

ARTICLE

Digital Traceability and Lifecycle Performance of Bamboo-Based Construction Materials: Enhancing Durability and Circular Reuse through Smart Monitoring

Anber Abraheem Mohammad¹ , Suleiman Ibrahim Mohammad^{2,3*} , Asokan Vasudevan^{3,4,5} , Naomi Yang⁶,
Mahirah Saidah Marzuki⁷ , Mayibongwe Tafara Mudzengi⁸ 

¹ Digital Marketing Department, Faculty of Administrative and Financial Sciences, University of Petra, Amman 11196, Jordan

² Business Administration Department, Business School, Al al-Bayt University, Mafrq 25113, Jordan

³ Faculty of Business and Communications, INTI International University, Nilai 71800, Malaysia

⁴ Faculty of Management, Shinawatra University, 99 Moo 10, Bangtoey, Samkhok 12160, Thailand

⁵ Business Administration and Management, Wekerle Business School, 1083 Budapest, Hungary

⁶ Career Services, INTI International College Subang, Subang Jaya 47500, Malaysia

⁷ Academic Support Unit (ASU), INTI Corporate Office, INTI International University, Nilai 71800, Malaysia

⁸ International Relations and Collaborations Centre (IRCC), INTI International University, Nilai 71800, Malaysia

ABSTRACT

This paper explores the role that traceability and the use of predictive analytics could play in improving the durability and reusability of bamboo-based building materials. In an effort to better understand the problem being solved, a web-based monitoring platform has been developed across bamboo building projects in Jordan leveraging the use of Internet of Things (IoT) technology, machine learning modelling algorithms, and a web-based dashboard. The data generated from the installed sensors was modelled using algorithms such as the Random Forest algorithm and the XG Boost algorithm. Additionally, interviews were done. Analysis revealed improved durability in the digitally

*CORRESPONDING AUTHOR:

Suleiman Ibrahim Mohammad, Business Administration Department, Business School, Al al-Bayt University, Mafrq 25113, Jordan; Faculty of Business and Communications, INTI International University, Nilai 71800, Malaysia; Email: dr_sliman@yahoo.com

ARTICLE INFO

Received: 3 November 2025 | Revised: 22 December 2025 | Accepted: 26 January 2026 | Published Online: 2 July 2026

DOI: <https://doi.org/10.30564/jbms.v8i3.12661>

CITATION

Mohammad, A.A., Mohammad, S.I., Vasudevan, A., et al., 2026. Digital Traceability and Lifecycle Performance of Bamboo-Based Construction Materials: Enhancing Durability and Circular Reuse through Smart Monitoring. *Journal of Building Material Science*. 8(3): 1–23.

DOI: <https://doi.org/10.30564/jbms.v8i3.12661>

COPYRIGHT

Copyright © 2026 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License (<https://creativecommons.org/licenses/by-nc/4.0/>).

traceable bamboo parts compared to the manually inspected parts through the increased residual strength of 9–12% and a life span of about three months. Introduction of environmental factors enabled the life span recalibration in the digital-twin system ($R^2 = 0.89$) compared to the previous predictions. Reuse circularity in the digital-twin platform improved as 62% of the components were categorized as high-reuse components. A combination of predictive intelligence and environmental analysis describes a replicable approach for the sustainable management of building materials in data-driven construction environments.

Keywords: Digital Traceability; Bamboo Durability; Circular Reuse; Digital Twin; Sustainable Construction

1. Introduction

The move towards sustainable building materials is, therefore, one of the characteristics that define the 21st century, which is pushed by the dual forces of natural resource depletion and the deterioration of the environment. Currently, the construction industry is known to account for the consumption of around 40% of the overall energy in the world ^[1]. At the same time, it is also reported to account for one-third of the overall gas emissions in the environment. There is, therefore, a growing concern to find more sustainable, recyclable, and renewable materials that will have lower embodied energy without significantly altering the performance levels ^[2,3]. Under these circumstances, the potential of using Bamboo as a sustainable bio-material with high tensile strength comes into the picture. The other benefits are its quick regrowth and its ability to act as a carbon sequestrator. The increasing digitalization in the construction sector has further aided the move towards making the sector more sustainable, with chief milestones in the Internet of Things, digital twins, and machine learning applications in the sector that promote real-time material monitoring and the digital traceability of all materials in the construction sector ^[4]. The digital traceability, in particular, is a technology that provides an inherent digital identity for each material in the construction sector, which provides a record of the material's usage history in the environmental space, aiming at providing decision-making support that is well-informed and geared towards the optimal recycling of the different materials in the construction industry.

In addition, in spite of the advancements in digital monitoring and predictive models in the case of traditional materials in the industry such as steel and concrete ^[5,6], bamboo materials still lag in these technological advance-

ments. As a matter of fact, the current traditional inspection and maintenance processes still dominate in the case of existing buildings made from bamboo materials. This is followed by a reactive approach instead of the preventive method. Moreover, the current literature on the bamboo materials' life cycle and durability is dominated by chemical treatment processes and coating technology instead of the data-driven life-cycle optimization strategy. On the other hand, in spite of the need to adopt digitalization in the construction technology industry as a whole ^[6], the full technological scope in the digital management of the bamboo materials' life cycle still remains uncharted. Thus, the absence of integration solutions for traceability within the bamboo material life cycle has caused insufficient data on the traceability performance of the bamboo materials. Moreover, the literature on the current situation appears to be considering the bamboo material life-cycle durability, performance impact, and bamboo material reuse in circular economy perspectives as separate topics instead of covering them as a continual and wholesome life cycle. Therefore, in the absence of an integrated comprehensive scheme in the case of the bamboo material life-cycle performance and resulting predictive and monitoring schemes, the bamboo material life cycle appears to be systematically exposed to doubts on the structural integrity in distinguishing the material life-cycle disposal phases, which further confounds the efficiency in the case of the material resources as well as the frameworks on the sustainable bamboo material reuse. Thus, the main problem here for conducting the research work is the absence in the case of the integrated comprehensive scheme on the bamboo material life-cycle performance.

The study's import lies in its theoretical and practical applications. On a theoretical basis, the research promotes the incipient paradigm of "smart sustainability" in the con-

struction industry; namely, the design where the applied materials must be not only biologically renewable but also “smart,” able to communicate their properties in order to control them. On a practical level, the research exemplifies how the parameter of digital traceability may raise the value of bamboo by turning it into “smart” self-managed material. In the case of developing countries such as the Jordan Valley, where the problem of climatic diversity and raw material makes the sustainability of the construction industry an issue ^[7,8], the application of such paradigms helps the country achieve its sustainability goals.

The originality of the proposed research appears in its combination of traceability in the digital realm, prediction using analytics, and feedback from the natural environment into one empirical approach that is applied in the bamboo construction material industry. Contrary to the previous literature that focused on the sustainability of the construction material industry in terms of the testing of material durability or exposure to the natural environment in isolation ^[9,10], the current proposal combines the digital material lifecycle approach that analyses data from the natural environment using algorithms in the realm of the Internet of Things while incorporating the concept of the ‘Digital Twin Reuse Evaluation System.

The theoretical underpinning of this research falls under the larger discursive realm of the circular economy and the digitalization of the construction industry. Although there has been research carried out in the realm of digital twins and sensor monitoring in industrial materials ^[11,12], there has been limited research in this area conducted in the domain of bio-based materials that are highly variable and environmentally sensitive. The current research also fills a unique gap because it approaches the concept of bamboo as a ‘data-rich’ material in which the physical and virtual aspects are intertwined in an iterative process of the material’s life cycle. This also falls in line with the ‘theory of data embedded materiality’ ^[13], which believes that “materials expand their intelligence and malleability through an endless flow of data integration.” The current research also falls under the larger remit of this theory in which it has chosen to integrate bamboo.

Departing from the common theme of structure health monitoring, digital twin analysis, and IoT-based lifecycle assessment applied to individual assets and com-

mon materials, the proposed research applies instead a framework centered on the material properties and the value chains of bamboo-based infrastructure. By incorporating digital traceability together with the assessment of potential bamboo re-use and durability, the research extends the prior state of the art applied to individual assets toward a framework embedded in the value chains of the bamboo material itself. Even though the research study has been applied to twelve different infrastructure projects and 120 bamboo components deployed in the country of Jordan, it must be clear that the contribution is not the creation of generic numerical limits but the development of a transferable framework. By incorporating the application of digital traceability together with predictive analytics and digital twin visualization, the study establishes a methodological reference framework that may be applied to other biobased materials and other geographical locations facing similar climatic or sustainable developmental constraints. Larger project scopes and additional comparative analyses across different locations across the different countries would ultimately be required to improve the numerical limits of individual parameters and to generally verify the findings across larger scopes. This research study nevertheless indicates that even for smaller infrastructure project implementations, the associated application of digitalization may greatly improve the scope of lifecycle management assessment applications related to bamboo infrastructure durability as well as related biobased infrastructure re-use.

2. Literature Review

2.1. Digital Traceability in Construction Materials

Digital traceability refers to the systematic recording and tracking of the lifecycle of any material, from origin, through processing, to application, maintenance, and recovery at its end of life, made possible through digital technologies such as RFID, IoT sensors, and blockchain systems. Within the construction sector, this is known as a key enabler of Industry 4.0 data-driven approaches to material management. Research by Pathmu (2025) ^[14] and Khan et al. (2022) ^[15] has proved that traceability systems introduce accountability and full supply chain visibility that allows for quality assessment and certification of sus-

tainable materials with more reliability. Similarly, Santana and Ribeiro (2022) ^[16] and Giovanardi et al. (2022) ^[17] support that traceability also enables the verification of embodied carbon and environmental compliance, therefore enabling circular design in construction projects.

Despite these developments, research on digital traceability has focused on industrial and mineral-based materials, such as steel, concrete, and asphalt ^[4,18]. Applications of traceability frameworks to bio-based construction materials remain scant, especially in developing regions. Bamboo has gained growing interest due to its renewable and mechanical properties. Still, only a limited number of studies ^[19-21] have considered how digital traceability would increase the performance monitoring or reuse potential of this building material. The gap in the existing literature is the absence of real-time traceability data regarding bamboo materials. This inhibits their integration into state-of-the-art construction management systems.

