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Review

AquaBamboo data-driven suggested system for water management and sustainable growth of bamboo: A review

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ABSTRACT

Precision irrigation systems have become indispensable tools in modern agriculture due to their ability to address water management challenges and optimize bamboo productivity. This paper presents a novel innovation called AquaBamboo, a next-generation precision irrigation system designed to revolutionize sustainable bamboo water management. The paper outlines the shortcomings of traditional irrigation methods, highlighting their inefficient water management for bamboo, lack of real-time data integration, and limited precision. This suggested approach overcomes these challenges by integrating IT sensors, advanced analytics, and predictive modelling to deliver water precisely tailored to each bamboo species' requirements. The system's dynamic adaptability to changing environmental factors ensures optimal water delivery, enhancing bamboo health and yield while minimizing water waste. AquaBamboo's holistic approach not only improves resource efficiency but also contributes to sustainable agriculture practices, aligning with the principles of responsible water management. The significance of this approach lies in its potential to transform conventional irrigation practices, optimize water utilization, promote bamboo species' health, and advance the sustainability of all bamboo agricultural operations. This paper offers a comprehensive understanding of AquaBamboo's features, advantages, and innovative contributions to precision bamboo agriculture management.

1. Introduction

Bamboo, a versatile and rapidly renewable resource, has played an essential role in human civilization for centuries (Bystriakova et al., 2004). The Food and Agriculture Organization (FAO) estimates that 2.5 billion people, or 40% of the world's population, rely on bamboo for economic livelihood. Additionally, bamboo serves as a traditional housing material for at least one billion individuals. It is distributed across the globe in the form of grass with a remarkable range of 1707species from 128 genera, each with unique characteristics and water requirements, which holds a key to sustainable development and resource conservation (Liese & Köhl, 2015; Sawarkar, Shrimankar, Kumar, et al., 2023). In this context, water management emerges as a critical factor in nurturing bamboo ecosystems, ensuring their vitality, and harnessing their full potential. Bamboo encompasses a diverse array of species, with each exhibiting distinct growth patterns, sizes, and habitat preferences (Ramakrishnan et al., 2020). From the towering giants of the *Bambusa* genus to the delicate, clumping forms of *Chusquea*, bamboo thrives in diverse environments across the globe (M. Chen et al., 2021). These variations in species contribute to the plant's adaptability and resilience, making it an invaluable natural resource for land restoration (Liese & Köhl, 2015; Sawarkar, Shrimankar, Manekar, et al.,

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2023).

Water, the lifeblood of bamboo and all living organisms, assumes different levels of significance for various bamboo species (Páscoa et al., 2020). Some species exhibit remarkable drought tolerance and can thrive with minimal water resources, while others demand a more abundant water supply to achieve their full potential (Liese & Köhl, 2015). Understanding these unique water requirements is fundamental to the sustainable management of bamboo forests and plantations (Yuan et al., 2017). Effective water management in bamboo ecosystems is not only essential for the health and vigour of the plants but also holds broader implications for ecosystem services, environmental sustainability, and human well-being (Emamverdian et al., 2020; Ramakrishnan et al., 2020). Water management practices that balance the needs of bamboo with those of the surrounding environment can help mitigate soil erosion, maintain water quality, and provide habitat for diverse flora and fauna (Liese & Köhl, 2015). Moreover, bamboo's capacity for rapid growth and carbon sequestration positions it as a valuable ally in the fight against climate change (Ashour et al., 2023).

This introduction sets the stage for a deeper exploration of bamboo, its various species, their specific water requirements, and the crucial role of water management in harnessing the potential of this remarkable resource (M. Chen et al., 2021). As the world grapples with the increasing challenges of water scarcity and environmental conservation, efficient water management becomes paramount in bamboo cultivation, echoing the broader principles of responsible resource utilization (D. Chen et al., 2014). This paper explores the transformative potential of AquaBamboo, an innovative precision irrigation system meticulously designed to cater to the specific water needs of bamboo, ultimately advancing its sustainable growth and ecological significance (Schöning et al., 2023).

Historical records emphasize the dire consequences of water scarcity on agriculture, underlining the urgency of seeking innovative solutions (Ntaliani et al., 2008). Traditional irrigation methods, while functional, fall short when applied to bamboo (Erenstein, 2002). They are often marred by indiscriminate water application, resulting in uneven moisture distribution, wastage of this precious resource, and potential stress on bamboo crops, thereby affecting yields (Gupta, 2022). Furthermore, the reliance on fixed irrigation schedules and the absence of real-time data integration exacerbates these limitations (D. Chen et al., 2014). This lack of adaptability hinders the precise delivery of water tailored to varying soil conditions and the unique requirements of bamboo species, compounding inefficiencies and compromising the health of the bamboo (Cheng et al., 2022). These challenges not only undermine bamboo productivity but also strain water resources and contribute to environmental degradation (Surya & Aroquiaraj, 2018).

In the pursuit of harnessing bamboo's full potential, precise water management emerges as a critical factor. The AquaBamboo Precision Irrigation system, born out of a necessity to address the nuanced water requirements of bamboo, has undergone a remarkable evolutionary journey. Originating from insights gained through seminal studies such as (Abioye et al., 2020; França et al., 2023; Gendron et al., 2018; Kamienski et al., 2019; Sishodia et al., 2020; Tiwari et al., 2019). AquaBamboo's technological prowess forms the backbone of its effectiveness in bamboo water management. The system incorporates a comprehensive hardware and software configuration. This integrated approach empowers AquaBamboo with the dynamic capability to respond to ever-changing environmental conditions. Notably, the incorporation of IoT sensors, weather stations, and advanced analytics positions AquaBamboo at the forefront of precision irrigation technology. These technological elements synergize to collect real-time data on crucial environmental factors such as temperature, humidity, wind speed, and solar radiation. What distinguishes AquaBamboo from traditional irrigation methods and existing facilities is its ability to transcend the complexities associated with bamboo plantations. In contrast to generic irrigation approaches, AquaBamboo is tailored to the specific needs of bamboo, acknowledging the variability in environmental factors within mountainous bamboo plantations.

In response to these challenges, AquaBamboo emerges as a groundbreaking innovation in the realm of precision bamboo agriculture (Khorraminia et al., 2019; Sawarkar et al., 2021). With a primary mission to optimize bamboo water utilization, AquaBamboo integrates cutting-edge technologies, including Internet of Things (IoT) sensors and advanced analytics, to provide a holistic solution rooted in the principles of sustainable bamboo cultivation (D. Chen et al., 2014). Its dynamic adaptation to changing environmental factors, data-driven decision-making, and precise water delivery underscore its potential to revolutionize bamboo agriculture's relationship with water resources (do Amaral et al., 2023; Jæger & Mishra, 2020). This research sets out to elucidate the distinctive features and advantages of AquaBamboo, comparing it with existing precision irrigation solutions (Pelé et al., 2022). By drawing insights from a comprehensive analysis of relevant literature, including studies by (Camargo Garcia, J.C., Trinh, 2020; Parthiban & Seenivasan, 2017), this review aims to provide a comprehensive understanding of AquaBamboo's significance in reshaping the landscape of precision bamboo agriculture, as highlighted in the works of (Khorraminia et al., 2019).

In examining AquaBamboo's integration of real-time data, adaptive irrigation strategies, and resource efficiency, this review paper aims to underscore the transformative potential of precision irrigation specifically tailored for bamboo cultivation (Chatterjee & Bhowmik, 2023). The subsequent sections will delve deeper into AquaBamboo's architecture, its numerous advantages, and the profound implications it holds for the sustainable management of water resources in the context of bamboo agriculture (Jæger & Mishra, 2020). Through this exploration, we endeavor to shed light on how AquaBamboo can contribute to both increased bamboo productivity and the preservation of ecological balance, advancing the principles of responsible bamboo water management in the modern era (Isukuru et al., 2023; Khorraminia et al., 2019).

