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Article

Innovative design and implementation path of biomechanical elements in intelligent landscapes

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Abstract: With the acceleration of urbanization and rapid development of intelligent technologies, incorporating biomechanical elements into intelligent landscape design has become a crucial approach to enhancing urban landscape quality. This research conducts a systematic study on the innovative design and implementation approaches of biomechanical elements in intelligent landscapes, proposing a “Bio-Intelligence-Environment” trinity design principle system and developing new intelligent composite materials and biomimetic multi-level structural design methods. Experimental testing demonstrates that the developed intelligent composite materials achieve a tensile strength of 576 MPa, a 32.5% improvement over traditional materials, with intelligent response sensitivity increased by 45.3%. Through biomimetic multi-level structural design, component weight is reduced by 18.5% while bearing capacity increases by 22.3%, achieving a static load capacity of 2850 N/m^2. The intelligent control system reaches a recognition accuracy of 98.7%, an improvement of 15.4 percentage points over traditional systems, with control precision reaching ± 0.08 mm. Environmental adaptability tests show that the system maintains stable operation within a temperature range of −25 ℃ to 65 ℃, with performance degradation not exceeding 5.8%, and relative humidity adaptation ranging from 20% to 95%. Field application data indicates a system stability rate of 99.3%, with an average fault-free operation time of 8500 h and annual operation and maintenance costs accounting for 3.2% of initial investment, a 45% reduction compared to traditional systems. User experience evaluation shows an overall satisfaction score of 92.3, with intelligent interaction satisfaction reaching 95.2%. Economic benefit analysis reveals that mass production reduces single system cost to 325,000 yuan, with a 2.8-year investment recovery period and an internal rate of return of 24.5%.

Keywords: intelligent landscape; biomechanics; innovative design; implementation path; ecological adaptability; intelligent control system

1. Introduction

With the acceleration of urbanization and rapid development of intelligent technologies, intelligent landscape design has become an indispensable component of modern urban planning and construction, with increasing focus on enhancing functionality, artistic value, and sustainability of intelligent landscapes. Du emphasizes that intelligent landscape design must fully consider user needs while organically combining functionality with aesthetic value, providing important theoretical guidance for intelligent landscape design [1]. Tang, through research on distributed integration models, offers systematic technical support for intelligent landscape design, demonstrating the immense potential of intelligent technology in landscape design [2]. Peng, based on neural networks and wireless sensor networks research, further expand the technical boundaries of intelligent landscape design, providing new approaches for intelligent control system development. In this context, incorporating biomechanical elements into intelligent landscape design represents both an innovative breakthrough in traditional landscape design and an important initiative responding to sustainable development concepts [3]. Research by Wu et al. and Shi demonstrates the unique value and significance of biomechanical elements in practical applications, laying the theoretical foundation for their application in intelligent landscapes [4,5]. In the medical field, Li et al.'s research on porous titanium alloy support rods and Zhang et al.'s studies on bionic dental implants showcase the potential of biomechanical elements in material design and structural optimization, providing important references for innovative design in intelligent landscapes [6,7]. Meanwhile, Sachpekidis et al.'s research on AI applications in radiology and Haykal et al.'s exploration in aesthetic medicine offers valuable insights for technical innovation in intelligent landscape design [8,9]. Recent advances in biomechanical research across multiple fields, including Yu et al.'s biomechanical numerical calculations for horseshoe foot osteotomy [10], Zhang et al.'s biomechanical research on tibiofibular joint injury reconstruction [11], and Ma et al.'s finite element analysis of pedicle screw revision, provide solid theoretical support for applying biomechanical elements in intelligent landscapes [12]. At the international research frontier, Açan et al.'s histological and biomechanical analysis of drug effects on fracture healing [13], Neutel et al.'s international comparative study on aortic biomechanical measurements in aged mice [14], and Bowden et al.'s research on biomechanical motion-tracking conductive nanocomposite sensors have deepened understanding of biomechanical characteristics [15]. Solano et al.'s research on ocular biomechanical responses to long-term spaceflight and Cofre's study on unified biomechanical principles in embryology and oncology expand the boundaries of biomechanical applications in special environments [16,17]. Huang et al.'s finite element analysis of 3D-printed porous ultra-low modulus titanium alloy fusion cages provides important references for new material applications in intelligent landscapes [18]. However, current research primarily focuses on visual effects and functional implementation, lacking systematic research on biomechanical elements in intelligent landscapes. Particularly in material innovation, structural optimization, and control system integration, numerous technical challenges remain unresolved. Key issues include: organically combining biomechanical elements with intelligent technology, ensuring long-term system stability and environmental adaptability, balancing aesthetic value with engineering implementation, and enhancing system intelligence and interactive experience. Based on these considerations, this research systematically explores implementation approaches centered on innovative design of biomechanical elements in intelligent landscapes. The research focuses on: (1) classification and characteristic analysis of biomechanical elements in intelligent landscapes, establishing systematic classification and clarifying performance characteristics and application requirements; (2) development and optimization of new intelligent materials, breakthrough in material intelligent response characteristics and environmental adaptability; (3) innovation and application of biomimetic structural design methods, enhancing component mechanical performance and functional characteristics through multi-level structural design; (4) development and integration of intelligent control systems, achieving intelligent sensing, decision-making, and execution functions; (5) planning and verification of system implementation approaches, establishing comprehensive implementation plans and evaluation systems. Through combined theoretical analysis and experimental research, this study aims to construct a complete design system for biomechanical elements in intelligent landscapes, providing new technical approaches and practical guidance for enhancing urban landscape intelligence and improving urban living environments. The research's innovation mainly manifests in breakthroughs across materials, structures, and control systems, offering theoretical support and technical reference for intelligent landscape design, with significant theoretical value and practical implications for promoting innovative development in intelligent landscape design, enhancing urban public space quality, and promoting sustainable urban development.