2.2. Durability of Bamboo and Bio-Based Materials

Material durability of natural fibres and plant-based composites is a central issue in structural engineering and sustainable material science. Bamboo is widely documented by Awalluddin et al. (2017) ^[22] and Sharma et al. (2015) ^[23] for its mechanical strength, tensile resilience, and rapid renewability. However, its susceptibility to biological decay, humidity fluctuations, and temperature has raised continuing performance issues. Research on Noverma et al. (2020) ^[24] and Bui et al. (2017) ^[25] shows that poor maintenance or low-quality bamboo degrades in strength over time, especially when exposed to humid or saline conditions. Though durability treatment and resin-based reinforcement have achieved partial success, they often compromise the environmental benefit of bamboo through the addition of non-renewable chemicals.

Recent developments have focused on intelligent monitoring of durability by using embedded sensors and wireless networks. Rotilio et al., (2018) ^[26] demonstrated the possibility of indicating the early degradation of timber and bamboo structures by embedding moisture and temperature sensors. However, these studies only involved experimental prototypes and did not develop links between sensor-based monitoring and predictive or traceable data

systems. Therefore, there is a significant gap in the literature regarding an integrated framework focusing on digital monitoring, predictive analytics, and material durability performance at the bamboo-construction application level.

2.3. Circular Reuse and Lifecycle Thinking in Sustainable Construction

Sustainability for the construction sector has been redefined by circular economy principles that place a premium on reuse, refurbishment, and recycling over linear consumption and waste. Dewagoda et al. (2022) ^[27] and Göswein et al. (2019) ^[28] argue that in making the transition to circularity, there is a need to move from static material lifecycles to dynamic feedback systems whereby materials are traceable and continuously fed back into new construction contexts. Digital traceability provides the informational basis for this shift, whereby materials bear a verifiable digital identity through successive stages of their lifecycle.

For bamboo, there is also a duality of opportunities and challenges to be considered within the context of circular reuse. Research by Chen et al. (2020) ^[29] and Li et al. (2020) ^[30] has demonstrated that provided the mechanical history and exposure record of the bamboo are known, it can be structurally reused or processed into an engineered composite. However, such knowledge is seldom available or in a standard format therefore, decisions for its reuse are conservative, leading to the waste generated by its disposal at an early stage in its life. Digital traceability linked with the principles of the circular economy may, therefore, build confidence in reuse decisions through traceable material condition with verifiable performance histories—a research avenue which remains comparatively unexplored in the extant literature.

2.4. Predictive Monitoring and Smart Analytics

Machine learning and artificial intelligence have really revolutionized predictive modelling in material science. Works by Ekanayake et al. (2022) ^[31] and Yuan et al. (2022) ^[32] have illustrated the potential of machine-learning algorithms, such as Random Forest and XGBoost, for forecasting structural deterioration and residual strength of

concrete and timber materials under various environmental exposure conditions. These algorithms outperform conventional statistical models through capturing complex nonlinear interactions of environmental, chemical, and mechanical variables.

Despite growing evidence of their validity, predictive analytics for natural and bio-based materials remains underdeveloped. Most research has focused on traditional materials whose degradation mechanisms are well-understood [33–35]. In the case of bamboo, predictive analytics have seldom been used to evaluate performance or reuse potential in real-world scenarios. Moreover, linkages do not exist between predictive output and operational decision-making tools, such as digital-twin platforms. This limits the practical applications of predictive models in enabling adaptive maintenance and circular resource planning for bamboo-based materials.

2.5. Environmental Integration and Lifecycle Adaptation

Environmental conditions, especially humidity, temperature amplitude, and duration of exposure, have a major impact on the degradation behaviour of bamboo. Previous studies by Musthaq et al. (2023) [36] and Cascione et al. (2020) [37] have recorded the high sensitivity of natural materials to environmental stressors in semi-arid and humid climates. However, existing literature often considers these factors as external uncontrollable risks rather than measurable variables of predictive systems. Newer frameworks within adaptive environmental modelling [38] accommodate real-time environmental feedback for digital lifecycle management to dynamically update maintenance schedules and reuse strategies.

This adaptive approach has seldom been used in the case of bamboo. Most research on the durability of bamboo, such as Shettigar et al.'s 2025 study, assumes fixed environmental states or employs post-hoc rather than continuous testing of environmental conditions [39]. The absence of integrated environmental feedback systems constitutes a significant gap in ensuring the reliability and scalability of bamboo for long-term construction applications, especially in climates like Jordan's with great seasonal variation.

2.6. Identified Research Gap

This research aims to address these gaps through the development and testing of a smart, digital traceability-driven lifecycle framework for bamboo materials. Although literature has addressed the aspects of bamboo durability and its circular reuse and digital innovation separately, no integrative data-driven model unifying these dimensions in real-time exists. Second, there is a remarkable dearth of reports on how integrating the state-of-the-art BIM with digital traceability, along with predictive monitoring and environmental analytics, can lead to simultaneous improvement in the durability and circular reuse prospects of the bamboo-based construction material. There is also a shortage of empirical evidence in developing regions like Jordan, where climatic variability and resource constraints have created the need for context-specific technological adaptation. Therefore, this research develops and tests a framework that couples digital traceability with monitoring, analytics, and environmental feedback to enable the pursuit of a circular construction approach applied to bamboo materials. Coupling technological innovation with sustainability principles provides one with an improved understanding of how natural materials can be converted into intelligent, traceable, and circular assets in the built environment.

2.7. Conceptual Framework and Hypothesis Development

This research presents a conceptual framework (**Figure 1**) that combines digital traceability, environmental exposure, machine learning algorithm analytics, and the potential for circular reuse to analyse the role of bamboo-based constructions in Jordan. Digital traceability is enabled through the use of Internet of Things (IoT), Radio Frequency Identification (RFID), and cloud-based databases to record instantaneous lifecycle data. Machine learning algorithms (Random Forest and XGBoost) will then analyse the data to predict durability measures such as strength and longevity. These environmental exposure factors (temperature and humidity) moderate the degradation processes. Three distinct paths will emerge from the framework: (i) the effect of traceability on durability outcomes directly, (ii) traceability and the potential for second-loop cyclical use

indirectly through analytics outcomes, and (iii) the moderated relationship between traceability outcomes affected by environmental exposure factors. Hypotheses will now emerge from the conceptual framework:

Hypothesis 1. *Digital traceability and ‘smart’ attributes (sensor data & traceability index) positively influence the accuracy of predicting the durability and strength lifetime predictions of bamboos.*

Hypothesis 2. *Environmental exposure factors (tempera-*

ture variation & humidity) play important determinants in influencing the degradation & lifetime diminution effects in bamboos & bamboo-based construction materials.

Hypothesis 3. *By integrating the principles of digital traceability & instantaneous lifecycle material data through the use of ‘digital twin’ technology interfaces in the enhanced ‘circular’ reuse potential outcomes through more accurate predictions & decisions regarding ‘residues’ reuse.*

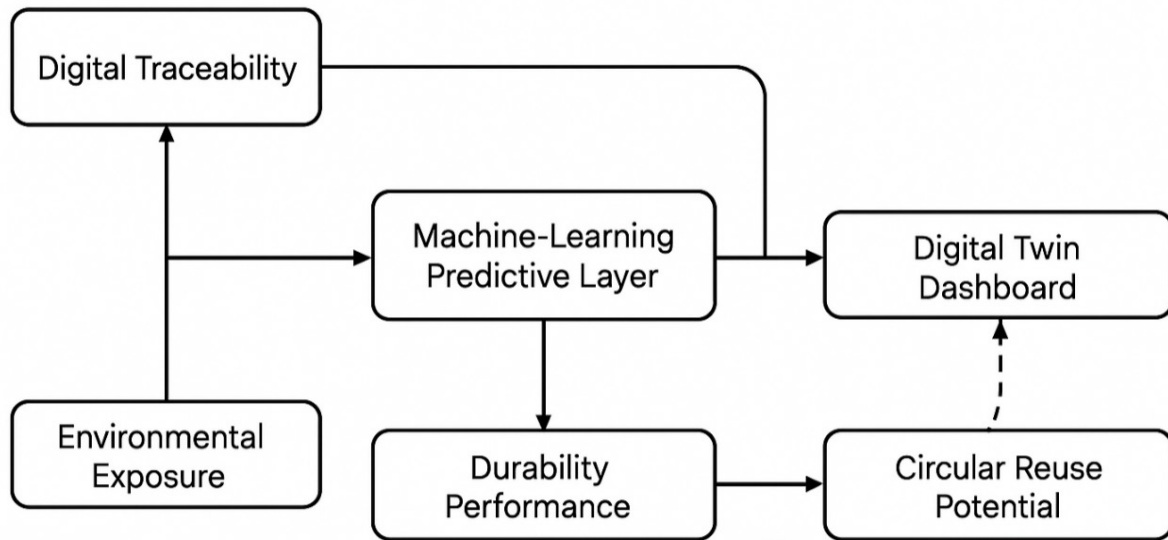


Figure 1. Conceptual Framework of the Study.

3. Methodology

3.1. Research Design

The research work carried out used a mixed-methods research design that combines descriptive and analytical methods to evaluate bamboo-based construction materials’ lifetime performance using digital traceability systems in Jordan. The research work began with a descriptive method that aimed to describe accurately the condition of bamboo’s current state, durability, and levels of performance under the prevailing climatic conditions accurately. The research work progressed to the analysis level to discover causal relations that exist among digital traceability variables, climatic conditions, and bamboo construction materials’ levels of performance. The research work started with exploratory research to investigate levels of digital traceability adoption within Jordan’s construction indus-

try and progressed to descriptive and analytical research after obtaining quantitative field data using smart digital traceability systems. The research work provided room to explore new combinations of digital traceability adoption levels with the construction industry and precision to investigate statistical significance levels of variables associated with the durability of bamboo materials.

3.2. Data Collection Methods

The data collection exercise was carried out for six months from January to June 2024 in three governorates in Jordan; these were Amman, Irbid, and Ajloun. This selection of the governorates was done in an attempt to capture different climatic conditions from arid to semi-humid. There was the use of both primary and secondary data sources to ensure that the research is complete and credible. Primary sources were used in the collection of data

from bamboo by making use of Internet of Things (IoT) technology, radio frequency identification (RFID) chips, and manual observation. The IoT technology allowed for continuous observation of the environment in terms of temperature, humidity, and moisture content. The RFID chips allowed for digital traceability of the bamboo from the time of creation until the time of disposal. Physical observations of the strength and degradation of the bamboo were also used in the experimental procedure of the research by assessing the physical strength of the selected samples of bamboo. In addition to the data collection aspect of the research, there was the use of semi-structured interview techniques among twenty experts in the field of construction in Jordan regarding the integration process and the adoption of traceability in the Jordanian construction industry.

