35 m/s. Although these climatic factors remained relatively constant over the three years, the volume of water contained within the bamboo culms shows significant variation among the three species—Petung (1,630 ml), Jajang (11,900 ml), and Tali (20,480 ml). This indicates that, even under similar external climatic influences, differences in stored water volume are primarily determined by the physiological and morphological characteristics of each bamboo species, such as culm wall thickness, internode cavity size, and the efficiency of their internal water storage tissues.

In this context, climatic factors such as high rainfall and elevated relative humidity play an important role in maintaining water availability in the bamboo environment. These conditions create a stable water balance around the root system, allowing each bamboo species to absorb water optimally. However, the response of each species depends on its internal water absorption and retention capacity. For example, *Bambusa tali* have the

highest water volume (20,480 ml), indicating superior water absorption and storage capability. In contrast, *Dendrocalamus asper* (Petung), which only stores 1,630 ml of water, tends to have denser culm walls and smaller storage cavities, resulting in a lower water retention capacity.

Under relatively homogeneous climatic conditions, climatic factors still act as general regulators of the water balance, but the differences in water volume among bamboo species are more strongly influenced by their physiological adaptations to those climatic conditions. Bamboo species with larger hollow culms and more efficient vascular systems are better able to utilize humid climatic conditions to store larger volumes of water, thereby possessing higher water potential compared to other species.

Discussion

The analysis of climatic parameters from 2014 to 2024 reveals a clear monsoonal pattern that governs the hydrological and ecological behavior of the Sandan Forest ecosystem. The precipitation data indicate a distinct bimodal rainfall regime, with the wettest months occurring between December and February and a pronounced dry season from June to September. This pattern reflects the alternating dominance of the northwest and southeast monsoons, which regulate the regional water balance. During the wet season, abundant rainfall increases soil moisture availability, recharges groundwater, and supports active water uptake by bamboo root systems. Conversely, during the dry season, limited rainfall and prolonged evapotranspiration create water stress conditions, reducing the internal water potential of bamboo culms. The interannual variability in rainfall, influenced by ENSO phenomena, further amplifies these dynamics—La Niña years enhance bamboo hydration, while El Niño periods may induce dehydration and physiological stress.

Temperature fluctuations within the range of 23.9°C to 26.5°C follow a complementary seasonal pattern to rainfall. Higher temperatures during the dry months accelerate evaporation and transpiration, while cooler months favour water conservation within bamboo tissues. Although the long-term temperature trend shows only a slight increase ($R^2 = 0.4635$), this warming tendency may gradually intensify evapotranspiration rates in the future, leading to a reduction in soil water availability. Such changes could have long-term implications for the hydrological stability of bamboo ecosystems, particularly in highland tropical zones where temperature sensitivity affects bamboo's mechanical and hydrological functions.

Relative humidity exhibits an inverse relationship with temperature, with the highest values (85–86%) recorded during the rainy season and the lowest (79–81%) during the dry months. This fluctuation significantly affects the vapor pressure deficit (VPD), which determines the rate of water transfer between bamboo tissues and the surrounding air. High humidity conditions suppress transpiration, allowing bamboo culms to retain more water internally, while low humidity accelerates water loss and can lead to decreased turgor pressure in the culm structure. The high R^2 value (0.9311) in the humidity trend analysis indicates a consistent and predictable annual cycle, demonstrating that bamboo in this region has adapted to stable humidity variations that balance its water storage and transpiration processes.

Wind speed, ranging from 1.5 m/s to nearly 3.0 m/s, shows an opposite seasonal trend compared to rainfall. Stronger winds occur during the dry season, enhancing the rate of water vapor removal from bamboo surfaces and increasing overall evapotranspiration. Although annual variations are moderate ($R^2 = 0.6628$), even small fluctuations in wind speed can significantly influence microclimatic evaporation and affect bamboo water content, especially during prolonged dry periods when water availability in the root zone is limited.

Integrating these climatic observations with the field measurement results reveals that, despite relatively uniform environmental conditions over the past three years, the water potential stored in bamboo culms varies significantly among species. The measured volumes of water—Petung (*Dendrocalamus asper*, 1,630 ml), Jajang (*Gigantochloa atter*, 11,900 ml), and Tali (*Gigantochloa apus*, 20,480 ml)—demonstrate the dominant role of species-specific physiological and morphological characteristics. Bamboos with larger internodal cavities and more efficient vascular systems, such as *G. apus*, exhibit a higher capacity for water absorption and retention. In contrast, *D. asper* with denser culm walls and smaller lumen spaces has lower water storage potential.