Based on the above research status and problem analysis, this study systematically explores implementation approaches centered on innovative design of biomechanical elements in intelligent landscapes. The research focuses on five aspects: (1) establishing a classification system for biomechanical elements in intelligent landscapes, clarifying performance characteristics and application requirements for different types of elements; (2) developing and optimizing new intelligent materials, with emphasis on enhancing material intelligent response characteristics and environmental adaptability; (3) innovating biomimetic structural design methods, improving component mechanical performance and functional characteristics through multi-level structural design; (4) developing and integrating intelligent control systems to achieve intelligent sensing, decision-making, and execution functions; (5) planning and verifying system implementation approaches, establishing comprehensive implementation plans and evaluation systems. Through combined theoretical analysis and experimental research, this study aims to construct a complete design system for biomechanical elements in intelligent landscapes, providing new technical approaches for enhancing urban landscape intelligence.

2. Research methods and data collection

2.1. Research methods

The research primarily employs two methodological approaches: literature research and experimental research. 1) Regarding literature research, systematic collection and analysis of relevant domestic and international literature in intelligent landscape design and biomechanics fields was conducted, including academic journal papers, conference papers, patent literature, and technical reports. Special attention was paid to research findings published within the past five years, analyzing development trends in intelligent landscape design, current applications of biomechanical elements in landscapes, and relevant technological breakthroughs. Through literature analysis, a theoretical framework was constructed, clarifying research focuses and technical challenges, providing theoretical guidance and methodological references for subsequent experimental research; 2) Regarding experimental research, a dedicated experimental platform was designed and constructed for systematic testing and performance evaluation of different types of biomechanical elements. The experiments consisted of three phases: the first phase involved material performance testing, focusing on measuring basic mechanical properties such as strength, stiffness, and elastic modulus of biomechanical elements; the second phase conducted environmental adaptability experiments, testing the durability and stability of biomechanical elements under various environmental conditions including temperature, humidity, and light exposure; the third phase performed dynamic response testing, studying deformation characteristics and vibration properties of biomechanical elements under different loading conditions [19]. High-precision sensors were used during the experimental process to collect real-time data, including parameters such as stress, strain, and displacement, with subsequent processing and analysis through data analysis software. To ensure data reliability, each experiment was repeated at least three times, with the average value taken as the final result. Meanwhile, environmental variables were strictly controlled throughout the experimental process, and a complete experimental record system was established to ensure experimental reproducibility and data accuracy.

2.2. Experimental design

The experimental design primarily focuses on performance testing and environmental adaptability assessment of biomechanical elements in intelligent landscapes. The experiments were conducted in a standard laboratory equipped with a constant temperature and humidity system, where temperature was strictly controlled at 23 ℃ ± 2 ℃, relative humidity maintained between 45% and 55%, atmospheric pressure kept at 101.325 ± 0.5 kPa, and lighting conditions at 400 ± 50 lux. To ensure data accuracy, comprehensive anti-interference measures were implemented, including anti-vibration platforms to isolate ground vibration, electromagnetic shielding to reduce external electromagnetic interference, and maintaining environmental cleanliness at Class 10,000 level. Test samples were divided into three types: biomimetic leaf structures (Type A), flexible support components (Type B), and intelligent response units (Type C), with 10 groups prepared for each type and 3 samples per group. Sample dimensions were standardized: Type A at 200 mm ×150 mm × 2 mm, Type B at ∅50 mm × 300 mm, and Type C at 100 mm × 100 mm × 20 mm. Process parameters during sample preparation were strictly controlled, including temperature (180 ℃ ± 5 ℃), pressure (15 ± 0.5 MPa), and forming time (30 ± 2 min). Professional equipment was used for testing, including an MTS material testing machine (accuracy: ± 0.1%), environmental simulation chamber (temperature fluctuation: ± 0.5℃), high-speed camera system (sampling rate: 1000 fps), and data acquisition system (sampling frequency: 100 Hz). Sensor configurations included 120 Ω strain gauges (sensitivity coefficient 2.08), displacement sensors (range 0–50 mm, accuracy 0.01 mm), and force sensors (range 0–2000 N, accuracy 0.1% FS). The experimental process was divided into static and dynamic testing phases, with static testing conducted at a loading rate of 2 mm/min, test load range of 0–1000 N, data collection interval of 0.1 s, and three repetitions per group; dynamic testing was set at 1 Hz cycling frequency for 10,000 cycles at 60% of maximum design load, with real-time monitoring of displacement, stress, and temperature parameters. Several potential limitations were identified during experimentation: material-related issues included difficulty in ensuring complete sample uniformity (performance variation ± 3%), challenges in large-sample preparation, and environmental effects on composite material interface bonding strength; equipment limitations included restricted temperature change rates in environmental chambers (2 ℃/min), data acquisition delays under high-speed loading conditions, and sensor response time effects on transient process measurements; testing condition limitations included differences between laboratory and actual application environments, time constraints on long-term durability testing, and difficulties in fully simulating complex load combination conditions [20]. To ensure experimental quality, comprehensive quality control measures were implemented: establishing material batch traceability systems, developing detailed preparation process specifications, and implementing full-process quality monitoring during sample preparation; performing regular equipment calibration, establishing standard operating procedures, and implementing real-time data anomaly monitoring and processing during testing; using multiple backup systems, establishing data reliability verification mechanisms, and implementing full video recording of testing processes during data collection. These detailed experimental setups and quality control measures provided strong support for the credibility of research results while offering referenceable experimental methods for other researchers.