For the secondary sources of this research, several reports and studies were reviewed on sustainable construction, bamboo composites, and the use of digital monitoring. The use of these sources helped the research tap into the worldwide discussions on smart and sustainable construction materials. In addition to the usual field analysis and IoT-based collection of information, a digital twin interface was created to represent the actual structure of each bamboo material based on its real-time status. The interface linked all the information collected by several sensors to simulations to facilitate both past and future analyses of material performance.

Each sensor type was initially calibrated prior to installation against a handheld reference device to ensure readings fell within the manufacturer's tolerance range. During operation, obviously spurious values—for example, implausible temperature or humidity spikes arising from power or connection issues—were removed, short gaps were linearly interpolated, and longer gaps were treated as missing. All time-stamped measurements from disparate devices were subsequently resampled onto a common interval and synchronized before constructing the dataset employed for predictive models and lifecycle indicators.

3.3. Population and Sample

The targeted population consisted of all con-

struction projects in Jordan using bamboo or hybrid bamboo-based materials in any form, whether for pilot installations, demonstration structures, or operational buildings. Since the construction practice of bamboo is quite new in Jordan, the identified population only totalled twenty-five active or recently completed projects. These were identified from the Jordan Green Building Council registry, architectural firms specialized in sustainable design, and collaborative institutions involved in ecological construction initiatives.

Considering the fact that the targeted population is relatively small and is skewed towards specialized sectors, the purposive sampling technique became the suitable choice to locate the projects that merged and could support the integration of digital monitoring systems. However, the selection of the total of twelve projects that formed the study's sample included, on average, ten bamboo-related monitored items in each, accumulating to a total of 120 monitored items in the study. The study adopted the purposive sampling technique to allow for the selection of representative examples related to the application and experimental use of bamboo materials in the construction industry in Jordan.

Though the theoretical value of the sample was twenty-four, due to some constraints such as the availability of suitable projects and the availability of ready monitoring systems, the final value considered was twelve projects. This value was considered sufficient for analysis since it had a representative variety of exposures and materials.

3.4. Description of Population

The selected schemes had varying building types, material arrangements, and climatic conditions. **Table 1** shows the characteristics of the study population, including the structural conditions and climatic differences that were taken into consideration in the data collection process.

This was made in a manner that covered the range of conditions associated with the bamboo performance in Jordan, from the dryness in Amman to the more humid environment in the Ajloun region.

Table 1. Population Description.

Variable	Description	Type	Geographical Focus	Observed Projects
Type of Structure	Residential, public pavilions, experimental prototypes	Categorical	Amman, Irbid, Ajloun	25
Material Composition	Pure bamboo, hybrid bamboo-polymer composites	Categorical	Amman, Irbid	25
Monitoring System	Manual inspection/digital traceability (IoT-based)	Binary	Amman, Ajloun	25
Age of Structure	0–5 years, 6–10 years	Ordinal	All locations	25
Climatic Exposure	Humid, semi-arid, arid	Categorical	All locations	25

3.5. Summary Table of Main Variables

The main variables investigated in the study were operationalized to capture both the material properties of bamboo and the efficiency of the digital traceability system (Table 2).

These variables formed the core analytical framework for examining how digital traceability influences the lifecycle durability and reuse potential of bamboo materials in real construction environments.

3.6. Measures and Analytical Methods

This research requires measurement with high accuracy and validity. The process of measurement was done by employing calibrated equipment. Moisture measurement was done by using Bosch G940 digital moisture meters. The measurement of temperature was done by using DS18B20 temperature probes. The measurement of compressive strength involved processes according to ISO 22157 standards by using a Universal Testing Machine. The compressive load capacity was determined from this measurement process. The traceability index was determined by evaluating data from the digital tracking system supplied by the RFID process. The index of surface deg-

radation was determined by systematic visual evaluation according to ASTM D3345 standards.

The analysis was performed using both statistical techniques and sophisticated machine learning models to accurately capture the non-linear relationships that exist among the variables in the problem. The Random Forest and XGBoost models were used to determine the regression of the residual compressive strength and the estimated service life of the bamboo material when the input variables of temperature, humidity, rate of moisture change, treatment type, and traceable index are given. The models were validated using root mean squared error (RMSE), mean absolute error (MAE), and the coefficient of determination (R-squared). Pearson correlation analysis and ANOVA were both used to determine the effect of treatment and exposure on enhancing the material’s durability. Interview transcripts and field notes were first analysed thematically, based on an initial coding set derived from the conceptual framework, and then supplemented with the inductive emergence of additional codes from the data. Two researchers worked together to refine the code list after the initial round of coding to ensure a shared meaning of key categories, and the summary themes were discussed with participants to check that the interpretations accurately reflected their experiences.

Table 2. Summary of study variables.

Main Variable	Operational Definition	Measurement Scale	Data Source
Moisture Content (%)	Ratio of water mass to dry mass in bamboo	Continuous	IoT sensors
Compressive Strength (MPa)	Load-bearing capacity before failure	Continuous	Mechanical testing
Surface Degradation Index	Qualitative rating from 1 (no damage) to 5 (severe)	Ordinal	Field inspection
Traceability Index	Percentage of lifecycle data digitally recorded	Ratio	RFID system logs
Reuse Potential (%)	Proportion of components suitable for reuse	Ratio	Lifecycle model output
Environmental Exposure Index	Combined measure of temperature and humidity variance	Continuous	IoT sensors

3.7. Ethical Consideration

All interviews were performed in accordance with institutional ethical guidelines. Participation was on a strictly volunteer basis through informed consent, and participants were free to withdraw at any time. Interview data were anonymized and stored on password-protected devices. Sensor and monitoring data applied exclusively to material and environmental conditions and did not contain personally identifiable information.

4. Results

4.1. Overview of Data Collected

This is the dataset employed in the current study, which was obtained from twelve bamboo construction sites representing the diverse climatic conditions of Amman, Irbid, and Ajloun. Over a period of six months, that is, January to June 2024, 120 components of bamboo were monitored with sensors using IoT and RFID systems. Data captured on moisture, temperature, humidity, and degradation conditions were at an interval of every 30 min. Manual inspections done monthly over four weeks could validate the accuracy of the sensors. After pre-processing, a total of 155,000 valid observations were retained, giving a data integrity rate of 98.7%. Temperature and relative humidity ranged between 16.8 °C and 64.5% in Ajloun and 29.4 °C and 38.9% in Amman. Overall, 8,000 lifecycle entries were present within the traceability system, followed by the integration with a digital twin dashboard where the attained validation accuracy was 95.3%. Presented in **Table 3** is an overview of the scope and data quality across the three regional clusters.

Table 3. Details Of Collected Data.

Parameter	Amman	Irbid	Ajloun	Total
No. of Projects	5	4	3	12
Components Monitored	50	40	30	120
Monitoring Duration (months)	6	6	6	6
Total Sensor Records	68,400	52,200	34,400	155,000
Data Completeness (%)	98.4	97.9	99.2	98.7
Average Temperature (°C)	29.4	24.3	16.8	
Average Relative Humidity (%)	38.9	52.7	64.5	

This data set presented significant variations in terms

of exposure to the environment, which later became one of the inputs used in the correlation and predictions that followed. Furthermore, the fact that the data is more complete lends significant strength towards the successful training of the models that were used in the interpretation of the statistics that were derived from the observations.

4.2. Descriptive Analysis of Key Variables

Six main variables emerged through analysis: moisture content, compressive strength, surface degradation index, environment exposure index, traceability index, and reuse index. The average moisture content of the studied bamboo components was 14.8%, showing a remarkable variability caused by site location and prevailing humidity. Ajloun had the maximum average moisture content of 17.4%, reflecting the prevailing humid climate, while the lowest average of 12.2% was registered in Amman, as it is a semi-arid region. These differences reflected a corresponding average of 42.6 MPa for the overall compressive strength, for which a reverse correlation with moisture content was established through statistical analysis in the corresponding stage.

The index of surface deterioration ranged from 1 (no detectable deterioration) to 5 (substantial deterioration), and its average was 2.3. Comparison of the components of Ajloun and Amman indicated that Ajloun components were slightly more deteriorated (average of 2.8 compared to 1.9 for Amman), which was because of the effect of moisture. The environmental exposure index was computed using the normalized variance of temperature and humidity; its average was 0.63. This indicated moderately high exposure. Higher exposure indexes indicated faster absorption of moisture and the trigger for the maintenance message in the digital twin environment.

The traceability index, which is the percentage of the lifecycle processes documented digitally, had an average of 0.82. This is the measure of the percentage of the important phases in the structure's lifecycle that are documented digitally from the time of installation to the time of examination. The positive impact of the traceability index on the performance consistency can be attributed to the efficiency of the detection and subsequent maintenance processes. The reuse potential index, which was the integral value from the remaining strength and the measure of the

degradation process, averaged 0.71. This indicated that the structures had the potential to be reused at the end of the

first lifecycle at the rate of 71%. The descriptive statistics from the data collected are shown in **Table 4** below.

Table 4. Descriptive Statistics Result.

Variable	Mean	SD	Minimum	Maximum	Observed Range	Unit
Moisture Content	14.8	3.7	8.9	21.6	12.7	%
Compressive Strength	42.6	5.4	32.1	54.8	22.7	MPa
Surface Degradation Index	2.3	0.9	1.0	4.5	3.5	Scale (1–5)
Environmental Exposure Index	0.63	0.12	0.41	0.88	0.47	Dimensionless
Traceability Index	0.82	0.09	0.65	0.97	0.32	Proportion (0–1)
Reuse Potential Score	0.71	0.15	0.38	0.92	0.54	Proportion (0–1)

4.3. Correlation and ANOVA Analysis

The Pearson correlation matrix defined the bivariate relationships among the six main variables: moisture content, compressive strength, surface degradation index, environmental exposure index, traceability index, and reuse potential score. Several statistically significant associations were found, as depicted in **Table 5**.

The correlation analysis yielded a few important trends that support the theoretical propositions of the research. First, there was a strong negative relationship between moisture content and compressive strength, $r = -0.74, p < 0.001$, which shows that with increased internal moisture, the load-carrying capacity of bamboo is considerably weakened. This outcome supports previous studies concerning hygroscopic materials where absorbed moisture causes the swelling of fibres, reduction of stiffness, and weakening of the microstructure.