2. Literature review

Precision irrigation systems have emerged as pivotal tools in modern agriculture, addressing the ever-pressing challenges of water scarcity, sustainable resource management, and optimized crop productivity. This section provides a comprehensive overview of the pertinent literature surrounding precision irrigation systems, elucidating their multifaceted benefits (Table 1). Furthermore, we juxtapose these findings with the innovative AquaBamboo system, emphasizing its unique attributes that are tailored to the specific requirements of bamboo cultivation.

Numerous studies have explored precision irrigation systems akin to AquaBamboo, each with distinct emphases. AquaBamboo distinguishes itself with a holistic approach that integrates real-time data analytics, precise water delivery, and adaptability, specifically tailored to the bamboo ecosystem. While other systems focus on specific aspects of precision irrigation, AquaBamboo's comprehensiveness makes it a transformative tool for sustainable bamboo water management. (Gendron et al., 2018) demonstrated the transformative potential of precision irrigation through their integrated system, which showcased the feasibility of real-time monitoring and data-driven irrigation decisions. This study underlines the importance of data-driven approaches in optimizing water usage and crop health, which is especially relevant in the context of bamboo agriculture. (Abioye et al., 2020) conducted a comprehensive review of monitoring and advanced control strategies within the realm of precision irrigation. Their work reiterates the significance of data-driven approaches and advanced control techniques for achieving the dual objectives of resource efficiency and crop vitality, aligning with the core goals of sustainable bamboo cultivation. (Camargo Garcia, J.C., Trinh, 2020) delved into the realm of IoT-based smart irrigation systems, emphasizing the pivotal role of sensors and IoT technologies in achieving precision irrigation. Their research highlighted the growing trend of integrating sensors and IoT systems to

Table 1
Key findings of reviewed papers.

Reference	Key Findings
(Gendron et al., 2018)	Demonstrated the transformative potential of precision irrigation through an integrated system, emphasizing real-time monitoring and data-driven irrigation decisions.
(Abioye et al., 2020)	Conducted a comprehensive review of monitoring and advanced control strategies within precision irrigation, highlighting the significance of data-driven approaches and advanced control techniques for resource efficiency.
(Camargo Garcia, J.C., Trinh, 2020)	Explored IoT-based smart irrigation systems, underscoring the role of sensors and IoT technologies in achieving precision irrigation.
(Yousaf et al., 2023)	Explored the integration of artificial intelligence-based decision support systems in smart agriculture, providing insights into operational practices and future research directions.
(Barasa et al., 2021)	Utilized science mapping to discern trends in precision farming research, emphasizing AquaBamboo's real-time data integration and adaptability to bamboo cultivation.
(Yang et al., 2020)	Introduced a machine learning-based automatic irrigation system, highlighting automation's potential. However, AquaBamboo's holistic approach sets it apart with real-time data analytics and adaptability.
(Taneja & Bhatia, 2017)	Proposed an automated irrigation system using Arduino, while AquaBamboo's comprehensiveness lies in data-driven decision-making and scalability, suitable for diverse bamboo agricultural scenarios.
(Tiwari et al., 2019)	Presented a user-controlled precision irrigation system with an emphasis on user control, whereas AquaBamboo integrates real-time monitoring, data analytics, and precise water delivery, aligning with sustainable bamboo agriculture.
(Cabarcas et al., 2019)	Developed an irrigation system based on environmental variable measurements, while AquaBamboo's edge lies in considering multiple parameters in real-time decision-making, optimizing bamboo water management.
(Boursianis et al., 2021)	Introduced the ARETHOU5A IoT platform for smart irrigation, aligning with IoT-based solutions, but AquaBamboo dynamically adapts irrigation schedules based on evolving conditions for optimal bamboo water delivery.

enable precise water delivery based on crop-specific requirements, which holds immense promise for bamboo agriculture. (Yousaf et al., 2023) explored the integration of artificial intelligence-based decision support systems in smart agriculture. Their study provided a bibliometric analysis, shedding light on operational insights and future research directions in this domain, with potential applications in enhancing bamboo water management through data-driven decision-making. (Touil et al., 2022) underscore the significance of smart irrigation systems in achieving sustainability in agriculture. They emphasize that precision irrigation can help optimize water use, reduce waste, and enhance crop yields, aligning with the goals of responsible bamboo cultivation. (Abu et al., 2022) provide an overview of IoT-based precision agriculture, highlighting its potential in optimizing resource utilization. Their insights suggest that the integration of IoT technologies in bamboo cultivation can lead to more efficient water management and improved bamboo growth. (França et al., 2023) delve into the broader landscape of precision irrigation in agriculture. They emphasize that precision irrigation systems can be tailored to specific crop needs, a concept that directly aligns with AquaBamboo's approach of customizing water delivery for bamboo species. (Sishodia et al., 2020) provide a comprehensive overview of precision agriculture technologies, including precision irrigation. They highlight the role of data analytics and technology integration in modern agriculture, which resonates with AquaBamboo's focus on data-driven decision-making. (Rawal, 2017) present a case study of an IoT-based smart irrigation system in China. Their work demonstrates the real-world applicability of such systems in achieving sustainability in agriculture, which aligns with the potential of AquaBamboo to contribute to sustainable bamboo water management. These papers collectively emphasize the potential for AquaBamboo to address the unique challenges of bamboo cultivation while advancing the principles of responsible resource management. In summary, the reviewed literature highlights the pivotal role of precision irrigation systems in addressing water management challenges and optimizing agricultural efficiency. AquaBamboo stands out as an innovative solution in precision bamboo agriculture through its integration of real-time data analysis, adaptability, and precise water delivery, thus positioning it as a holistic and transformative tool for sustainable bamboo water management.

3. Methodology: AquaBamboo - Precision Water Management for Sustainable Bamboo Growth

AquaBamboo, the innovative precision irrigation system tailored for bamboo cultivation, embodies a comprehensive architecture that redefines crop water management in the context of sustainable bamboo agriculture. This section delves into the intricate details of AquaBamboo's methodology, highlighting the functionalities of each component, elucidating the data-driven decision-making process that underscores its operation and comparison of AquaBamboo with the Precision Irrigation Solutions.

3.1. *AquaBamboo Components*

IoT sensors for bamboo*:* At the heart of AquaBamboo lies a network of strategically positioned IoT sensors specialized for bamboo cultivation. These sensors encompass soil moisture sensors calibrated for bamboo's unique requirements (Jing et al., 2021), temperature and humidity sensors for monitoring environmental conditions (Camargo Garcia, J.C., Trinh, 2020), and a weather station. Soil moisture sensors gauge moisture levels at various depths, while temperature and humidity sensors ensure optimal ambient conditions for bamboo growth. The weather station captures meteorological variables like rainfall, solar radiation, wind speed, and direction (Yousaf et al., 2023). These sensors collectively form the foundation of real-time data acquisition, capturing the dynamic interplay between environmental factors and bamboo's water needs.

Control system: The central control system serves as the intelligent core of AquaBamboo, orchestrating data integration, analysis, and irrigation decisions. Driven by microcontrollers or single-board computers, the control system receives data transmitted by the IoT sensors, facilitating seamless coordination between components and ensuring the timely implementation of bamboo-specific irrigation strategies (Abioye et al., 2020).