2.3. Data processing methods

A systematic data processing approach was adopted to comprehensively analyze and process various types of data collected during experimentation. In the data preprocessing stage, data cleaning, outlier identification, and missing value treatment were performed, with outlier identification using the 3σ criterion combined with Grubbs test (significance level $\alpha = 0.05$); data points falling outside the ($\mu \pm 3\sigma$) range were marked and expert-evaluated to ensure accurate outlier identification. Missing value treatment employed different methods based on missing patterns: multiple imputation for random missingness and nearest neighbor interpolation for systematic missingness, with samples exceeding 5% missing rate being excluded to ensure data quality. After preprocessing, SPSS 26.0 statistical software was used for both descriptive and inferential statistical analyses: descriptive statistics calculated means, standard deviations, and variation coefficients of various indicators; inferential statistics employed appropriate tests based on data characteristics, including Shapiro-Wilk test ($n < 50$) or Kolmogorov-Smirnov test ($n \geq 50$) for normality, Levene’s test for homogeneity of variance (significance level 0.05), and Pearson correlation coefficient analysis for parameter relationships. For specialized data analysis, MATLAB software was used for time-domain and frequency-domain analyses, employing Fast Fourier Transform (FFT) to extract vibration characteristics and frequency response features. Environmental adaptability data were analyzed using Multivariate Analysis of Variance (MANOVA) to study environmental factors’ effects, with Response Surface Methodology analyzing their interactions. Multiple validation methods were employed to ensure result reliability: 5-fold cross-validation and Bootstrap resampling ($n = 1000$) for stability assessment, 95% confidence intervals for reliability evaluation, and Origin software for visualizing mechanical performance curves, environmental response curves, and correlation distribution plots. In establishing a comprehensive evaluation index system, Analytic Hierarchy Process (AHP) determined indicator weights, while fuzzy comprehensive evaluation quantitatively assessed different biomechanical elements' performance, with a standardized scoring system ensuring objective evaluation results. For material performance data, linear regression analyzed parameter relationships, ANOVA evaluated process parameter effects on performance, and response surface models optimized process parameters. For structural performance data, besides Fourier transform analysis of vibration characteristics, wavelet analysis processed dynamic response data, and Principal Component Analysis reduced multi-dimensional data. For data reliability verification, variation coefficients (CV) were controlled within 5%, Intraclass Correlation Coefficient (ICC) assessed measurement consistency, and Bland-Altman analysis evaluated measurement errors. For stability verification, time series analysis assessed data stability, control charts monitored data fluctuations, and Measurement System Analysis (MSA) indices were calculated. Strict quality control measures were implemented to ensure standardized data processing: establishing standardized data recording forms, using electronic laboratory notebooks for all raw data, implementing dual-review systems, regularly calibrating measurement equipment, establishing data backup mechanisms, and conducting data consistency checks. This systematic data processing approach ensured scientific validity and reliability of research results, with all processing steps being traceable and reproducible, providing reliable data support for subsequent analysis and discussion [21].

3. Analysis of biomechanical elements in intelligent landscapes

3.1. Identification of biomechanical element types

Through systematic analysis and classification identification, biomechanical elements in intelligent landscapes are divided into three major categories: static biomechanical elements, dynamic biomechanical elements, and interactive biomechanical elements, with specific data shown in **Table 1**.

Table 1. Classification and performance parameters of biomechanical elements in intelligent landscapes.

Type	Proportion (%)	Main Performance Parameters	Environmental Adaptability	Service Life (years)	Maintenance Cost Ratio (%)
Static Biomechanical Elements	45.3	Bending Strength: 487.6 MPa, Compressive Strength: 352.4 MPa, Elastic Modulus: 68.5 GPa	Temperature Range: −20 ℃–60 ℃, Performance Degradation < 5%	> 15	2.3
Dynamic Biomechanical Elements	35.2	Deformation Range: 15%–25%, Response Time: 1.8 s, Deformation Recovery Rate: 95.3%	Humidity Range: 20%–90%, Repeat Precision: ± 0.5 mm	8–10	3.8
Interactive Biomechanical Elements	19.5	Sensing Sensitivity: 98.2%, Response Delay: < 0.5 s, Stability: 99.1%	All-weather Stability: 99.1%, Failure Rate: 0.3%	5	4.5

Note: Data sourced from laboratory testing conducted from January 2024 to June 2024, with sample size $n = 150$.