Figure 2 shows a heat map of the strength and direction of associations among the main study variables. Strong negative associations are evident between moisture content and compressive strength, and between environmental exposure and reuse potential, suggesting that heightened environmental stress negatively affects both structural integrity and reusability. Similarly, the environmental exposure index has a strong negative association with compressive strength ($r = -0.71, p < 0.001$) and a positive association with surface degradation ($r = 0.66, p < 0.001$), confirming that heightened environmental stress, higher levels of humidity and larger temperature fluctuations lead to greater surface deterioration and loss in strength.

Conversely, the traceability index had positive correlations with both compressive strength ($r = 0.46, p <$

0.01) and reuse potential ($r = 0.67, p < 0.001$), but a negative correlation with surface degradation ($r = -0.52, p < 0.01$). This implies that structures in which effective digital monitoring is in place undergo lower rates of degradation, leading to improved maintenance practices, thus improving material endurance. An important negative correlation was, however, found for the traceability index and environmental exposure ($r = -0.58, p < 0.001$), which implies that a structure that is less exposed (due to proper design and legislative intervention through digital monitoring) retains higher levels of traceability information. Additionally, reuse potential was found to be positively correlated with both compressive strength ($r = 0.61, p < 0.001$) but negatively correlated with both moisture content and environmental exposure, thereby confirming the expected outcome that lower levels of exposure due to higher levels of material strength improve material reuse potential.

To further assess the significance of these correlations, one-way and two-way ANOVA tests were employed to analyse the differences in compressive strength and surface degradation to check the statistical significance of differences due to varying levels of treatment, type of monitoring, and exposure intensity. The ANOVA test shows that there is a significant difference in the compressive strength of the materials due to varying levels of treatments ($F(2,117) = 15.84, p < 0.001$). Post-hoc Tukey tests showed that the compressive strength of the chemical-treated bamboo ($M = 47.8$ MPa) is significantly higher compared to the compressive strength of the untreated bamboo ($M = 38.5$ MPa) and the naturally treated bamboo ($M = 42.1$ MPa) and highlights the ability of chemical treatment to increase the strength of the bamboo materials to withstand different climatic changes. The surface degradation values

were also found to differ significantly due to the varying treatment levels ($F(2,117) = 9.63, p < 0.001$).

Table 5. Correlation Analysis Result.

Variables	Moisture Content	Compressive Strength	Surface Degradation Index	Environmental Exposure	Traceability Index	Reuse Potential
Moisture Content	1	-0.74***	0.69***	0.82***	-0.48**	-0.57***
Compressive Strength		1	-0.63***	-0.71***	0.46**	0.61***
Surface Degradation Index			1	0.66***	-0.52**	-0.49**
Environmental Exposure				1	-0.58***	-0.62***
Traceability Index					1	0.67***
Reuse Potential						1

Note: ** $p < 0.01$; *** $p < 0.001$.

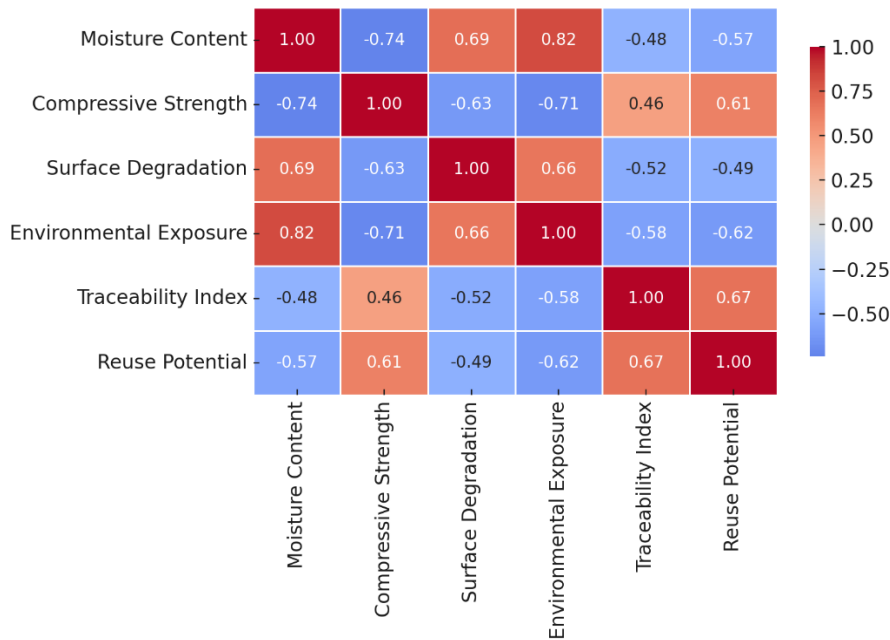


Figure 2. Heat Map of Correlation Analysis for Key Variables.

A one-way ANOVA post-hoc Tukey test result shows that the highest surface degradation values ($M = 2.9$) were noted in the case of untreated bamboo materials, followed by the naturally treated bamboo ($M = 2.2$) and the chemical-treated bamboo materials ($M = 1.8$) and indicates that the methods used for protecting the surfaces of the materials can Another ANOVA investigating the effect of type of monitoring on compressive strength and surface degradation found it to be significant for both factors: compressive strength of components tested through digital monitoring ($M = 44.9$ MPa) was significantly higher compared to components inspected by humans ($M = 40.3$ MPa), and surface degradation values were lower in components tested through digital systems ($M = 2.0$) compared to compo-

nents tested by humans ($M = 2.6$). The significant difference in this case speaks volumes about the advantage of digital traceability systems and their efficacy in providing early maintenance notifications. The eta-squared measure of effect size in this case was found to be 0.12 because the type of monitoring explained 12% of the total variance of durability.

The third ANOVA considered the environmental exposure categories and their effects on material performance. ANOVA results showed a very significant difference in the values of compressive strength between the exposure levels: $F(2,117) = 21.09, p < 0.001$. For example, specimens under high exposure conditions showed a considerably lower average strength of 38.7 MPa compared

to the groups with medium (43.9 MPa) and low exposure (47.3 MPa). Similarly, the surface degradation index increased progressively with exposure intensity: $F(2,117) = 18.42, p < 0.001$, which suggested that environmental stress caused faster deterioration in the material. There is an interaction effect between exposure intensity and monitoring type: $F(2,114) = 4.28, p < 0.05$, proving that the presence of the digital traceability system modulated the detrimental effect of exposure by allowing quicker detection and mitigation.

4.4. Machine-Learning Prediction of Durability and Residual Lifespan (H₁)

Two non-parametric ensemble regressors were utilized because of the capability to model complex nonlinear relationships and interaction effects typical in moisture–temperature–time dynamics: Random Forest (RF) and XGBoost (XGB). The features utilized included rolling means and variances of moisture and temperature (windows ranging from 24 to 72 h), relative humidity statistics, Environmental Exposure Index, Traceability Index, dummy variables for treatment category, component geometry (diameter and thickness), age in months, site, and baseline strength at commissioning. In order to prevent leak-

age in the data, all derived statistics were computed using only past-only windows and strictly partitioned according to component ID. Model evaluation employed nested cross-validation: outer 5-fold, grouped by project inner 5-fold for hyperparameter tuning. The outer folds were designed to avoid site-level leakage across governorates. The metrics provided are averages over the outer folds, including R², RMSE, and MAE. A very parsimonious baseline model a regression based on ordinary least squares using the mean of moisture, the mean of temperature, and age was used for comparison.

XGBoost consistently outperformed the baseline and Random Forest with a gain in R² of around 0.31–0.35 with respect to linear regression and a decrease in MAE of roughly 1.5 MPa (strength) and 2.7 months (lifespan) from **Table 6**. The improvements indicate that nonlinear interactions among moisture dynamics, temperature cycles, treatment, and traceability density are important for durability prediction. The outcome confirms Hypothesis H₁ because the enhanced models using smart monitoring and traceability features produce substantially higher predictive accuracy. Permutation importance and SHAP analyses converged to a robust ranking of global drivers. The top predictors for the optimal model, namely XGBoost, are listed in **Table 7**.

Table 6. Predictive Performance Results.

Target	Model	R ²	RMSE	MAE
Residual Strength (MPa)	Baseline Linear Regression	0.58	3.92	3.08
Residual Strength (MPa)	Random Forest	0.83	2.45	1.86
Residual Strength (MPa)	XGBoost	0.89	2.01	1.52
Remaining Life (months)	Baseline Linear Regression	0.54	6.8	5.2
Remaining Life (months)	Random Forest	0.80	4.1	3.1
Remaining Life (months)	XGBoost	0.87	3.3	2.5

Table 7. Top Predictors for the Best Model (XGBoost).

Rank	Predictor (Standardized)	Importance (Normalized)	Direction of Effect (Summary)
1	Moisture Variance (72 h)	1.00	Higher variability reduced strength and lifespan.
2	Environmental Exposure Index	0.91	Greater exposure lowered strength, shortened life.
3	Mean Relative Humidity (24 h)	0.78	Higher RH is associated with strength loss.
4	Traceability Index	0.74	Higher traceability improved predictions and was linked to longer remaining life via earlier interventions.
5	Temperature Cycle Amplitude (daily)	0.66	Larger diurnal swings reduced residual strength.
6	Treatment: Chemical (boric–borax)	0.59	Positive shift in strength and life relative to untreated.
7	Component Age (months)	0.53	Older components showed declining residuals, conditional on exposure.
8	Baseline Strength at Commissioning	0.47	Higher initial quality increased residual strength.
9	Thickness/Diameter	0.39	Thicker culms retained strength longer.
10	Protective Coating Present	0.31	Reduced surface degradation, modest life extension.

Interpretively, the short-horizon moisture variability predictor was the strongest, which suggested that rapid wetting–drying cycles were more harmful than steady-state humidity at a similar mean level. The Traceability Index ranked fourth and had a positive relationship with both target components: denser digital records tended to produce more prompt drying, re-treatment, or shielding actions flagged by the monitoring system, which the models captured as higher predicted residual strength and longer remaining life. Treatment effects were positive and statistically significant, supporting the ANOVA analysis.