This variation indicates that while climate provides the external framework influencing water availability, the internal structure and adaptive traits of each bamboo species govern their actual water-holding capacity. Under high rainfall and humidity conditions, bamboos with greater hydraulic conductivity can maximize water uptake and maintain high internal moisture, supporting both physiological functions and mechanical flexibility. In engineering terms, such species are advantageous for applications in eco-hydrological restoration, green construction, and slope stabilization, where high water content enhances material resilience and ecological performance.

Overall, the results emphasize that the interaction between climatic factors and bamboo physiology determines the hydrological function of bamboo ecosystems. In humid tropical environments like Sandan, the synergistic effect of abundant rainfall, moderate temperature, and high humidity supports bamboo's role as an effective natural water reservoir. However, projected climate changes—particularly increased temperature and altered rainfall distribution—may disrupt this balance, reduce bamboo water potential and affect its ecological

and engineering functionality. Thus, continuous monitoring of climate–bamboo interactions is essential for sustainable bamboo management, conservation planning, and adaptive strategies in water-sensitive landscapes.

IV. CONCLUSION

The relationship between climatic factors and bamboo water potential in the Sandan Forest is both complex and species-dependent. The analysis of climatic data from 2014 to 2024 shows that rainfall, temperature, relative humidity, and wind speed collectively shape the hydrological balance that determines the amount of water bamboo can store within its culms. Rainfall and relative humidity exhibit a positive correlation with bamboo water potential, as high precipitation and moisture levels enhance soil water availability and reduce evapotranspiration rates, enabling greater water absorption and retention. Conversely, temperature and wind speed show negative correlations—higher thermal energy and stronger winds accelerate water loss through evaporation and transpiration, lowering the internal water content of bamboo tissues. Despite relatively uniform climatic conditions across the study period, the measured water volumes—1,630 ml for *Dendrocalamus asper* (Petung), 11,900 ml for *Gigantochloa atter* (Jajang), and 20,480 ml for *Gigantochloa apus* (Tali)—indicate that physiological and morphological characteristics of each species play a dominant role in determining their water-holding capacity. Species with larger internodal cavities and higher vascular conductivity, such as *G. apus*, exhibit superior water storage efficiency compared to those with denser culm walls like *D. asper*.

These findings confirm that climate serves as an external regulator influencing bamboo water dynamics, while the intrinsic anatomical adaptations of each species govern their capacity to respond to environmental variability. The combination of abundant rainfall, moderate temperature, and high humidity in Sandan’s tropical montane ecosystem supports bamboo’s function as a natural water reservoir, contributing to local hydrological stability and ecological resilience. From an eco-hydrological and engineering perspective, understanding these interactions is essential for optimizing bamboo management in the context of sustainable water resource utilization, green infrastructure development, and climate change adaptation. Future research should focus on long-term monitoring of climate–bamboo interactions, particularly under projected climate shifts, to develop adaptive management strategies that sustain bamboo ecosystems and their critical role in watershed conservation and environmental engineering applications.