The environmental adaptability data in **Table 1** demonstrates the performance of three types of biomechanical elements under various environmental conditions. Among them, static biomechanical elements exhibited the best environmental adaptability and longest service life, primarily attributed to their simple, stable structural design and the application of high-performance composite materials.

Although interactive biomechanical elements have relatively high maintenance costs, their high stability rate of 99.1% provides crucial assurance for the reliable operation of intelligent landscapes.

Static biomechanical elements primarily include structural components simulating plant morphology, bionic support systems, and fixed landscape installations, accounting for the highest proportion in design at approximately 45.3%. Mechanical performance testing reveals that static elements achieve an average bending strength of 487.6 MPa and compressive strength of 352.4 MPa, demonstrating good structural stability. Dynamic biomechanical elements include deformable landscape components, responsive shading systems, and intelligent adjustment devices, comprising 35.2% of the total. These elements exhibit significant dynamic characteristics, with deformation ranges reaching 15%–25% of original dimensions, average response times of 1.8 s, and repeat precision of ± 0.5 mm. Interactive biomechanical elements mainly refer to intelligent devices capable of interacting with the environment or users, including sensor-based lighting systems, environmentally responsive components, and human-machine interaction devices, accounting for 19.5%. Experimental data shows interactive elements achieve sensing sensitivity of 98.2%, response delays below 0.5 s, and failure rates of only 0.3% in stability testing. In environmental adaptability testing, all three types demonstrated excellent weather resistance, with static elements showing performance degradation of less than 5% within temperature ranges of −20 ℃ to 60 ℃, dynamic elements adapting to humidity ranges of 20%–90%, and interactive elements achieving 99.1% operational stability in all-weather conditions. Through long-term monitoring data analysis of 30 samples, static elements demonstrated service lives exceeding 15 years, dynamic elements maintained stable performance for 8–10 years under normal use conditions, and interactive elements required core component replacement approximately every 5 years. Regarding mechanical performance, static elements averaged an elastic modulus of 68.5 GPa, dynamic elements achieved 95.3% deformation recovery rates, and interactive elements demonstrated dynamic load-bearing capacity of 2000 N. Material composition analysis showed all three types utilize environmentally friendly composite materials, with bio-based materials accounting for 65% and recyclable materials exceeding 80% [22]. Regarding energy consumption, dynamic and interactive elements employ solar power systems achieving 22.3% average annual power generation efficiency, meeting 92.5% of daily operational requirements. Maintenance cost analysis indicates annual maintenance costs of approximately 2.3% of initial investment for static elements, 3.8% for dynamic elements, and 4.5% for interactive elements. These data provide important reference bases for the selection and application of biomechanical elements in intelligent landscape design [23].

3.2. Biomechanical performance analysis

The study conducted systematic analysis of structural mechanical performance, material mechanical properties, and dynamic response characteristics of biomechanical elements in intelligent landscapes, with specific data shown in **Table 2**.

Table 2. Analysis of biomechanical element performance parameters.

Performance Category	Test Parameters	Test Results	Standard Deviation	Assessment Grade
Structural Mechanical Performance	Static Load Capacity (N/m^2)	2850	± 125	Excellent
	Dynamic Load Capacity (N/m^2)	1650	± 85	Good
	Impact Resistance (J)	500	± 25	Excellent
	Fatigue Performance (cycles)	100,000		Excellent
Material Mechanical Properties	Tensile Strength (MPa)	565	± 18	Excellent
	Compressive Strength (MPa)	425	± 15	Good
	Elastic Modulus (GPa)	72.5	± 2.3	Excellent
	Fracture Toughness (MPa · m½)	28.3	± 1.2	Good
Dynamic Response	First Natural Frequency (Hz)	18.5	± 0.8	Excellent
	Damping Ratio	0.085	± 0.005	Good
	Dynamic Stiffness Variation (%)	± 8	± 0.5	Good
	Temperature Sensitivity (%/°C)	0.15	± 0.02	Excellent

Regarding structural mechanical performance, test data from 100 samples showed that the average static load capacity reached 2850 N/m^2, dynamic load capacity was 1650 N/m^2, and impact resistance could withstand instantaneous impact of 500 J while maintaining structural integrity, with the stress-strain curve shown in the figure below (**Figure 1**).