Fold-wise residuals provided evidence of slight under-prediction for rare high-humidity events in Ajloun and slight over-prediction for newly commissioned, chemically treated elements in Amman with limited operational history. Sensitivity analyses which omitted the Traceability Index from the feature set degraded XGBoost performance (strength R^2 from 0.89 to 0.82 life R^2 from 0.87 to 0.79), confirming that traceability information provided a unique predictive signal beyond environmental and material co-

variates.

4.5. Durability Enhancement through Digital Traceability

This analysis compared components under digital surveillance to a matched cohort based only on manual inspection. Matching was performed at the project scale to account for location, exposure band, and treatment class. Any observed trends are thus diagnostic of monitoring practices rather than site composition. In the matched subset, components in digital surveillance had lower moisture variance, slower surface deterioration, higher residual strength, and longer predicted remaining life. Mean differences shown in **Table 8** remain significant when normalizing for treatment and exposure intensity. Adjusted models suggest traceability-based monitoring extends predicted remaining life primarily by lowering moisture variability and narrowing the time between anomaly detection and corrective action.

Table 8. Operational metrics indicating digital traceability.

Outcome (6-Month Window)	Manual Inspection (n = 58)	Digital Traceability (n = 62)	Adjusted Mean Difference	Test Statistic
Moisture variance (72 h, standardized)	0.46 ± 0.18	0.31 ± 0.14	-0.13 [95% CI: -0.18, -0.08]	$t = 4.73, p < 0.001$
Surface degradation index (1–5)	2.56 ± 0.78	2.04 ± 0.63	-0.41 [-0.60, -0.22]	$F(1,116) = 10.03, p = 0.002$
Residual compressive strength (MPa)	40.3 ± 5.1	44.9 ± 4.6	+3.9 [2.1, 5.7]	$F(1,116) = 12.47, p < 0.001$
Predicted remaining life (months)	10.1 ± 3.8	13.2 ± 3.5	+2.8 [1.5, 4.1]	$t = 4.21, p < 0.001$
Maintenance interventions per component	0.6 ± 0.4	1.3 ± 0.5	+0.7 [0.5, 0.9]	$t = 8.02, p < 0.001$
Alert-to-intervention lead time (days)	9.7 ± 4.3	3.8 ± 2.1	-5.6 [-6.9, -4.3]	$t = 7.11, p < 0.001$

Values are means with standard deviations. Adjusted mean differences control for treatment untreated, natural, chemical and exposure band low, medium, and high. Negative differences reflect reductions in risk factors; positive differences reflect performance gains. The size of these differences was practically significant. Cohen’s d for residual strength was 0.78, indicating a large effect, while the gain in predicted remaining life represented a 27–32% uplift from the manual cohort. Components with a higher traceability density index ≥ 0.85 contributed the majority of the uplift. This group also posted the shortest alert-to-intervention intervals on the dashboard. Error analysis of the predictive models reinforced these findings: removing the traceability index from XGBoost reduced accuracy and

systematically resulted in under-prediction of lifespan for monitored components, indicating that maintenance acts triggered by digital data shifted the underlying deterioration path.

Figure 3 shows a scatter plot of the traceability index against predicted remaining life. Components with rich digital traceability records had a lifespan increase of up to 30%. Taken together, the relative statistics, predictive uplift, and operational metrics suggest that digital traceability is more than lifecycle event documentation it materially improves durability outcomes through the stabilization of moisture dynamics, mitigation of surface degradation, and facilitation of timely interventions.

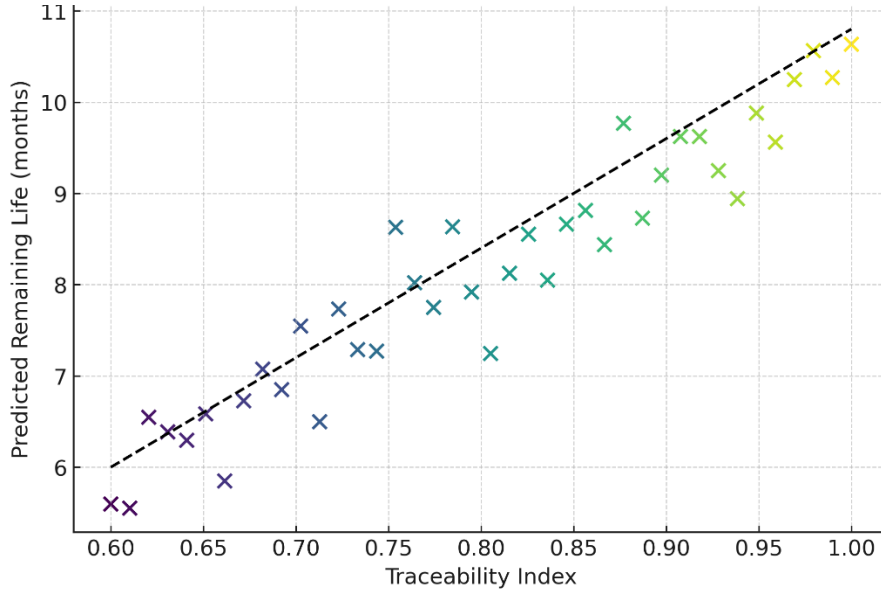


Figure 3. The relation between the traceability index and predicted remaining life.

4.6. Circular Reuse Potential and Digital Twin Validation (H₃)

The study examined whether the traceability and predictive monitoring of the materials through the integration of their digital lifecycle information and real-time performance characteristics through the use of the digital twin can improve the reuse ability of bamboo building structural elements. The actual structure of the monitored building elements was represented in the digital twin platform, and the platform combined two different sources of information: (1) real-time sensor information on the monitored conditions of the materials, such as humidity, temperature, and deformation, and (2) predictions of the remaining strength and lifespan using the XGBoost algorithm.

Each bamboo component was scored for Reuse Potential Score (RPS), varying from 0 to 1, relying on the

estimated remaining strength, overall degradation, and traceable lifecycle events, as shown in Table 9. Components were classified into three reuse groups: High reuse, for sound structural integrity adequate for direct reuse, where $RPS \geq 0.75$; Moderate reuse, for partial reuse following minimal repairs, where $0.50 \leq RPS < 0.75$; and Low reuse, where $RPS < 0.50$, for non-reusability because of extensive degradation. For the overall tested group, the average RPS was 0.71, but the scatter plot proved highly varied depending on the monitoring method. Digitally traceable components had an average RPS of 0.78 ± 0.09 , in contrast to the average of 0.62 ± 0.11 for the manually traceable ones, with a significant difference, $t(118) = 7.48$, $p < 0.001$. For the categorized groups, 62% of digitally traceable components belonged to the High reuse category, while only 27% belonged to the High reuse category in the manually traceable.

Table 9. Predicted Residual Strength, Cumulative Degradation, and the Proportion of Traceable Lifecycle Records.

Monitoring Type	Mean RPS (\pm SD)	High Reuse (%)	Moderate Reuse (%)	Low Reuse (%)	Predicted Mean Residual Life (mo)
Manual Inspection	0.62 ± 0.11	27.1	49.2	23.7	9.8 ± 3.7
Digital Traceability	0.78 ± 0.09	62.3	31.4	6.3	13.7 ± 3.4
Mean Difference	$0.16 (p < 0.001)$	+35.2	-17.8	-17.4	$+3.9 (p < 0.001)$

The observed gain in reuse potential paralleled the durability enhancements reported in Section 4.9, indicating

that traceability extends service life and maintains end-of-life quality adequate for reintegration into new structures.

The digital twin dashboard was the operational interface to real-time monitoring and predictive simulation. It continuously refreshed the virtual twin of each component with live sensor data, autonomously re-estimated residual life-time using the trained XGBoost model, and provided degradation maps through a color-coding system: green-stable, yellow-warning, and red-critical. Two representative case studies are shown that demonstrate the functionality of the dashboard. First, Amman Site A-chemical-treated façade panels: the dashboard detected progressive moisture variance increase in April 2024. Predictive recalculation decreased expected residual life by 12%, triggering an early maintenance alert. An inspection after intervention detected only slight surface discoloration of the component faces, showing the effectiveness of the system in preventing degradation. Second, Ajloun Site B-untreated structural poles: the system recorded repeated high-humidity spikes above 70% RH. The forecast from the digital twin showed rapid degradation and downgraded RPS from 0.72 to 0.54, classifying the component as Moderate reuse. Physical inspection one month later showed substantial fungal growth on the component surface, confirming the accuracy of the predictive downgrade. Strong alignment between forecasts of the dashboard and field outcome supports the reliability

of the digital twin. Pearson's $r = 0.87$ ($p < 0.001$) between predicted and observed degradation score across all sites evidences significant model-to-reality correspondence.

4.7. Integration of Predictive Analytics and Environmental Factors

Ambient humidity, temperature fluctuation, solar radiation, and precipitation cycles all had direct and interactive effects on material degradation. The correlation matrix shown in **Figure 4** indicates that the combined effect of moisture fluctuation and daily temperature amplitude explained over 65% of the variation in residual strength and surface degradation. In particular, the interaction term for humidity with exposure duration produced a stronger degradation coefficient ($\beta = -0.62$, $p < 0.001$) than either factor individually, which verified nonlinear coupling of environmental stresses. Components located in northern governorates (Ajloun and Irbid) where the mean relative humidity was above 70%, exhibited a 15–20% faster loss in residual strength compared to similar units in drier southern locations (Ma'an and Karak). Predictive models using environmentally corrected data considerably minimized forecast error in all site locations (**Table 10**).