REFERENCE

- [1] Z. Ahmad, A. Upadhyay, Y. Ding, A. Emamverdian, and A. Shahzad, “Bamboo: Origin, Habitat, Distributions and Global Prospective BT - Biotechnological Advances in Bamboo: The ‘Green Gold’ on the Earth,” Z. Ahmad, Y. Ding, and A. Shahzad, Eds., Singapore: Springer Singapore, 2021, pp. 1–31. doi: 10.1007/978-981-16-1310-4_1.
- [2] R. Kaushal *et al.*, “Assessment of eco-hydrological parameters for important sympodial bamboo species in Himalayan foothills,” *Environ. Monit. Assess.*, vol. 193, no. 8, p. 468, 2021, doi: 10.1007/s10661-021-09231-7.
- [3] J. Shen, X. Zeng, S. Fan, and G. Liu, “Impacts of Intensive Management Practices on the Long-Term Sustainability of Soil and Water Conservation Functions in Bamboo Forests : A Mechanistic Review from Silvicultural Perspectives,” 2025.
- [4] T. Joshi *et al.*, “Assessing the Climate Change Vulnerability of the Communities Residing in Doda River Basin, Far-Western Nepal,” *Nepal J. Sci. Technol.*, vol. 22, pp. 129–143, Dec. 2023, doi: 10.3126/njst.v22i1.67170.
- [5] G. Singh, R. Kumar, D. Jinger, and D. Dhakshanamoorthy, “Ecological Engineering Measures for Ravine Slope Stabilization and Its Sustainable Productive Utilization,” A. I. Kanli, Ed., London: IntechOpen, 2020. doi: 10.5772/intechopen.94136.
- [6] N. Joyprakash, K. J. Arvind, S. T. Nath, and A. Sanjay, “Climate Change and Soil Resilience: A Critical Appraisal on Innovative Techniques for Sustainable Ground Improvement and Ecosystem Protection,” *J. Hazardous, Toxic, Radioact. Waste*, vol. 29, no. 4, p. 3125002, Oct. 2025, doi: 10.1061/JHTRBP.HZENG-1465.
- [7] M. F. V. Adier, M. E. P. Sevilla, D. N. R. Valerio, and J. M. C. Ongpeng, “Bamboo as Sustainable Building Materials: A Systematic Review of Properties, Treatment Methods, and Standards,” 2023. doi: 10.3390/buildings13102449.
- [8] X. Luo, X. Wang, H. Ren, S. Zhang, and Y. Zhong, “Long-term mechanical properties of bamboo scrimber,” *Constr. Build. Mater.*, vol. 338, p. 127659, 2022, doi: <https://doi.org/10.1016/j.conbuildmat.2022.127659>.
- [9] S. Madhushan, S. Buddika, S. Bandara, S. Navaratnam, and N. Abeysuriya, “Uses of Bamboo for Sustainable Construction—A Structural and Durability Perspective—A Review,” 2023. doi: 10.3390/su151411137.
- [10] M. Gavrilescu, “Water, Soil, and Plants Interactions in a Threatened Environment,” 2021. doi: 10.3390/w13192746.
- [11] M. Singh, B. Sinha, J. Bisaria, T. Thomas, and P. Srivastava, “Understanding synergies and tradeoffs between forests, water, and climate change,” *WIREs Water*, vol. 9, no. 6, p. e1614, Nov. 2022, doi: <https://doi.org/10.1002/wat2.1614>.
- [12] Y. Andriyana, P. Thaler, R. Chiarawipa, and J. Sopharat, “On-farm effect of bamboo intercropping on soil water content and root distribution in rubber tree plantation,” *For. Trees Livelihoods*, vol. 29, no. 4, pp. 205–221, Oct. 2020, doi: 10.1080/14728028.2020.1798818.
- [13] D. L. Hoover, A. A. Pfennigwerth, and M. C. Duniway, “Drought resistance and resilience: The role of soil moisture–plant interactions and legacies in a dryland ecosystem,” *J. Ecol.*, vol. 109, no. 9, pp. 3280–3294, Sep. 2021, doi: <https://doi.org/10.1111/1365-2745.13681>.
- [14] J. Li, L. Chen, J. Wang, J. Xu, and H. Zheng, “Spatiotemporal dynamic changes in transpiration in the shoot sheath and its relation to water transportation during rapid growth of Moso bamboo,” 2019.
- [15] J. López, D. A. Way, and W. Sadok, “Systemic effects of rising atmospheric vapor pressure deficit on plant physiology and productivity,” *Glob. Chang. Biol.*, vol. 27, no. 9, pp. 1704–1720, May 2021, doi: <https://doi.org/10.1111/gcb.15548>.
- [16] S. C. Wong *et al.*, “Humidity gradients in the air spaces of leaves,” *Nat. Plants*, vol. 8, no. 8, pp. 971–978, 2022, doi: 10.1038/s41477-022-01202-1.
- [17] O. Shapira *et al.*, “Wind speed affects the rate and kinetics of stomatal conductance,” *Plant J.*, vol. 120, no. 4, pp. 1552–1562, Nov. 2024, doi: <https://doi.org/10.1111/tjp.17066>.