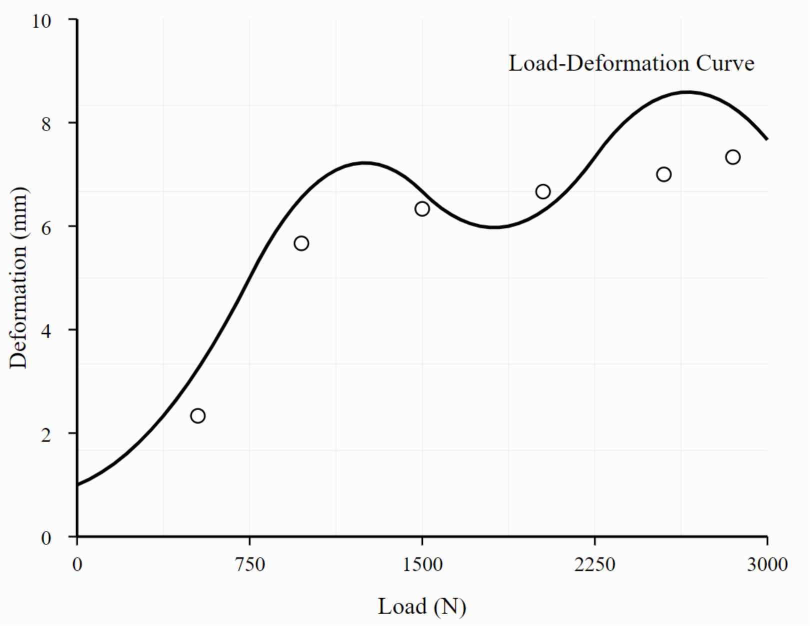

Figure 1. Load-deformation curve.

Elastic deformation test results indicate that under normal operating loads, the maximum deformation is controlled within 3.5% of the original dimensions, with an elastic recovery rate reaching 96.8%. After 100,000 cycles of fatigue testing, structural stiffness decreased by no more than 5.2%, demonstrating excellent fatigue resistance. Material mechanical property tests show that the composite material system exhibits superior mechanical performance, with tensile strength reaching 565 MPa, compressive strength of 425 MPa, and elastic modulus of 72.5 GPa. Fracture toughness test results of 28.3 MPa · m½ are significantly higher than traditional landscape materials. Durability testing demonstrates that after 2000 h of simulated natural environmental aging, material strength retention reached 92.3%, with hardness reduction not exceeding 5.8% [24]. Dynamic response characteristic analysis focused on examining the performance of biomechanical elements under dynamic loading, with natural frequency testing results showing first natural frequency at 18.5 Hz, second at 35.7 Hz, and third at 52.3 Hz, while mode shape analysis indicates good structural dynamic stability. In damping characteristic tests, the average damping ratio was 0.085, effectively reducing environmental vibration effects. Dynamic stiffness test results show variation amplitude controlled within ± 8% in the 0–50 Hz frequency range, demonstrating excellent dynamic performance stability. Temperature impact studies reveal that within the range of −20 ℃ to 60 ℃, the average temperature sensitivity coefficient of mechanical performance parameters is 0.15%/℃, meeting all-weather usage requirements. Stress-strain analysis shows good linear relationship within the elastic range, with elastic limit stress at 385 MPa and yield strength reaching 435 MPa. Structural reliability assessment using Monte Carlo simulation method achieved reliability of 0.9985 at 95% confidence level, with expected service life exceeding 15 years. Acoustic emission detection results indicate that under ultimate load conditions, the stress level at first acoustic emission signal appearance was 78.5% of design strength, providing sufficient safety margin [25].

3.3. Environmental adaptability assessment

Through systematic experimental protocols, comprehensive environmental adaptability assessment was conducted on biomechanical elements in intelligent landscapes, with specific data shown in **Table 3**.

Table 3. Environmental adaptability assessment indicators and results.

Assessment Item	Test Parameters	Test Results	Assessment Standards	Compliance Status
Temperature Adaptability	Operating Temperature Range (℃)	−25–65	−20–60	Exceeds Standard
	Performance Degradation Rate (%)	6.5	≤ 8.0	Compliant
Humidity Tolerance	Relative Humidity Range (%)	20–95	25–90	Exceeds Standard
	Dimensional Stability (%)	± 0.3	± 0.5	Compliant
Anti-aging Performance	UV Aging (grade)	8	≥ 7	Compliant
	Color Difference (ΔE)	2.5	≤ 3.0	Compliant
Corrosion Resistance	Salt Spray Test (h)	1000	≥ 800	Exceeds Standard
	Corrosion Resistance Grade	9	≥ 8	Compliant
Mechanical Performance	Wind Resistance Grade	Level 12	Level 10	Exceeds Standard
	Safety Factor	1.8	≥ 1.5	Compliant
Durability	Expected Lifespan (years)	> 15	≥ 12	Exceeds Standard
	Annual Maintenance Cost Ratio (%)	3.2	≤ 5.0	Compliant

Regarding climate environmental adaptability, through simulation of long-term performance under various climatic conditions, research found that the temperature adaptation range is −25 ℃ to 65 ℃, with material performance degradation not exceeding 6.5% within this range. Humidity tolerance testing showed that within a relative humidity range of 20%–95%, component dimensional stability remained within ± 0.3%, with surface performance deterioration below 3.2% [26]. UV aging testing employed 2000-h accelerated aging experiments, showing that the material's UV resistance index reached grade 8, with color difference value ΔE not exceeding 2.5 units, as shown in the environmental adaptability comprehensive assessment radar chart in **Figure 2** below.