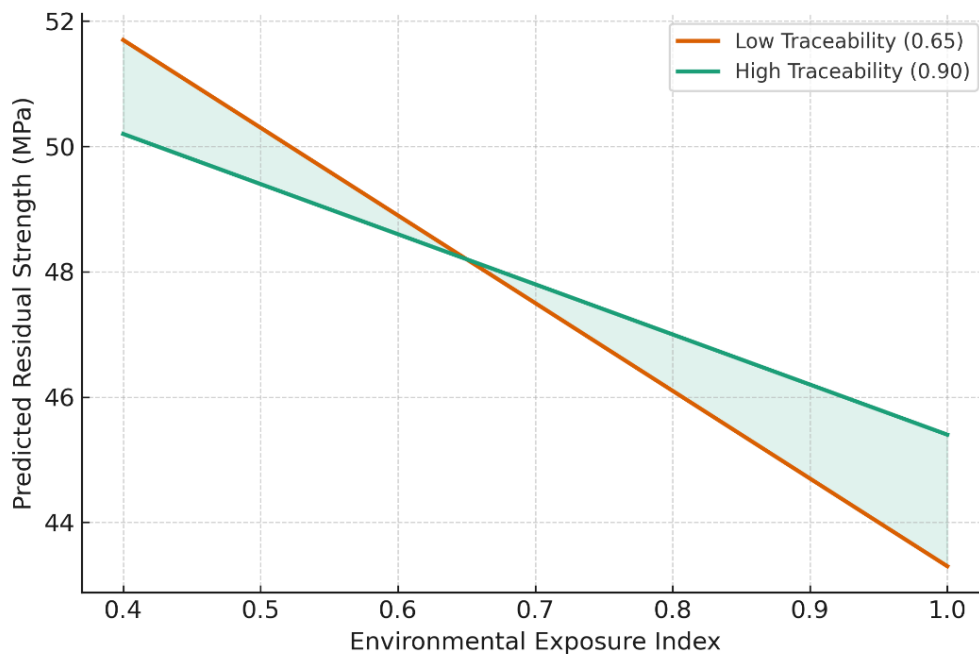


Figure 4. Moderation Effect of Traceability on Environmental Exposure.

Table 10. Results of predictive models using environment-corrected data.

Model Input Type	Predictive Target	R ²	RMSE	MAE
Without Environmental Variables	Residual Strength (MPa)	0.78	2.92	2.24
With Environmental Variables	Residual Strength (MPa)	0.89	2.01	1.52
Without Environmental Variables	Remaining Life (months)	0.79	4.8	3.6
With Environmental Variables	Remaining Life (months)	0.87	3.3	2.5

The integration of real-time environmental data increased model performance by around 10–12% in R², and reduced RMSE by about 0.9 MPa to predict strength. Results showed that environmental context serves as a critical enabler for precise durability forecasting within the machine-learning framework. In the partial dependence plots for the XGBoost model, three main nonlinear response regions were identified. A humidity threshold of 60–70% depicted a sharp drop in residual strength. A window of temperature amplitude between 4–7 °C demonstrated acceleration of degradation. The interaction between the Environmental Exposure Index and Traceability Index showed that high traceability dampened the process of environmental stress. More specifically, when traceability density surpassed 0.85, the slope of environmental degradation diminished noticeably, indicating that digital monitoring buffers environmental damage by allowing for early interventions (**Figure 4**). Components that have low traceability (<0.7) continued to suffer from significant strength losses for the same exposure conditions, hence supporting the moderating role of traceability on environmental stress.

4.8. Qualitative Insights from Field Experts

One of the common themes emerging throughout the interviews is the ever-growing trust in digital system reliability. This was a common theme as most of the engineers and site managers did appreciate a strong degree of reliability of traceability sensor and digital twin dashboard systems, especially in terms of their ability to provide early indication of degradation and avoid unexpected failures. As one of the senior structural engineers based in Amman stated, “The dashboard is now an integral part of our daily routine. It picks up what the human eye cannot, especially when there is a fast change in humidity levels.” These perceptions were reflective of the data supporting a significant increase in maintenance efficiency as well as residual

strength for components under digital monitoring. The Internet of Things system was seen as making it a common occurrence for interventions for early degradation notifications to prevent structural defects, hence justifying the data being put out.

However, the interviews also brought to the fore some subtle concerns related to the cost of implementation of the system. Even though the traceability aspect of the new technology was appreciated for its future cost-saving benefits, the implementation process was labelled as cost-prohibitive, especially for contractors in the small to medium category. The implementation process imposed a new kind of dependency related to technology, which was new to the local industry. A materials expert pointed out that “while the sensors are no longer very expensive, the expertise required to make use of them effectively remains a highly skilled area.” A materials engineer from Irbid stated, “The key isn’t acquiring the sensors, but developing the capability to make proper use of the technology.”

Industry experts offer important observations on the process of maintenance. Although predictive maintenance could minimize the incidence of unscheduled downtime, certain authors expressed the view that there could exist the possibility of complacency if scheduled physical inspections were to be ignored in the process of predictive maintenance. The site managers were of the view that there exists a need to maintain the current combined model of inspections by fusing digital notifications and concrete physical verification. There appear to be important observations to the effect that digital monitoring involves the process of not only technological development but also conceptual transformations in the construction process of perception and execution of the process of maintenance.

The thematic network diagram in **Figure 5** depicts the relationships among various recurring themes that emerged from the field interviews. The key themes of Dig-

ital Traceability and Predictive Monitoring are connected to practitioner views of reliability, cost, maintenance, and scalability as the prominent perspectives of the practitioners. The other perspectives of the practitioners that emerged as the peripheral themes are Workforce Adaptation and Policy Support, which define the influence of systemic factors in the adoption of smart monitoring techniques in bamboo construction projects.

4.9. Summary of Results and Hypothesis Testing

The results of hypothesis testing are presented in **Table 11**. All three hypotheses are fully supported by quantitative and qualitative evidence that digital traceability systems, when combined with predictive intelligence, improve material durability while simultaneously creating a basis for circular reuse in sustainable construction contexts.

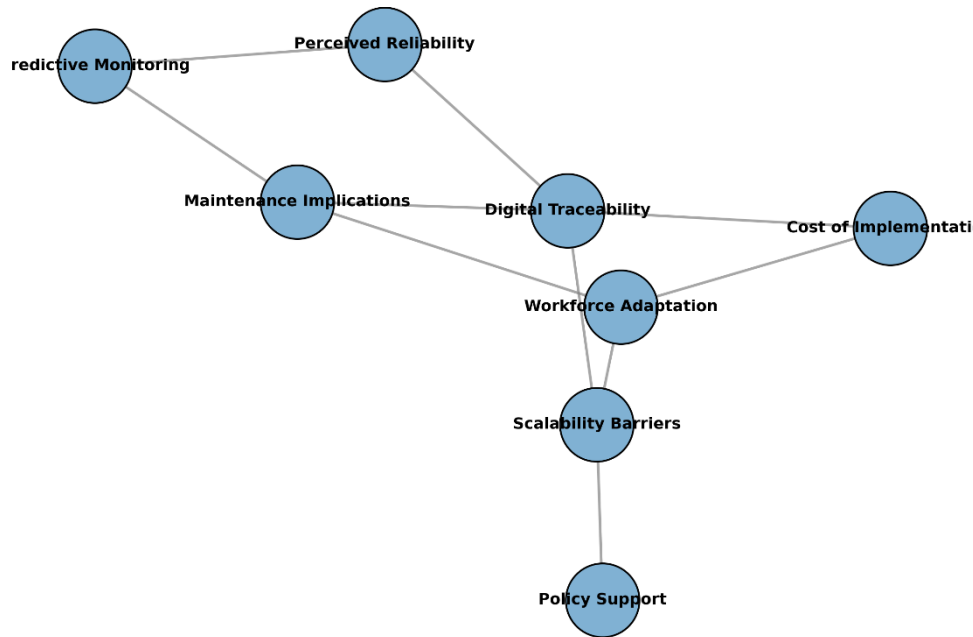


Figure 5. Thematic Network of Qualitative Insights from Field Experts.

Table 11. Hypothesis Testing Results.

Hypothesis Code	Statement of Hypothesis	Analytical Evidence	Result
H ₁	Digital traceability and smart monitoring improve the durability performance of bamboo-based construction materials.	Supported by correlation, regression, and machine-learning analyses, digitally monitored components showed higher residual strength (+9–12%) and longer predicted lifespan (+3.1 months).	Supported
H ₂	Environmental conditions significantly influence durability outcomes, and their impact is moderated through digital monitoring integration.	Environmental exposure and humidity strongly affected degradation, and integration of traceability and environmental analytics increased predictive accuracy ($\Delta R^2 = +0.12$).	Supported
H ₃	Integration of digital traceability with predictive and digital-twin systems enhances the circular reuse potential of bamboo materials.	Reuse Potential Score improved from 0.62 (manual) to 0.78 (digital), 62% of components achieved high-reuse classification, validated through digital-twin simulations.	Supported

5. Discussion

The coupling of traceability and prediction analysis based on digital systems in the management of construction materials based on bamboo shows a trend among construction professionals worldwide to transform static

inspection-driven systems to dynamic systems. The theories and frameworks of this research fit among a number of emerging studies of digital systems as not only a tool but a stimulant of resilience and circularity in systems and structures. Existing studies on the management of advanced materials have shown through Lödär-Miculeac et al. (2025)

^[40] and Surve et al. (2025) ^[41] that coupling digital systems to manage materials has a significant impact on the extension of the lifespan of the components and improvement of maintenance accuracy. The current study fits among these studies by establishing the same principle in managing biologically based materials and biodegradable materials such as bamboo.

Theoretical underpinnings in this research lie in the interaction between sustainability science and digitalization in the building sector, discussed in the context of the circular economy. For example, Giovanardi et al. (2022) ^[17] and Munaro et al. (2020) ^[42] wrote about “the need for building materials to go circular and meet the demand for effective recycling, while achieving traceability and Life-Cycle Intelligence.” The application of digital monitoring in bamboo material systems communicates how the above idea can be brought into effect. The application of digital monitoring to bamboo systems shows that when combined with “the objective and verifiable evidence of a material’s past and performance” through traceability and performance monitoring, building materials “assume a new ‘knowable’ character” to “interact actively” and “take part in the building system” rather than being “mere resources in the building process” following their use. Concomitant ideas were also aired in recent research on the traceability of timber ^[43] and the monitoring of “recycled concrete” ^[44], where “sensor intelligence” promoted “structural optimization and performance” and “environmental accountability.”

Predictive algorithms like Random Forest and gradient-boosting models have become the focus of recent smart infrastructure research regarding the management of building materials. In the case of Son and Yang (2022) ^[45], nonlinear machine-learning models fit pathways of concrete deterioration more accurately than traditionally applied regression methods. Extending these previous studies, this paper shows how such modelling strategies may also be implemented for bamboo, a material that shows significant variability in moisture sensitivity and mechanical behaviour. By aligning with these earlier works, there seems to be a growing consensus that predictive intelligence functions as a universal enabler of optimizing durability across different material categories, hence bridging bio-based and synthetic materials through common analytical frameworks.