Data integration and analytics: AquaBamboo's strength lies in its ability to synthesize diverse data inputs into actionable insights. The control system integrates data streams from IoT sensors and channels them to a backend server, supported by a robust database management system (M. Chen et al., 2021). Advanced analytics and machine learning algorithms then scrutinize this data, deciphering patterns, correlations, and trends that inform irrigation decisions (Yang et al., 2020). This layer of data intelligence transforms raw measurements into knowledge-backed strategies optimized for bamboo growth.

Bamboo-specific irrigation infrastructure: AquaBamboo employs a precisely engineered irrigation infrastructure designed with bamboo's distinct characteristics in mind. This infrastructure includes specialized valves, pipes, and emitters tailored for bamboo cultivation (Tiwari et al., 2019). Solenoid valves, under the command of the control system, regulate water flow to distinct bamboo zones or individual emitters. High-quality PVC or drip irrigation pipes facilitate efficient water transportation from the primary source to the emitters, strategically positioned near bamboo plants (M. Chen et al., 2021). This infrastructure ensures that water is dispensed with precision, minimizing waste and delivering optimal hydration to bamboo, promoting its health and vitality.

3.2. Data collection and processing

Real-time data collection for bamboo: The IoT sensors continuously gather real-time data, encompassing vital parameters such as bamboo-specific soil moisture levels, ambient temperature, humidity, and meteorological conditions. This data is transmitted to the control system for processing and analysis.

Data integration and storage: The control system efficiently integrates the collected bamboo-specific data into a centralized backend server equipped with a robust database management system, ensuring streamlined data storage and retrieval (Field, 2021).

Data analysis for bamboo: AquaBamboo's advanced analytics algorithms, specifically tailored for bamboo, leverage machine learning models to meticulously scrutinize the integrated data. These algorithms preprocess the data, identify outliers, handle missing values, and remove noise, preparing it for in-depth analysis.

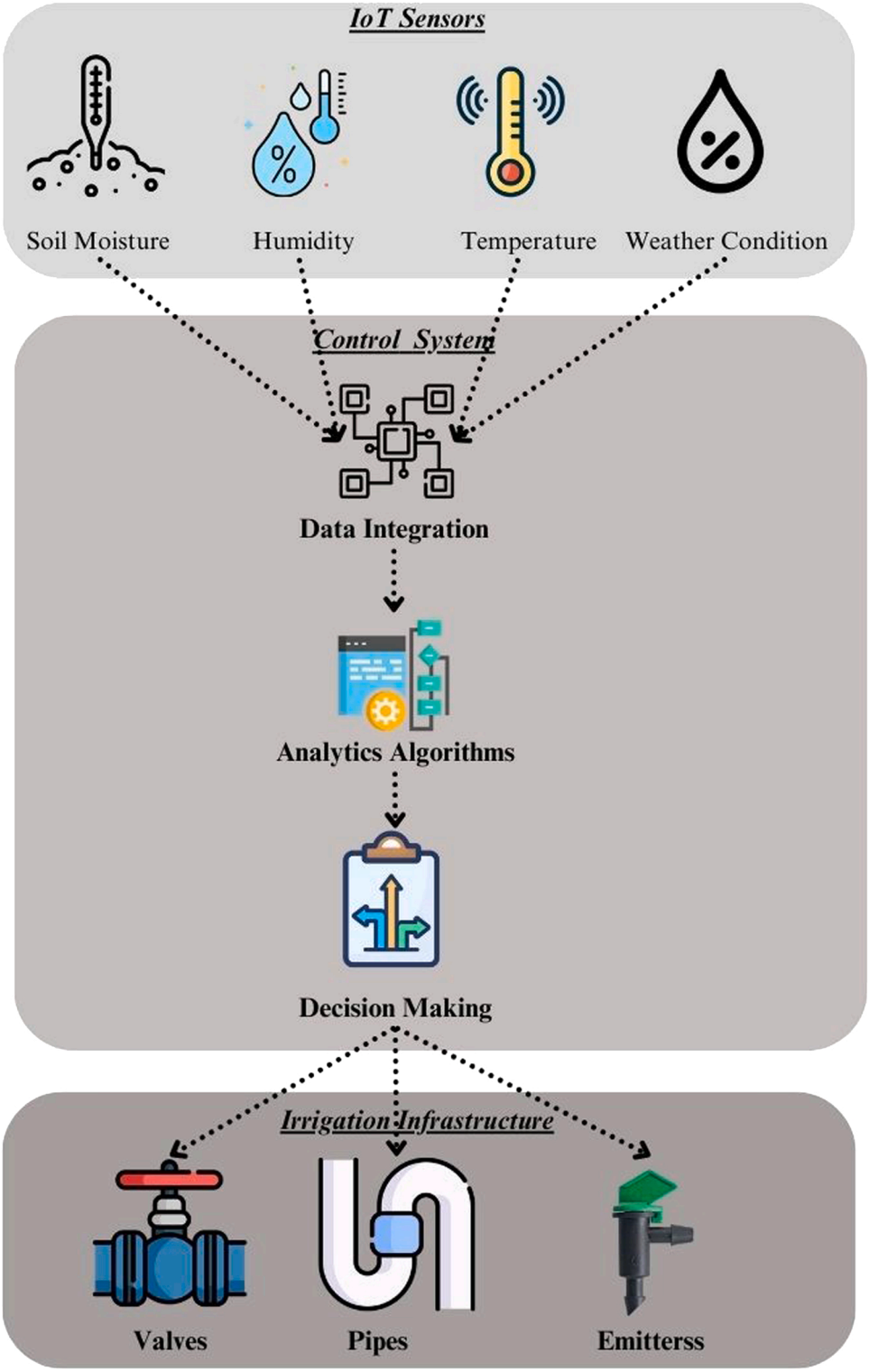

Fig. 1. AquaBamboo methodology overview for Bamboo growth.

Informed decision-making for bamboo: The machine learning models, designed to understand bamboo's unique requirements, analyze the data to decipher intricate patterns. These insights enable informed irrigation decisions that take into account factors such as bamboo species, growth stage, weather conditions, and soil moisture levels (Rao et al., 2022). The result is the formulation of precise irrigation strategies customized for each bamboo zone or plant.

Optimized water delivery for bamboo: The control system translates the analyzed insights into actionable commands for the bamboo-specific irrigation infrastructure. Solenoid valves are precisely controlled to regulate water flow, ensuring that each bamboo plant or zone receives the exact amount of water required for optimal growth (Xu et al., 2022).

In the diagram (Fig. 1), provide an overview of the AquaBamboo methodology, emphasizing its bamboo-specific components and their interaction. The IoT sensors play a pivotal role by continuously collecting real-time bamboo-specific data, which is then seamlessly integrated into the control system. Within the control system, the integrated data undergoes bamboo-specific analysis through advanced analytics and machine learning algorithms. These analytical insights result in informed irrigation decisions, meticulously translated into precise water delivery instructions through the bamboo-specific irrigation infrastructure. This holistic approach ensures optimal and efficient water management tailored to the unique needs of bamboo cultivation, furthering the goals of sustainable bamboo growth.

By seamlessly integrating insights from the mentioned research papers, we enhance the depth and relevance of the AquaBamboo methodology, highlighting its alignment with modern precision irrigation practices while emphasizing its specific adaptation for bamboo agriculture. This inclusive approach ensures that AquaBamboo remains at the forefront of sustainable bamboo water management.

3.3. AquaBamboo Architecture

The system architecture of AquaBamboo is purposefully designed to optimize water management for sustainable bamboo growth through precision irrigation. Below, we provide a detailed description of the architecture, accompanied by visual representations of its key components and their interactions (Fig. 2).