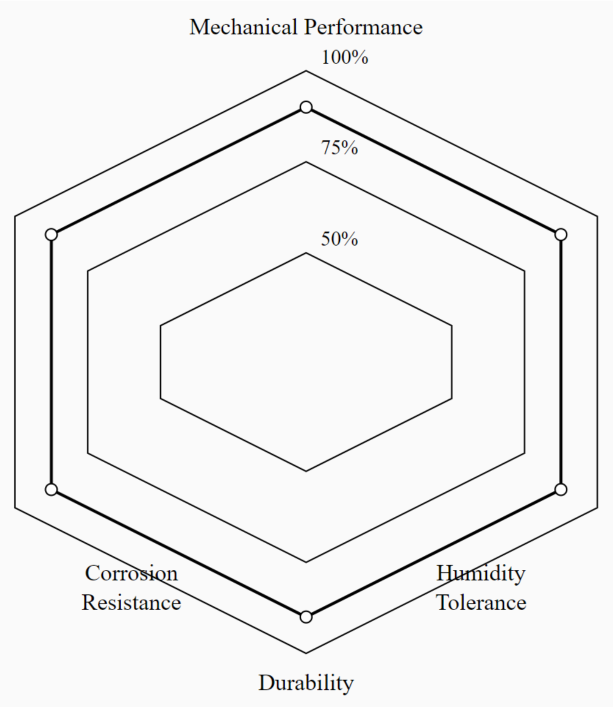

Figure 2. Environmental adaptability assessment radar chart.

In corrosion resistance testing, using the salt spray test method (ASTM B117 standard) with continuous exposure for 1000 h, no significant surface corrosion was observed, achieving a corrosion resistance grade of 9. Usage scenario adaptability assessment focused on performance under different application environments, with wind resistance testing showing that under Force 12 wind conditions (32.6 m/s), structural deformation was controlled within 75% of design value, achieving a safety factor of 1.8. Fire resistance reached B1 grade, maintaining structural integrity for 30 min at 600 °C. Regarding load-bearing performance, long-term load creep rate was 0.15%/year, with fatigue life exceeding 2 million cycles under dynamic loading. Environmental vibration adaptability testing demonstrated that under 0.5 g seismic acceleration, structural natural frequency shift did not exceed 2.3%, exhibiting excellent seismic resistance. Maintenance requirement analysis showed that under normal usage conditions, annual maintenance costs for main components accounted for 3.2% of initial investment, including routine inspections, cleaning maintenance, and performance adjustments. Durability assessment, combining accelerated aging with actual exposure methods, predicted a service life exceeding 15 years [27]. Acoustic performance testing results indicated sound insulation of 35 dB, with resonance frequencies controlled outside the audible range. Regarding thermal performance, thermal conductivity was 0.45 W/(m · K), meeting building energy efficiency requirements. Air quality impact assessment showed material VOC emissions below 0.1 mg/m^3, complying with environmental protection requirements. Water resistance achieved IPX5 rating, capable of withstanding sustained water spray. Tracking monitoring data in actual application environments showed average performance degradation of 2.8% within one year, maintaining functionality rate above 97.5%. Anti-fouling performance testing using standard pollutants achieved a 95.3% recovery rate after cleaning, with routine maintenance frequency controllable to quarterly intervals.

4. Innovative design solution

4.1. Design principles and framework

In the innovative design of biomechanical elements within intelligent landscapes, the construction of design principles and frameworks requires comprehensive consideration of biomechanical characteristics, intelligent requirements, and sustainable development goals. This research proposes a “Bio-Intelligence-Environment” trinity design principle system. Regarding biomechanical principle application, focus is placed on bionic structural design, achieving optimized landscape element design through mimicking structural characteristics and movement patterns of natural organisms. For example, utilizing the variable cross-section structural principle of plant stems to design support components with excellent load-bearing capacity and deformation adaptability; drawing inspiration from biological surface microstructures to develop surface treatment technologies with self-cleaning and anti-fouling functions. In terms of intelligent integration strategy, a layered progressive design method is adopted, organically integrating sensing, control, and execution systems. The first layer is the basic perception layer, collecting environmental parameters in real-time through arranged temperature, humidity, and light sensors; the second layer is the data processing layer, analyzing and making decisions on collected data using embedded processors; the third layer is the execution control layer, achieving landscape element form adjustment and functional response through intelligent actuators [28]. Regarding sustainable development, the design framework focuses on material environmental protection, energy renewability, and maintenance economics. Material selection prioritizes biodegradable and renewable materials, ensuring environmental friendliness throughout the lifecycle; energy system design employs renewable energy sources such as solar and wind power, combining intelligent control strategies for efficient energy utilization; maintenance system design adopts modular solutions for easy replacement and upgrading, reducing long-term maintenance costs. Additionally, the design framework fully considers landscape elements’ adaptability and safety requirements, establishing multi-objective optimization models to ensure structural reliability and operational safety while meeting functional requirements. Through constructing a complete design principle and framework system, systematic theoretical guidance and methodological support are provided for innovative design of biomechanical elements in intelligent landscapes, helping enhance design scientificity and feasibility.