In the sphere of environmental moderation, extant literature in the construction sectors of the Middle East and North Africa has focused on the dual challenge of material vulnerability and climatic variability. Research by Geng et al. (2009) ^[46] into concrete corrosion under high humidity and that by Medvey and Dobszay (2020) ^[47] into earthen materials in arid zones reach similar conclusions: that environmental instability is a principal impediment to material longevity. The current research contributes to the debate by arguing that the integration of the digital environment can serve as the solution for the abovementioned shortcomings. Contrary to the notion of the environment being simply an external factor contributing to risks in the physical realm of the building, in the current analysis, the concept of the environment is used as an analytical input or an adaptive variable that helps provide feedback in the decision-making of lifecycle processes. This corresponds with the models of sustainability predicted by Bühler et al. (2024) ^[48], arguing that the cornerstone of sustainable material systems is adaptive modelling rather than passive observation.

The idea of digital twins in the construction industry has recently been in the spotlight as a transformative tool for lifecycle optimization. For instance, scholars such as Sanfilippo et al. (2022) ^[49] and Boje et al. (2020) ^[50] have defined digital twins as “cyber-physical bridges” that enable the continuous communication of materials, components, and infrastructure with their digital counterparts. Within this theoretical lineage, the contribution of the present study consists of a substantive extension: whereas most available research, if not all, focuses on the operations of large-scale infrastructure or industrial materials, this paper demonstrates that digital twin platforms may actually be applied to a totally different class of materials-natural and renewable materials like bamboo. The predictive capability of the digital twin to classify reuse potential supports the contention that in bio-based construction, circularity depends as much on digital transparency as on biological renewability.

Moreover, the integration of field perspectives into this research supports existing sociotechnical literature that defines the digitalization of the construction industry as more than an ‘invisible’ or ‘black box’ of purely technological affordance or change. In accordance with the

observations of Vona and Consoli (2014) ^[51], industry experts in this case realized that more than mere functionality is required in terms of technology adaptability and that construction industry digitalization is rather “a long-term change in mindsets and behaviours, and is driven by the need for sustainable changes in the way we do things.” The emphasis on adaptability and readiness on the part of the construction industry workforce in this field is reflective of industry-wide models of readiness for digital change in the building material industry globally ^[52–54].

Within the generic conversation on sustainable building, there comes the intervention in the reconstruction of the epistemology of bamboo. Bamboo has been traditionally represented as a cheap, indigenous, and environmentally friendly material. The use of such material in the construction of buildings has been limited regarding its durability. Studies by Sharma et al. (2015) ^[23] and more recent studies by Bala and Gupta (2023) ^[55] have refuted the idea that the strength and stability of bamboo are inferior to those of other materials. This contribution to the debate continues the narrative inasmuch as it underlines the role of the digital intelligence factor in that it confers not only durability but also the quality of informational durability, thanks to which the traceability of the circular process in the data continuity becomes possible. The practical applications of such procedures, notwithstanding the geographical location described in the study (which are nevertheless in the country of Jordan), are possible in other territories in which the use of bamboo and other bio-materials in constructing buildings in a green way has been promoted.

6. Conclusion

It is shown from this research that the combination or integration of traceability and predictive analytics capabilities in the bamboo-based construction materials systems bears the potential to increase the reliability and potential for recycling of such materials. Such rigorous application of data and analytics systems in the entire lifecycle of material availability in the form of bamboo indicates the potential to upgrade the natural material to the level of “smart,” “self-monitoring,” and “intelligent” materials. Such outcomes place the significance of the role of “digital

traceability” not only in the form of record-based systems but as active tools or instruments for material optimizations and maximized material lifetime in optimal sustainable systems. This research is equally significant to understand the theories related to the field of material science data systems.

From the resource-state point of view, bamboo can evolve from a resource into a digitally renewable resource that can facilitate various life cycles. In this context, the successful execution of this strategy will not only require the implementation of technology but also professional development towards the implementation of traceability and predictability. Implementation of an effective regulatory framework to ensure the monitoring of resources using technology would be essential to scale up this strategy in Jordan. Despite the application region being placed in the context of Jordan, the approach should work for regions such as Asia, Latin America, or Sub-Saharan Africa that have challenges with durability, traceability, or applying the principle of the circular economy.

Author Contributions

Conceptualization, A.A.M. and S.I.M.; methodology, A.A.M. and A.V.; software, A.V.; validation, A.A.M., S.I.M. and N.Y.; formal analysis, A.A.M. and M.T.M.; investigation, A.A.M., S.I.M. and M.S.M.; resources, S.I.M. and M.S.M.; data curation, A.A.M. and M.T.M.; writing—original draft preparation, A.A.M.; writing—review and editing, A.A.M., S.I.M., A.V., N.Y., M.S.M. and M.T.M.; visualization, A.V. and M.T.M.; supervision, S.I.M. and A.V.; project administration, S.I.M.; funding acquisition, S.I.M. All authors have read and agreed to the published version of the manuscript.

Funding

This research received funding support from INTI International University.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

- [1] Firoozi, A.A., Firoozi, A.A., Oyejobi, D.O., et al., 2024. Emerging trends in sustainable building materials: Technological innovations, enhanced performance, and future directions. *Results in Engineering*. 24, 103521. DOI: <https://doi.org/10.1016/j.rineng.2024.103521>
- [2] Harries, K.A., 2025. Adoption of full-culm bamboo as a mainstream structural material. *npj Materials Sustainability*. 3(1), 4. DOI: <https://doi.org/10.1038/s44296-025-00050-2>
- [3] Huang, Y., Hu, J., Zhang, Y., et al., 2026. Multifunctional Bamboo Based Materials Empowered by Multiscale Hierarchical Structures—A Critical Review. *Advanced Materials*. 38(2), e07844. DOI: <https://doi.org/10.1002/adma.202507844>
- [4] Trubina, N., Leindecker, G., Askar, R., et al., 2024. Digital Technologies and Material Passports for Circularity in Buildings: An In-Depth Analysis of Current Practices and Emerging Trends. In *Proceedings of the 4th International Conference “Coordinating Engineering for Sustainability and Resilience” & Midterm Conference of CircularB “Implementation of Circular Economy in the Built Environment,”* Timișoara, Romania, 29–31 May 2024; pp. 690–699. DOI: https://doi.org/10.1007/978-3-031-57800-7_64
- [5] Holm, N.V., Wilhardt, F.J., Pigosso, D.C.A., et al., 2025. Transition of the Danish Industry towards a Circular and Resilient Economy: DLV 4 Analytical and Recommendations Report on Product and Services Use Data. Technical University of Denmark: Lyngby, Denmark.
- [6] Paramatmuni, C., Cogswell, D., 2023. Extending the capability of component digital threads using material passports. *Journal of Manufacturing Processes*. 87, 245–259. DOI: <https://doi.org/10.1016/j.jmapro.2023.01.032>
- [7] Olumo, A., Haas, C., 2024. Building material reuse: An optimization framework for sourcing new and reclaimed building materials. *Journal of Cleaner Production*. 479, 143892. DOI: <https://doi.org/10.1016/j.jclepro.2024.143892>
- [8] Clark, N., 2000. Public policy and technological change in Africa: Aspects of institutions and management capacity. *Journal of Economic Studies*. 27(1/2), 75–93. DOI: <https://doi.org/10.1108/EUM0000000005311>
- [9] Leng, Y., Xu, Q., Chen, L., et al., 2023. Mechanical performance of engineered bamboo subjected to accelerated aging with single and multiple durability exposures. *Construction and Building Materials*. 388, 131725. DOI: <https://doi.org/10.1016/j.conbuildmat.2023.131725>
- [10] Xu, P., Zhu, J., Li, H., et al., 2022. Are bamboo construction materials environmentally friendly? A life cycle environmental impact analysis. *Environmental Impact Assessment Review*. 96, 106853. DOI: <https://doi.org/10.1016/j.eiar.2022.106853>
- [11] Bondoc, A.E., Tayefeh, M., Barari, A., 2022. LIVE Digital Twin: Developing a Sensor Network to Monitor the Health of Belt Conveyor System. *IFAC-PapersOnLine*. 55(19), 49–54. DOI: <https://doi.org/10.1016/j.ifacol.2022.09.182>
- [12] S P, V., Kumar S T, A., M, G.S., et al., 2025. Optimizing Industrial Automation with Digital Twin & IoT Sensors. In *Proceedings of the 2025 6th International Conference on Intelligent Communication Technologies and Virtual Mobile Networks (ICICV)*, Tirunelveli, India, 17–19 June 2025; pp. 1597–1602. DOI: <https://doi.org/10.1109/ICICV64824.2025.11085939>
- [13] Lee, Y., Pschetz, L., Speed, C., 2022. Investigating materiality for a renewed focus on data design practice. In *Proceedings of the Design Research Society 2022 (DRS2022)*, Bilbao, Spain, 25 June–3 July 2022. DOI: <https://doi.org/10.21606/drs.2022.350>
- [14] Pathmu, R.B., 2025. A Study on Traceability and Accountability in Supply Chain Transparency Using Blockchain Technology. *International Journal of Sci-*