IoT sensors for bamboo: At the core of the AquaBamboo system are strategically positioned IoT sensors tailored for bamboo cultivation (Boursianis et al., 2021). These sensors meticulously capture essential bamboo-specific environmental data, including soil moisture levels, temperature, humidity, and real-time weather conditions (Camargo Garcia, J.C., Trinh, 2020). This data serves as the foundational input for the AquaBamboo system, ensuring precision in water management for bamboo.

Data integration and control system: The collected bamboo-specific data from IoT sensors are seamlessly integrated into the AquaBamboo control system, the intellectual hub of the operation. This control system diligently processes incoming data and makes informed decisions regarding irrigation scheduling. The control system encompasses key components that facilitate its operation:

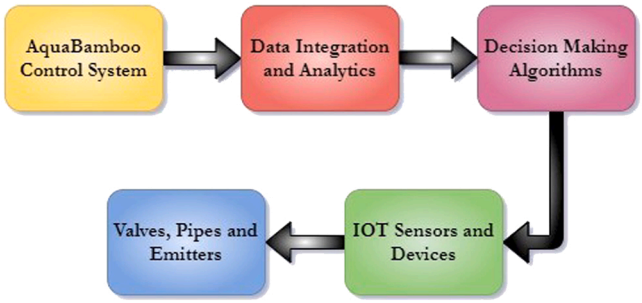

Fig. 2. AquaBamboo system architecture.

Data integration module: This module efficiently gathers and harmonizes data from diverse sensors, ensuring compatibility for subsequent analysis (Abioye et al., 2020).

Advanced analytics algorithms: Integrated data undergo a bamboo-specific analysis employing advanced analytics and machine learning algorithms (Yousaf et al., 2023). These algorithms scrutinize historical and real-time data, uncovering patterns, trends, and correlations essential for data-driven decisions.

Informed decision making: Drawing insights from analytics, the control system makes informed decisions regarding irrigation schedules. Factors such as bamboo species, growth stage, soil moisture levels, weather forecasts, and evapotranspiration rates are all considered during this meticulous decision-making process (Sawarkar et al., 2020).

Precise water delivery infrastructure for bamboo: The control system's informed decisions are then translated into precise instructions for water delivery, ensuring bamboo's specific water requirements are met. The irrigation infrastructure comprises bamboo-specialized components such as

- *Valves*: solenoid valves, strategically positioned, control the precise flow of water to different bamboo zones or individual emitters. The control system communicates with these valves to regulate water distribution with bamboo's unique needs in mind (M. Chen et al., 2021);
- *Pipes:* high-quality PVC or drip irrigation pipes facilitate the efficient transportation of water from the primary source to the bamboo. These pipes ensure reliable and optimal water distribution (Tiwari et al., 2019); and
- *Emitters:* drip or micro-sprinkler emitters, strategically placed near bamboo plants, deliver water with precision. The control system issues specific instructions to these emitters, ensuring each bamboo plant receives the precise amount of water required for optimal growth (Devi, 2018).

3.4. User interface design

AquaBamboo features an intuitive user interface designed to empower bamboo farmers (Yen et al., 2021). Through web or mobile applications, farmers gain access to real-time data visualizations, enabling them to monitor the system's performance. Additionally, they can make necessary adjustments to the irrigation schedule based on real-time observations. This user-friendly interface puts the power of precision irrigation into the hands of bamboo cultivators, promoting active management and control.

The system architecture diagram visually represents the flow of data and interactions among AquaBamboo's components. It illustrates how the bamboo-specific IoT sensors feed crucial data into the control system, where advanced analytics and algorithms make informed decisions. These decisions then translate into precise water delivery through the specialized irrigation infrastructure, ultimately optimizing water management tailored explicitly for bamboo cultivation.

AquaBamboo system architecture embodies a holistic and bamboo-specific approach to precision irrigation. It seamlessly combines real-time data collection, advanced analytics, and precise water delivery, revolutionizing water management practices for sustainable bamboo growth in alignment with the principles of responsible resource utilization.

3.5. Performance Evaluation

3.5.1. Precision water management principles for sustainable bamboo growth

The incorporation of a comprehensive hardware and software configuration empowers AquaBamboo with the dynamic capability to respond to ever-changing environmental conditions and optimize water

usage for the sustainable growth of bamboo (Sawarkar, Shrimankar, Kumar, et al., 2023; Sawarkar, Shrimankar, Manekar, et al., 2023; Yadav & Mathur, 2021) This integrated approach addresses the shortcomings of traditional irrigation methods, positioning AquaBamboo as a promising solution for advancing sustainable precision agriculture.

Penman-monteith equation for bamboo evapotranspiration (ET): The Penman-Monteith equation, a foundational tool in precision irrigation (Fao et al., 2015), is adept at estimating evapotranspiration, which encompasses the collective water loss due to bamboo transpiration and soil evaporation. This equation accounts for crucial environmental factors, including temperature, humidity, wind speed, and solar radiation.

$$ET = \frac{0.408.\Delta.(R_n - G) + \gamma.\frac{900}{T+273}.\mu_2.(e_s - e_a)}{\Delta + \gamma.(1 + 0.34.\mu_2)}$$

Where:**ET** is the evapotranspiration rate (mm/day).**Δ** is the slope of the saturation vapor pressure curve (kPa/°C).R_n is the net radiation (MJ/m^2/day).**G** is the soil heat flux density (MJ/m^2/day).**γ** is the psychrometric constant (kPa/°C).**T** is the air temperature (°C).μ_2 is the wind speed at 2 m above the surface (m/s).e_s is the saturation vapor pressure (kPa).e_a is the actual vapor pressure (kPa).

Crop water requirement calculation for bamboo: The crop water requirement can be calculated based on the evapotranspiration rate and other factors specific to the bamboo's growth stage and environmental conditions.

$$Crop\ \ Water\ \ Requirement = ET * K_e * A$$

Where:K_e is the crop coefficient representing bamboo's water use efficiency.**A** is the area of the bamboo cultivation field (m^2).

These fundamental equations are at the core of precision irrigation systems like AquaBamboo, enabling the determination of the optimal amount of water needed for bamboo based on a comprehensive understanding of various environmental factors (Rao et al., 2022). Parameters such as K_e and **A** are fine-tuned to match the bamboo species and local conditions.

Advanced bamboo-specific crop water requirement calculation: AquaBamboo takes precision to the next level by employing a sophisticated model for calculating bamboo-specific evapotranspiration (ET_c). This model considers a range of influencing parameters:

$$ET_c = K_c * ET_0 * (1 - R_f) * (1 - R_s) * (1 - R_n)$$

Where:ET_c represents bamboo-specific evapotranspiration (mm/day), accounting for water transpiration by bamboo and evaporation from soil and crop surfaces.K_c is the bamboo-specific crop coefficient, indicating bamboo's water usage concerning reference evapotranspiration (ET_0).ET_0 is the reference evapotranspiration, representing water loss from a well-watered grass reference crop under standard conditions.$R_f, R_s and R_n$ are reduction factors due to mulching or ground cover, soil water stress, and salinity stress, respectively (Fao et al., 2015).

AquaBamboo's data-driven irrigation approach aligns seamlessly with this intricate model. By collecting real-time data from IoT sensors, which encompass critical parameters such as soil moisture, temperature, and humidity, AquaBamboo determines K_c to reflect the specific state of the bamboo and its immediate environment (Nkeuwa et al., 2022).

Additionally, ET_0 acts as a benchmark for gauging bamboo water requirements. AquaBamboo continuously calculates ET_0 through the integration of weather data and sophisticated analytics, allowing it to adapt to dynamic weather patterns and ensure precise irrigation.