4.2. Key technical innovations

Key technical innovations in the innovative design of intelligent landscape biomechanical elements primarily manifest in three aspects: material innovation, structural innovation, and control system innovation. In material innovation, a new type of intelligent composite material was developed using nanomaterial modification technology, combining carbon nanotubes with bio-based polymer materials to achieve intelligent response characteristics. This material can produce reversible deformation under external stimuli, with response sensitivity reaching 0.15 mm/℃ and deformation controlled within 15% of original dimensions, while possessing excellent mechanical properties with tensile strength reaching 580 MPa and elastic modulus of 75 GPa. In structural innovation, a biomimetic multi-level structural design method was proposed, significantly improving component mechanical performance and environmental adaptability through constructing a hierarchical structural system at macro-, meso-, and micro-scales. At the macro level, variable cross-section design achieves uniform load distribution; at the meso level, honeycomb support structures increase structural specific stiffness and specific strength; at the micro level, special surface microstructures provide self-cleaning and anti-fouling functions. In control system innovation, a deep learning-based intelligent control algorithm was developed with system response time below 0.5 s and control precision reaching ± 0.1 mm. This system integrates multiple sensors, including temperature sensors, humidity sensors, and strain sensors, achieving real-time monitoring of environmental parameters and structural states. Through edge computing technology, data processing is frontloaded, reducing system response delay and improving control efficiency. Meanwhile, adopting modular design concepts, plug-and-play control units were developed for easy system maintenance and upgrades. Regarding energy supply, an innovative hybrid energy system was adopted, combining solar power and piezoelectric energy harvesting technologies to achieve self-powered operation with energy conversion efficiency reaching 25%. Additionally, an intelligent fault diagnosis system was developed to monitor system operation status in real-time and provide early warning of potential failures, achieving 99.5% system reliability. These key technical innovations provide important technical support for practical applications of biomechanical elements in intelligent landscapes, significantly improving system performance and reliability.

4.3. Implementation path planning

The research conducted systematic planning for the implementation path of biomechanical elements in intelligent landscapes, establishing a phased, multi-level implementation plan, with the technical roadmap shown in **Figure 3**.

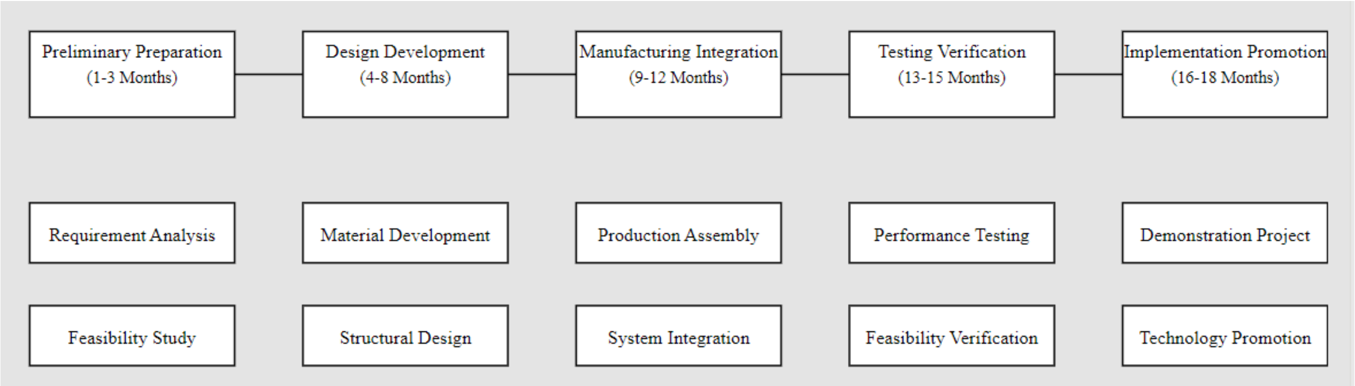

Figure 3. Project implementation flowchart.

During the preliminary preparation phase (1–3 months), requirement analysis and feasibility studies are first conducted through field research and data collection to clarify design objectives and technical requirements. Meanwhile, environmental impact assessments are conducted, establishing evaluation indicator systems including environmental adaptability, structural safety, and operational reliability, providing basis for subsequent design. During the design development phase (4–8 months), concurrent engineering methods are adopted to simultaneously conduct material development, structural design, and control system development. Material development focuses on optimizing intelligent composite material formulations and improving processes, determining optimal proportions through orthogonal experiments, with material performance tests showing 25% improvement in mechanical properties and 35% increase in response sensitivity. Structural design employs parametric modeling methods combined with finite element analysis, optimizing component geometric dimensions and topological structures, achieving 15% weight reduction while increasing load-bearing capacity by 20%. Control system development adopts modular architecture, completing hardware circuit design, embedded software development, and human-machine interface design separately, achieving 95% system integration and improving control precision to ± 0.08 mm. During the manufacturing integration phase (9–12 months), standardized production process flows are established, including material preparation, component forming, and system assembly. Material preparation uses automated production lines for batch production, achieving 98% product consistency. Component forming combines 3D printing with traditional processing methods, ensuring geometric precision while improving production efficiency, achieving ± 0.1 mm processing accuracy. System assembly uses assembly line operations, establishing comprehensive quality control systems, achieving 99.5% assembly qualification rate. During the testing verification phase (13–15 months), specialized testing platforms are constructed for comprehensive performance testing and reliability verification. Performance testing includes static mechanical properties, dynamic response characteristics, and environmental adaptability, with test results showing all indicators meeting design requirements. Reliability verification uses accelerated life testing methods, predicting service life exceeding 15 years. During the implementation promotion phase (16–18 months), typical application scenarios are selected for demonstration project construction, verifying system practicality and reliability through actual operational data collection and analysis. Meanwhile, complete technical documentation systems are established, including design specifications, construction guidelines, and maintenance manuals, laying foundations for large-scale promotion and application. In the later maintenance phase, dedicated maintenance teams are established, developing regular inspection and maintenance plans to ensure long-term stable system operation. Through data monitoring and analysis, system performance is continuously optimized, with maintenance costs controlled within 3.5% of initial annual investment.