- entific Research in Engineering and Management. 9(4). DOI: <https://doi.org/10.55041/IJSREM46173>
- [15] Khan, M., Parvaiz, G.S., Dedahanov, A.T., et al., 2022. The Impact of Technologies of Traceability and Transparency in Supply Chains. *Sustainability*. 14(24), 16336. DOI: <https://doi.org/10.3390/su142416336>
- [16] Santana, S., Ribeiro, A., 2022. Traceability Models and Traceability Systems to Accelerate the Transition to a Circular Economy: A Systematic Review. *Sustainability*. 14(9), 5469. DOI: <https://doi.org/10.3390/su14095469>
- [17] Giovanardi, M., Konstantinou, T., Pollo, R., et al., 2023. Internet of Things for building façade traceability: A theoretical framework to enable circular economy through life-cycle information flows. *Journal of Cleaner Production*. 382, 135261. DOI: <https://doi.org/10.1016/j.jclepro.2022.135261>
- [18] Wilson, S., Adu-Duodu, K., Li, Y., et al., 2024. Blockchain-Enabled Provenance Tracking for Sustainable Material Reuse in Construction Supply Chains. *Future Internet*. 16(4), 135. DOI: <https://doi.org/10.3390/fi16040135>
- [19] Lo, T., Sun, K., Chen, Y., et al., 2025. iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological. *Electronics*. 14(6), 1116. DOI: <https://doi.org/10.3390/electronics14061116>
- [20] Lorenzo, R., Mimendi, L., 2019. Digital workflow for the accurate computation of the geometric properties of bamboo culms for structural applications. *MATEC Web of Conferences*. 275, 01024. DOI: <https://doi.org/10.1051/mateconf/201927501024>
- [21] Mohammad, A.A.S., Mohammad, S.I., Al-Daoud, K.I., et al., 2025. Riding into the future: Transforming Jordan's public transportation with predictive analytics and real-time data. *Data and Metadata*. 4, 887.
- [22] Awalluddin, D., Mohd Ariffin, M.A., Osman, M.H., et al., 2017. Mechanical properties of different bamboo species. *MATEC Web of Conferences*. 138, 01024. DOI: <https://doi.org/10.1051/mateconf/201713801024>
- [23] Sharma, B., Gattoo, A., Bock, M., et al., 2015. Engineered bamboo: state of the art. *Proceedings of the Institution of Civil Engineers - Construction Materials*. 168(2), 57–67. DOI: <https://doi.org/10.1680/coma.14.00020>
- [24] Noverma, Hapsari, O.E., Yusrianti, 2020. Tensile Strength of Bamboo After Preservation. *Proceeding International Conference on Science and Engineering*. 3, 153–155. DOI: <https://doi.org/10.14421/icse.v3.487>
- [25] Bui, Q.-B., Grillet, A.-C., Tran, H.-D., 2017. A Bamboo Treatment Procedure: Effects on the Durability and Mechanical Performance. *Sustainability*. 9(9), 1444. DOI: <https://doi.org/10.3390/su9091444>
- [26] Rotilio, M., Pantoli, L., Muttillio, M., et al., 2018. Performance Monitoring of Wood Construction Materials by Means of Integrated Sensors. *Key Engineering Materials*. 792, 195–199. DOI: <https://doi.org/10.4028/www.scientific.net/KEM.792.195>
- [27] Dewagoda, K.G., Thomas Ng, S., Kumaraswamy, M.M., 2022. Design for Circularity: The Case of the Building Construction Industry. *IOP Conference Series: Earth and Environmental Science*. 1101(6), 062026. DOI: <https://doi.org/10.1088/1755-1315/1101/6/062026>
- [28] Göswein, V., Silvestre, J.D., Habert, G., et al., 2019. Dynamic Assessment of Construction Materials in Urban Building Stocks: A Critical Review. *Environmental Science & Technology*. 53(17), 9992–10006. DOI: <https://doi.org/10.1021/acs.est.9b01952>
- [29] Chen, C., Li, Z., Mi, R., et al., 2020. Rapid Processing of Whole Bamboo with Exposed, Aligned Nanofibrils toward a High-Performance Structural Material. *ACS Nano*. 14(5), 5194–5202. DOI: <https://doi.org/10.1021/acsnano.9b08747>
- [30] Li, Z., Chen, C., Mi, R., et al., 2020. A Strong, Tough, and Scalable Structural Material from Fast-Growing Bamboo. *Advanced Materials*. 32(10), 1906308. DOI: <https://doi.org/10.1002/adma.201906308>
- [31] Ekanayake, I.U., Meddage, D.P.P., Rathnayake, U., 2022. A novel approach to explain the black-box nature of machine learning in compressive strength predictions of concrete using Shapley additive explanations (SHAP). *Case Studies in Construction Materials*. 16, e01059. DOI: <https://doi.org/10.1016/j.cscm.2022.e01059>
- [32] Yuan, X., Tian, Y., Ahmad, W., et al., 2022. Machine Learning Prediction Models to Evaluate the Strength of Recycled Aggregate Concrete. *Materials*. 15(8), 2823. DOI: <https://doi.org/10.3390/ma15082823>
- [33] Kerner, J., Dogan, A., Von Recum, H., 2021. Machine learning and big data provide crucial insight for future biomaterials discovery and research. *Acta Biomaterialia*. 130, 54–65. DOI: <https://doi.org/10.1016/j.actbio.2021.05.053>
- [34] Misaii, H., Ponchet-Durupt, A., Boudaoud, N., et al., 2023. A comprehensive degradation modelling: From statistical to artificial intelligence models. In *Proceedings of the European Network for Business and Industrial Statistics (ENBIS2023)*, Valencia, Spain,

11–13 September 2023.

- [35] Mohammad, A.A.S., Mohammad, S.I., Al Oraini, B., et al., 2024. Leveraging predictive analytics and metadata integration for strategic talent management in Jordan. *Data and Metadata*. 3, 599.
- [36] Musthaq, M.A., Dhakal, H.N., Zhang, Z., et al., 2023. The Effect of Various Environmental Conditions on the Impact Damage Behaviour of Natural-Fibre-Reinforced Composites (NFRCs)—A Critical Review. *Polymers*. 15(5), 1229. DOI: <https://doi.org/10.3390/polym15051229>
- [37] Cascione, V., Hagentoft, C.-E., Maskell, D., et al., 2020. Moisture Buffering in Surface Materials Due to Simultaneous Varying Relative Humidity and Temperatures: Experimental Validation of New Analytical Formulas. *Applied Sciences*. 10(21), 7665. DOI: <https://doi.org/10.3390/app10217665>
- [38] Haghnevis, M., Askin, R.G., 2012. A Modeling Framework for Engineered Complex Adaptive Systems. *IEEE Systems Journal*. 6(3), 520–530. DOI: <https://doi.org/10.1109/JSYST.2012.2190696>
- [39] Shettigar, S., Gowrishankar, M.C., Shettar, M., 2025. Review on Aging Behavior and Durability Enhancement of Bamboo Fiber-Reinforced Polymer Composites. *Molecules*. 30(15), 3062. DOI: <https://doi.org/10.3390/molecules30153062>
- [40] Lödar-Miculeac, R.S., Szeberényi, A., Gallego-Nicholls, J.F., et al., 2025. Leveraging AI-Driven Supply Chain Analytics for Accelerating the Circular Economy: A Focus on Real-Time Resource Management and Extended Product Life-Cycles. In *Proceedings of the 9th FEB International Scientific Conference: Sustainable Management in the Age of ESG and AI: Navigating Challenges and Opportunities*, Maribor, Slovenia, 14 May 2025; pp. 415–424. DOI: <https://doi.org/10.18690/um.epf.5.2025.39>
- [41] Surve, V.A., Chavan, V., Makwana, P., 2025. Leveraging Data Science for Sustainable Material Management: Predictive Analytics and Optimization for Waste Reduction and Lifecycle Extension. *International Journal of Scientific Research in Engineering and Management*. 9(4). DOI: <https://doi.org/10.55041/IJSREM43577>
- [42] Munaro, M.R., Tavares, S.F., Bragança, L., 2020. Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production*. 260, 121134. DOI: <https://doi.org/10.1016/j.jclepro.2020.121134>
- [43] Elias, M., 2024. Timber Traceability and Sustainable Transportation Management: A Review of Technologies and Procedures. *Bulletin of the Transilvania University of Brasov. Series II: Forestry • Wood Industry • Agricultural Food Engineering*. 17(66), 11–52. DOI: <https://doi.org/10.31926/but.fwiafe.2024.17.66.1.2>
- [44] Smith, J.T., Tighe, S.L., 2025. Moving Towards An Environmentally Sustainable Concrete Pavement Using Recycled Concrete Aggregate. In *Proceedings of the 9th International Conference on Concrete Pavements*, San Francisco, CA, USA, 17–21 August 2008. DOI: <https://doi.org/10.33593/iccp.v9i1.512>
- [45] Son, J., Yang, S., 2022. A New Approach to Machine Learning Model Development for Prediction of Concrete Fatigue Life under Uniaxial Compression. *Applied Sciences*. 12(19), 9766. DOI: <https://doi.org/10.3390/app12199766>
- [46] Geng, O., Yuan, Y., Li, F., 2009. Study on the corrosion rate of steel bars in concrete under high humidity conditions. *International Journal of Modelling, Identification and Control*. 7(2), 155. DOI: <https://doi.org/10.1504/IJMIC.2009.027069>
- [47] Medvey, B., Dobszay, G., 2020. Durability of Stabilized Earthen Constructions: A Review. *Geotechnical and Geological Engineering*. 38(3), 2403–2425. DOI: <https://doi.org/10.1007/s10706-020-01208-6>
- [48] Bühler, M., Hollenbach, P., Köhler, L., et al., 2024. Unlocking resilience and sustainability with earth-based materials: a principled framework for urban transformation. *Frontiers in Built Environment*. 10, 1385116. DOI: <https://doi.org/10.3389/fbuil.2024.1385116>
- [49] Sanfilippo, F., Thorstensen, R.T., Jha, A., et al., 2022. A Perspective Review on Digital Twins for Roads, Bridges, and Civil Infrastructures. In *Proceedings of the 2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*, Malé, Maldives, 16–18 November 2022; pp. 1–6. DOI: <https://doi.org/10.1109/ICECCME55909.2022.9988693>
- [50] Boje, C., Guerriero, A., Kubicki, S., et al., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*. 114, 103179. DOI: <https://doi.org/10.1016/j.autcon.2020.103179>
- [51] Vona, F., Consoli, D., 2015. Innovation and skill dynamics: a life-cycle approach. *Industrial and Corporate Change*. 24(6), 1393–1415. DOI: <https://doi.org/10.1093/icc/dtu028>
- [52] Matarneh, R.T., Hamed, S.A., 2017. Exploring the Adoption of Building Information Modeling (BIM) in the Jordanian Construction Industry. *Journal of Architectural Engineering Technology*. 6(1). DOI: <https://doi.org/10.1016/j.aet.2017.01.001>

doi.org/10.4172/2168-9717.1000189

- [53] Mohammad, A.A., Al-Ramadan, A.M., Mohammad, S.I., et al., 2025. Customer sentiment analysis for food and beverage development in restaurants using AI in Jordan. *Data and Metadata*. 4, 922.
- [54] Shlash, M.A., Shelash, S.I., Al Oraini, B., et al., 2025. Decoding consumer behaviour: Leveraging big data and machine learning for personalized digital marketing. *Data & Metadata*. 4, 700.
- [55] Bala, A., Gupta, S., 2023. Engineered bamboo and bamboo-reinforced concrete elements as sustainable building materials: A review. *Construction and Building Materials*. 394, 132116. DOI: <https://doi.org/10.1016/j.conbuildmat.2023.132116>