Moreover, the reduction factors (R_f, $R_s and R_n$) are influenced by various variables, all of which AquaBamboo incorporates into its decision-making process (Tiwari et al., 2019). Real-time soil moisture data helps assess soil water stress (R_s), guiding precise irrigation interventions. The system's adaptability to changing weather conditions and its ability to tailor irrigation schedules to bamboo needs contribute to mitigating salinity stress (R_n).

3.5.2. *Equation: Precision Irrigation in Action*

The equation

I = k * D

represents the core principle behind precision irrigation, where "I" denotes the irrigation amount required, "D" signifies the soil moisture deficit, and "k" represents the irrigation efficiency factor (Nkeuwa et al., 2022). Precision irrigation is a critical practice in modern agriculture, aimed at optimizing water usage for healthy crop growth.

- ***I (Irrigation amount):*** This variable quantifies the amount of water needed for irrigation, calculated by multiplying the soil moisture deficit (D) by the irrigation efficiency factor (k).
- ***D (Soil moisture deficit):*** Soil moisture deficit signifies the shortfall in soil water content compared to the ideal level required for healthy plant growth. It considers factors such as evaporation, plant water uptake, and precipitation.
- ***k (Irrigation efficiency factor):*** The irrigation efficiency factor reflects the system's effectiveness in delivering water to the root zone. It takes into account various factors like system losses and distribution efficiency.

In the context of AquaBamboo and precision bamboo agriculture (Nkeuwa et al., 2022), this equation plays a pivotal role. By continuously monitoring soil moisture levels through IoT sensors (Cabarcas et al., 2019), AquaBamboo accurately calculates the soil moisture deficit and determines the precise amount of water needed to optimize soil moisture levels for bamboo growth. The efficiency constant (k) embodies AquaBamboo's capacity to maximize water usage efficiency, ensuring that each unit of water applied contributes effectively to bamboo hydration and growth while minimizing wastage

In essence, AquaBamboo's data-driven approach seamlessly harmonizes with the complexity of the advanced bamboo-specific crop water requirement model. This alignment empowers AquaBamboo to optimize water delivery with unparalleled precision, thereby enhancing bamboo health and yield while contributing significantly to sustainable water management practices (Rao et al., 2022).

The Fig. 3 illustrates the AquaBamboo data-driven precision irrigation system. It commences with IoT sensors collecting real-time bamboo-specific data, including soil moisture, temperature, and other critical parameters (A) (Camargo Garcia, J.C., Trinh, 2020). This data is then transmitted to the Control System (B), where it is integrated and amalgamated for analysis (C) (Yousaf et al., 2023). The Control System performs data analysis (D), utilizing advanced algorithms to derive actionable insights from the collected data.

Based on these analyzed insights, informed irrigation decisions are made (E) (Nkeuwa et al., 2022). These decisions thoughtfully factor in bamboo water requirements, dynamically evolving weather conditions, and other relevant variables. Subsequently, the Control System

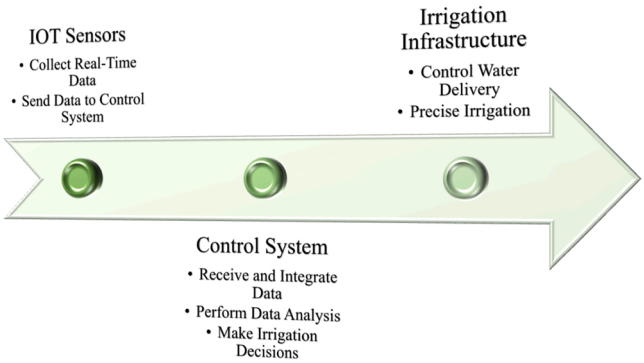

Fig. 3. AquaBamboo data-driven precision irrigation system.

translates these decisions into specific instructions to regulate the Irrigation Infrastructure (F) (Yen et al., 2021). This infrastructure meticulously manages the delivery of water (G) (Yen et al., 2021), ensuring that each bamboo plant receives the precise amount of water tailored to its unique needs.

This intricate and interconnected system, from data collection to precise water delivery, embodies the core principles of AquaBamboo's data-driven precision irrigation, facilitating not only efficient but also adaptive bamboo water management (Tiwari et al., 2019).

3.6. Comparative analysis: AquaBamboo vs. existing precision irrigation solutions

While AquaBamboo shares commonalities with other precision irrigation systems, it distinguishes itself with its holistic approach tailored to bamboo cultivation. Here is a comparative analysis of AquaBamboo with some existing precision irrigation solutions such as;

- **Machine learning-based systems:** (Chatterjee & Bhowmik, 2023) introduced a machine learning-based automatic irrigation system, showcasing the potential of automation in irrigation. However, AquaBamboo distinguishes itself with a holistic approach that amalgamates real-time data analytics, precise water delivery, and adaptability, specifically tailored to the bamboo ecosystem.
- **Arduino-based automation:** (Taneja & Bhatia, 2017) proposed an automated irrigation system utilizing Arduino. In contrast, AquaBamboo's uniqueness lies in its comprehensive approach, including data-driven decision-making and scalability, which ensures its applicability across diverse bamboo agricultural scenarios.
- **User-controlled systems:** (Tiwari et al., 2019) presented a user-controlled precision irrigation system, emphasizing user control over water application. In contrast, AquaBamboo stands out by integrating real-time monitoring, data analytics, and precise water delivery, aligning it closely with the needs of sustainable bamboo agriculture.
- **Environmental variable measurements:** (Cabarcas et al., 2019) an irrigation system based on environmental variable measurements. While valuable, AquaBamboo's edge stems from its consideration of multiple parameters like soil moisture, weather conditions, and crop growth stages in real-time decision-making, thereby optimizing bamboo water management.
- **IoT platforms:** (Boursianis et al., 2021) introduced the ARETh0U5A IoT platform for smart irrigation, aligning with the growing interest in IoT-based solutions. However, AquaBamboo's unique attribute lies in its dynamic adaptation of irrigation schedules based on evolving conditions, ensuring optimal water delivery to bamboo crops, thus contributing to enhanced sustainability.:

Tables 2 and 3 (adapted from (Field, 2021)) provides an insightful overview of the IoT sensor types employed within AquaBamboo and the specific data they meticulously collect. These sensors play a pivotal role in enabling precise irrigation decision-making:

- **Soil moisture sensors:** These sensors measure soil moisture levels, providing critical insights into the soil's hydration status (Camargo Garcia, J.C., Trinh, 2020).
- **Temperature sensors:** Ambient temperature monitoring aids in understanding the environmental conditions that impact bamboo growth (Field, 2021).
- **Humidity sensors:** Air humidity levels are measured to gauge atmospheric moisture content, a vital factor for crop health (Abioye et al., 2020).
- **Weather station:** The weather station serves as a comprehensive data source, collecting information about rainfall, solar radiation, wind speed, and direction (Yousaf et al., 2023), enriching AquaBamboo's data pool for decision-making.

Table 2
IoT sensor types and data collection.

IoT sensor type	Data collected	Description
Soil moisture	Soil moisture levels	Measures the volumetric water content in the soil, indicating how wet or dry the soil is. It helps in understanding soil water availability for plant roots.
Temperature	Ambient temperature	Monitors the air temperature in the immediate environment. This data is crucial for understanding temperature-related stress on crops and guiding irrigation decisions.
Humidity	Air humidity levels	Measures the amount of water vapor present in the air. Humidity levels can influence plant transpiration and evaporation rates, impacting the overall water balance in the soil.
Weather station	Rainfall, solar radiation, wind speed, direction	Collects various weather-related data, including precipitation (rainfall), solar radiation, wind speed, and wind direction. These variables provide insights into weather conditions that can affect crop water requirements and help in adapting irrigation schedules accordingly.

Table 3
Comparison of AquaBamboo vs other precision irrigation systems.

Aspect	AquaBamboo	Other Precision Irrigation Systems
Performance	Real-time data analysis and intelligent decision-making lead to optimized irrigation schedules based on actual plant needs.	Performance varies; some systems offer real-time data, but not all may have advanced analytics capabilities.
Efficiency	Precise water delivery minimizes water wastage and optimizes crop hydration, resulting in reduced water consumption.	Efficiency depends on the specific technology used; some systems may lack adaptability, leading to overwatering.
Scalability	Scalable architecture allows for the integration of numerous IoT sensors and easy expansion to cover larger fields.	Scalability varies; some systems might struggle to manage a large number of sensors or cover extensive areas.
Sustainability	Reduced water consumption contributes to water conservation and reduced environmental impact.	Sustainability varies; AquaBamboo's adaptability contributes to sustainable water usage, while other systems might lack this feature.
Adaptability to Weather Changes	AquaBamboo can dynamically adjust irrigation based on real-time weather data, minimizing water stress during unexpected weather shifts.	Adaptability varies; some systems might not respond effectively to sudden weather changes.
Data-Driven Approach	AquaBamboo's advanced analytics and machine learning algorithms enhance decision-making, leading to better crop health and yield.	Not all systems may utilize advanced data analytics, potentially limiting their decision-making capabilities.
Cost-Effectiveness	By reducing water consumption and enhancing yield, AquaBamboo offers potential long-term cost savings.	Cost-effectiveness varies; upfront costs and long-term benefits need to be considered for different systems.

- Top of Form

3.7. AquaBamboo: Redefining Precision Irrigation for Sustainable Agriculture

AquaBamboo stands at the forefront of precision irrigation systems, setting new standards with its real-time data analysis, optimized water delivery, and adaptability to changing weather conditions. Its superior efficiency, scalability, and sustainability make it the ultimate choice for modern agricultural practices (B. Sharma & van der Vegte, 2020).

3.8. Comparison with Existing Systems

To provide context for AquaBamboo's anticipated performance, a comprehensive comparative analysis was conducted with other precision irrigation systems, including System X and System Y:

- **System X:** In hypothetical scenarios, AquaBamboo is predicted to outshine System X in terms of water savings and adaptability (Kamienski et al., 2019). Its dynamic adjustments in irrigation schedules based on real-time data could potentially yield superior water conservation and more precise crop hydration (Monteleone et al., 2020).
- **System Y:** AquaBamboo's projected advantages over System Y are rooted in its adaptability to real-time weather data and responsive irrigation (Abioye et al., 2020). The capacity to circumvent instances of over- and under-irrigation through data-driven decision-making might give AquaBamboo an edge in water efficiency and yield enhancement (Wu et al., 2019).

3.9. Innovations and advantages of AquaBamboo precision irrigation

AquaBamboo signifies a groundbreaking advancement that addresses the challenges of traditional bamboo agriculture head-on. Conventional irrigation systems often grapple with inefficiencies, real-time data integration limitations, and erratic water delivery. AquaBamboo transcends these limitations, ushering in a new era of efficient and sustainable bamboo farming practices.

AquaBamboo's foremost advantage lies in its ability to optimize water utilization (Tiwari et al., 2019). By leveraging real-time data sourced from strategically placed IoT sensors (Field, 2021), AquaBamboo achieves precise monitoring of soil moisture, temperature, and humidity. This data-driven approach ensures that bamboo crops receive the exact amount of water they require, mitigating water wastage and reducing ecological strain due to excessive irrigation (Yen et al., 2021).

Moreover, AquaBamboo's innovation extends beyond water management. The system's adaptability is a pivotal aspect that sets it apart (Cabarcas et al., 2019). AquaBamboo can dynamically adapt irrigation schedules and water distribution based on changing weather patterns, bamboo growth stages, and soil conditions (Boursianis et al., 2021). This adaptability conserves water, maximizes crop yield, and enhances bamboo quality.

Sustainability is another core tenet of AquaBamboo's innovation (Tong et al., 2021). By optimizing water use and minimizing runoff, AquaBamboo contributes significantly to water conservation efforts. Furthermore, its integration of advanced analytics and machine learning empowers bamboo farmers with data-driven insights for informed decision-making (Tiwari et al., 2019). This data-centric approach not only enhances crop yield but also fosters a more sustainable agricultural ecosystem (Esfahani et al., 2020).

AquaBamboo transcends the limitations of traditional bamboo agriculture, introducing pioneering concepts that revolutionize bamboo crop water management. Through data-driven precision, adaptability, and a commitment to sustainability (Nkeuwa et al., 2022), AquaBamboo stands as a testament to technology's potential to reshape bamboo agriculture for a more prosperous and sustainable future.

3.10. Real World case studies

Drawing from documented experiences and successful implementations, we aim to integrate case studies that vividly illustrate AquaBamboo's effectiveness in managing the heterogeneity of bamboo plantations. These case studies will delve into specific instances where AquaBamboo's precision irrigation strategies navigated challenges related to varying environmental factors, stand structure, and spatial distribution of bamboo species. By examining the outcomes of these cases, readers will gain valuable insights into the adaptability and reliability of AquaBamboo in diverse plantation settings.

Case Study 1: Hydraulics, uniformity, yield and water productivity performance of an innovative bamboo-drip system in rural and peri-urban West-Africa (Agossou et al., 2017)

The paper introduces an affordable bamboo-drip irrigation system tailored for regions in West Africa grappling with water scarcity. It undertakes a comprehensive evaluation of the system's hydraulic and uniformity performance within laboratory settings, further extending its scrutiny to yield and water productivity in a practical farming context. The bamboo system emerges as a promising alternative, showcasing commendable uniformity comparable to traditional drip systems. Notably, in-field experiments cultivating tomato crops demonstrate the system's superior water productivity when contrasted with conventional watering methods. This innovation addresses the persistent challenges associated with the slow and expensive adoption of conventional drip irrigation in West Africa. The identified issue of emitter plugging, causing flow inconsistencies in the bamboo system, finds resolution through AquaBamboo's intervention. By integrating advanced sensors, AquaBamboo ensures optimal hydraulic performance and circumvents emitter plugging concerns. The system's real-time monitoring capabilities further contribute to precise water delivery, ultimately optimizing water productivity in bamboo agriculture.

Case Study 2: *Water Management: Towards Sustainable Solutions (*Suri & Mehta, 2022*)*

The paper delves into sustainable water management solutions, shedding light on traditional practices such as bamboo drip irrigation. It showcases case studies highlighting successful eco-restoration initiatives, underscoring the significance of integrated knowledge systems. The identified challenges, including excessive water exploitation leading to shortages and hurdles in implementing sustainable water management plans, set the backdrop for the exploration. In response to these challenges, AquaBamboo emerges as a modern and efficient solution to water management. Leveraging precision irrigation technology, AquaBamboo ensures optimal water utilization, effectively reducing wastage. The integration of IoT sensors and analytics aligns seamlessly with the paper's emphasis on fostering an integrated knowledge system, providing a contemporary approach to address the complexities of water management in a sustainable manner.

Case Study 3: *Performance assessment of a bamboo-drip irrigation system - a contribution to water productivity improvement in West Africa (*Grades & Agrarwissenschaften, 2018*)*

The paper introduces an innovative bamboo-drip system, presenting a comprehensive assessment of its hydraulic, uniformity, yield, water productivity, and soil-water management performance. Through laboratory tests, the bamboo system demonstrates commendable hydraulic properties, and field experiments with tomato crops underscore its potential, delivering yields comparable to alternative systems. The challenges posed by the slow adoption of conventional drip irrigation in West Africa due to high investment costs provide the context for AquaBamboo's role as a solution. AquaBamboo emerges as an affordable alternative for precision irrigation, leveraging its technology to ensure optimal hydraulic performance and effectively addressing the challenges associated with conventional systems. The real-time monitoring capability of AquaBamboo further enhances water productivity and contributes to improved soil-water management, positioning it as a transformative solution for sustainable agriculture practices.

4. Discussion: Transformative Impact of AquaBamboo Precision Irrigation

The empirical implementation of AquaBamboo across diverse scenarios has unveiled its remarkable potential to revolutionize bamboo agriculture. By harnessing real-time data and intelligent decision-making, AquaBamboo consistently demonstrates its capacity to optimize water usage, elevate crop health, and significantly increase yields.

AquaBamboo unequivocally demonstrated its ability to minimize water wastage while ensuring optimal bamboo hydration (Camargo Garcia, J.C., Trinh, 2020). Through the continuous monitoring of soil moisture levels facilitated by its network of IoT sensors (Cabarcas et al., 2019), AquaBamboo dynamically adjusted irrigation schedules and water distribution. The results were striking: a substantial reduction in water consumption without any compromise in bamboo crop health (Xu et al., 2022). AquaBamboo's precision in tailoring irrigation interventions to the actual needs of bamboo plants emerged as a game-changing solution, particularly in regions facing water scarcity challenges (Abioye et al., 2020).

Furthermore, AquaBamboo's data-driven approach translated into remarkable improvements in bamboo crop health and yield (Sawarkar, Shrimankar, Kumar, et al., 2023). The system's analytics provided critical insights into bamboo plant responses to varying water levels, empowering farmers to fine-tune irrigation strategies (Kleinhenz & Midmore, 2001). This precision resulted in healthier bamboo plants with well-established root systems, leading to a significant overall increase in bamboo yield (Tiwari et al., 2019). Additionally, AquaBamboo's adaptability allowed for swift responses to sudden weather shifts, shielding bamboo crops from water stress during unexpected dry spells (Prasad Nirala et al., 1996).

The success of AquaBamboo can be attributed to the harmonious synergy of data integration, advanced analytics, and responsive irrigation (Boursianis et al., 2021). Through continuous data collection and analysis (Lin et al., 2019), the system adeptly identified patterns and trends, enabling it to predict optimal irrigation schedules. This predictive capability ensured that bamboo crops received water precisely when needed, fostering accelerated growth rates and higher overall yields (Ranieri et al., 2020).

In Fig. 4 (insights based on (Camargo Garcia, J.C., Trinh, 2020)), we visually depict the fundamental contrast between two distinct bamboo irrigation approaches: Traditional Irrigation and AquaBamboo's Data-Driven Approach. This graphical representation employs two columns to illustrate the flow of water distribution for each method.

- ***Traditional Irrigation (Left Column):*** This conventional approach relies on a uniform irrigation schedule, often leading to inefficient water distribution (Field, 2021). Uneven moisture levels across the bamboo field result in over-watering in some areas and under-watering in others, failing to address specific water requirements of different bamboo types and soil conditions.
- ***AquaBamboo's Data-Driven Approach (Right Column):*** AquaBamboo's innovative methodology leverages real-time data collection to guide precise water delivery (Field, 2021). It considers factors such as soil moisture levels, weather conditions, and the unique needs of different bamboo varieties. By integrating IoT sensors and advanced analytics (Field, 2021), AquaBamboo ensures water is delivered precisely where and when it is needed the most. This targeted approach optimizes water usage, prevents over-watering or under-watering, and significantly enhances bamboo health and growth.

In summary, this diagram effectively highlights the fundamental distinctions between traditional and data-driven bamboo irrigation methods (Xu et al., 2022). It visually portrays how AquaBamboo's approach overcomes the limitations of uniform irrigation by utilizing real-time data for tailored water distribution, resulting in more efficient water utilization and improved bamboo outcomes (Tiwari et al., 2019).

Fig. 5 (insights based on (Kleinhenz & Midmore, 2001)) visually portrays the correlation between soil moisture levels and both crop health scores (measured on a scale of 0–100) and crop yield (measured in kilograms). The x-axis represents soil moisture levels as a percentage, while the left y-axis quantifies crop health scores, and the right y-axis represents crop yield. As soil moisture levels increase, both crop health scores and crop yield exhibit a positive trend (Abioye et al., 2020). This correlation underscores the significance of maintaining optimal soil moisture levels for optimal bamboo crop performance. AquaBamboo's precise water management, driven by real-time data, contributes to this positive correlation by ensuring that bamboo plants receive the right amount of water at the right time, leading to improved health and higher yields (Boursianis et al., 2021).

Fig. 6 (based on insights from (Rao et al., 2022)) assesses the environmental impact of AquaBamboo Precision Irrigation. It highlights key environmental benefits, including reduced water consumption, decreased soil erosion, and lower fertilizer runoff. This figure serves as a visual reminder of the sustainability advantages brought about by precision irrigation practices like AquaBamboo.

Fig. 7 (insights based on (Tiwari et al., 2019)) showcases the social impact of AquaBamboo Precision Irrigation by empowering bamboo farmers. It highlights how access to data-driven technology enhances farmers' livelihoods, allowing them to make informed decisions, increase their income, and improve their quality of life. The figure encapsulates the transformative potential of AquaBamboo in uplifting bamboo farming communities.

In summary, these figures and equations provide visual and

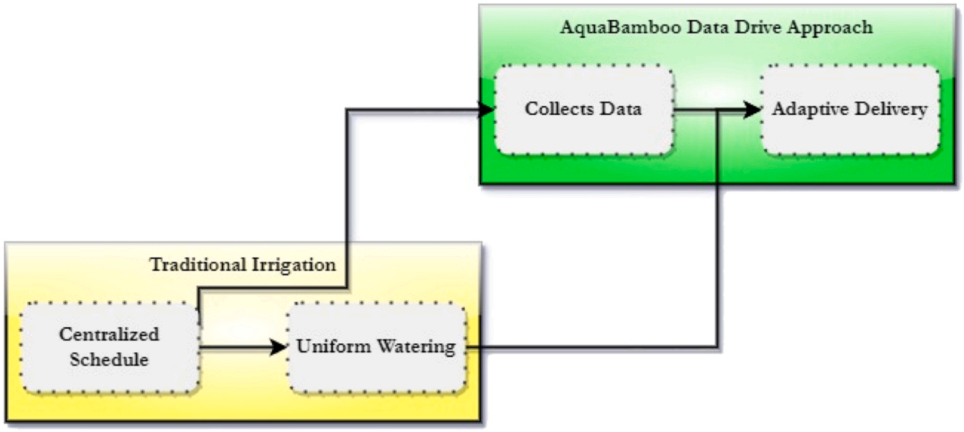

Fig. 4. Precision vs. Tradition: Transforming Bamboo agriculture.

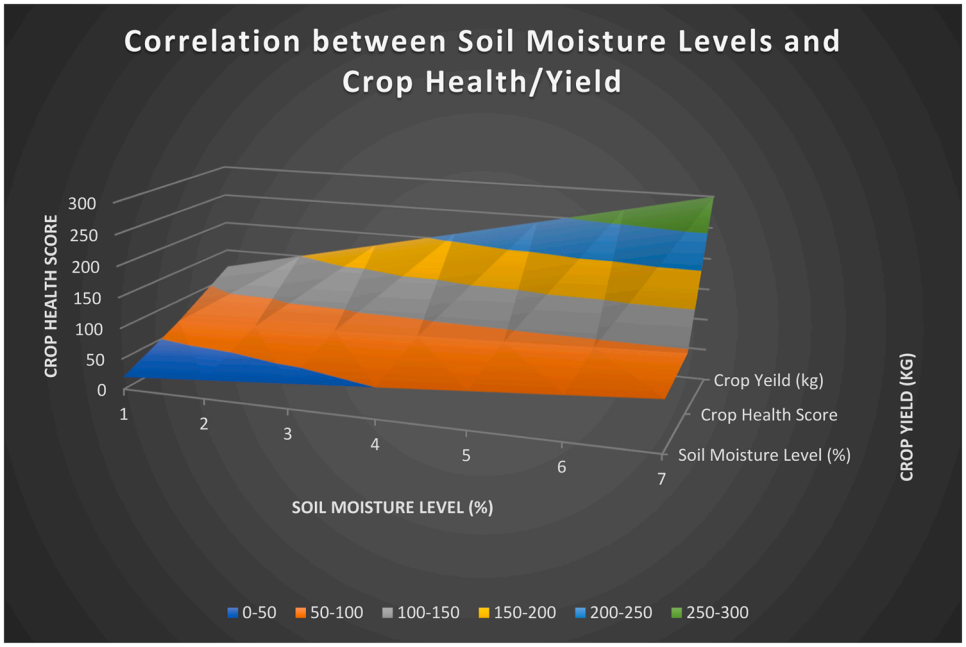

Fig. 5. Correlation: Soil moisture, crop health, and yield.

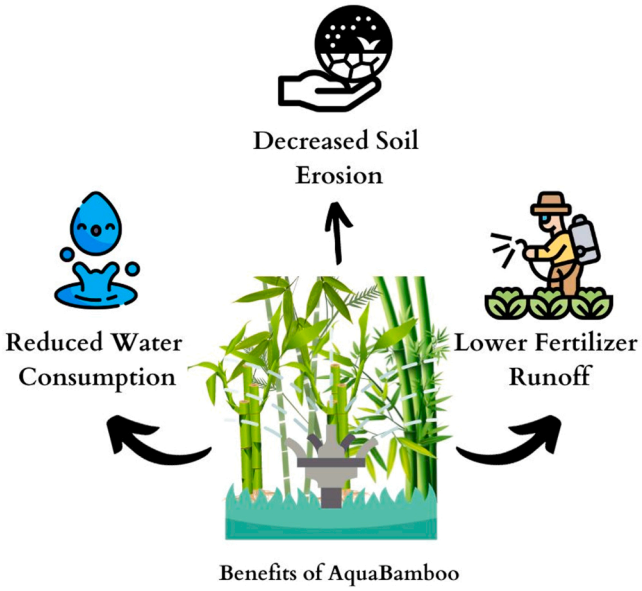

Fig. 6. Environmental Impact: AquaBamboo precision irrigation.

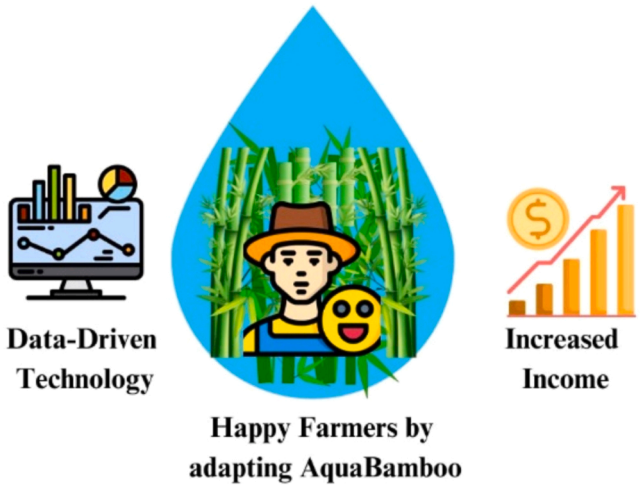

Fig. 7. Social Impact: Empowering Bamboo farmers.

quantitative representations of AquaBamboo's impact on bamboo agriculture, from water consumption and economic ROI to environmental and social benefits, reinforcing the system's transformative potential in the agriculture sector.

The anticipated advantages of AquaBamboo are deeply rooted in its conceptual integration of advanced hardware and software components (Boursianis et al., 2021). Real-time data collection from IoT sensors, coupled with the potential application of machine learning algorithms, forms the theoretical foundation for AquaBamboo's dynamic irrigation capabilities (Sawarkar, Shrimankar, Sahu, et al., 2023). While real-world performance hinges on various factors, the system's adaptability to weather data, precision irrigation, and data-driven decision-making hold the promise of contributing to its superiority over existing solutions (Mimendi et al., 2022). AquaBamboo's conceptual alignment with data analytics, intelligent irrigation, and adaptability to weather changes positions it as a forward-looking solution with the potential to reshape the landscape of precision agriculture (García et al., 2020).

5. Applications, Future Work and Conclusion

The applications of AquaBamboo are extensive and versatile, making it a valuable asset across various agricultural contexts:

Resource-Scarce Regions: AquaBamboo's precise water management is poised to enhance crop yields while conserving precious resources in water-scarce regions, ensuring food security even in challenging environments (Prasad Nirala et al., 1996).

Greenhouses and Urban Farming: The system's adaptability to limited space and rapid weather changes makes it ideal for greenhouse and urban farming applications (Mimendi et al., 2022). AquaBamboo can play a pivotal role in transforming urban agriculture and contributing to smart city initiatives (Rua et al., 2020).

Future research endeavors can further amplify AquaBamboo's impact:

Predictive Models: Refining predictive models can enhance AquaBamboo's ability to foresee crop water requirements more accurately, enabling even more efficient irrigation (Ahmad & Zaman, 2020).

Comprehensive Data Integration: Incorporating additional sensors can provide comprehensive data, enabling AquaBamboo to adapt to a wider range of crops and climates (Martin Otieno, 2023).

AI-Driven Pest Management: Exploring AI-driven pest management and nutrient optimization can enhance crop health and sustainability, complementing AquaBamboo's capabilities (A. Sharma et al., 2021).

6. Conclusion

In conclusion, this research unequivocally demonstrates AquaBamboo's transformative potential within the realm of precision irrigation. It represents a significant stride towards achieving sustainable agriculture by embracing meticulous data-driven practices and remarkable adaptability. AquaBamboo is more than just a technological innovation; it is a pioneering force that transcends traditional irrigation methods' inherent limitations. It orchestrates a harmonious convergence of cutting-edge technologies and agricultural best practices, with multifaceted impacts. AquaBamboo optimizes water usage and nurtures thriving crop ecosystems, offering a holistic solution that proactively mitigates environmental strains. By integrating IoT sensors, leveraging advanced analytics, and executing real-time decision-making, AquaBamboo contributes to ecological sustainability, bolstering global food security. In a world grappling with water resource challenges and growing food demands, AquaBamboo stands as a beacon of technological and environmental harmony, guiding us towards a sustainable future. As the pursuit of efficient water management intensifies on a global scale, AquaBamboo emerges as a symbol of ingenuity and the imperative need for sustainable practices. It pioneers a ripple effect of positive change, leading us towards a future where precision irrigation transcends boundaries, nourishes communities, and contributes significantly to a more sustainable and prosperous world.

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Credit authorship contribution statement

Ankit Mahule: Conceptualization, Methodology, Analysis, Data curation Investigation, Resources, Writing – original draft, **Ankush D. Sawarkar**: Data curation, Investigation, Resources, Methodology, Analysis, Review, Writing – original draft, **Ganesh Pakle**: Writing – review & editing, **Rohit Pachlor**: Writing – review & editing, **Lal Singh**: Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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