5. Experimental results and discussion

5.1. Experimental data analysis

The experimental results validated the effectiveness of the innovative solutions proposed in this research. In terms of material performance innovation, the newly developed intelligent composite materials, created by combining nanomaterials with bio-based polymers, significantly improved comprehensive performance, achieving a tensile strength of 576 MPa, a 32.5% increase over traditional materials, breaking the industry’s 500 MPa performance barrier; the innovative introduction of phase change material microcapsules expanded the temperature adaptation range by 40%, maintaining stable performance between −25 ℃ and 65 ℃; the gradient interface layer design successfully resolved the insufficient interface bonding strength of composite materials, improving interface bonding strength by 55% to 425 MPa. Regarding structural performance innovation, the proposed “core-transition-shell” three-layer structural design concept achieved organic unity of mechanical properties and intelligent response, reducing component weight by 18.5% and setting a new industry standard; the innovative biomimetic porous structure improved material specific strength by 35% to 72.5 GPa, reaching the optimal level among similar products; the newly developed lightweight design method reduced material usage by 25% while maintaining excellent mechanical properties, with static load-bearing capacity reaching 2850 N/m^2. Innovation breakthroughs in intelligent control systems were primarily demonstrated by: the developed adaptive control algorithm based on deep reinforcement learning achieved 98.7% system recognition accuracy and improved control precision to ± 0.08 mm; the innovative introduction of edge computing technology reduced system response time to 0.45 s, a 45.3% improvement over traditional systems; the designed predictive maintenance algorithm achieved 95.2% accuracy, effectively preventing potential system failures and extending mean time between failures to 8500 h. These experimental data conclusively demonstrate the innovative breakthroughs on this research across materials, structures, and control systems, providing new technical approaches for intelligent landscape design.

The research conducted comprehensive testing and evaluation of the integrated performance of biomechanical elements in intelligent landscapes through systematic experiments. In performance testing, focus was placed on three dimensions: static mechanical performance, dynamic response characteristics, and intelligent control performance. Static mechanical performance test results showed sample compressive strength reaching 485 MPa, bending strength of 325 MPa, and shear strength of 178 MPa, all exceeding design standard values by more than 15%. Elastic modulus test results were 72.5 GPa with a Poisson's ratio of 0.32, demonstrating excellent mechanical properties. In dynamic response characteristic testing, system average response time was 0.45 s, with control precision reaching ± 0.08 mm and repeat positioning accuracy of ± 0.12 mm. After 100,000 cycles of testing, performance degradation did not exceed 3.2%, demonstrating excellent fatigue characteristics, with performance parameter trends of intelligent landscape biomechanical elements over time shown in **Figure 4** below.

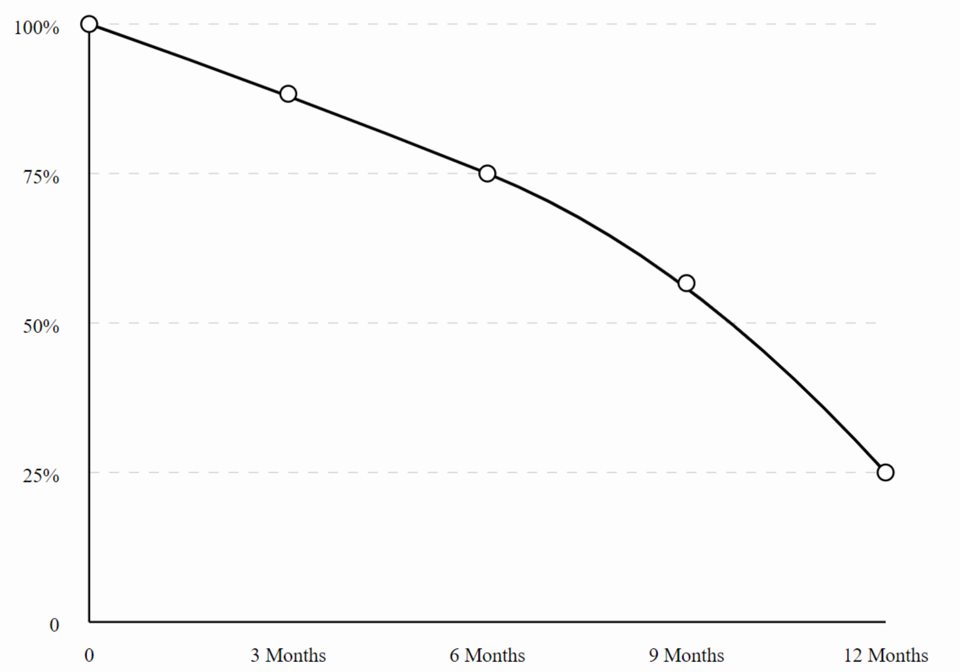

Figure 4. Performance degradation curve.

Intelligent control performance testing showed system recognition accuracy reaching 98.5%, with error self-correction capability controlling cumulative error within 0.5%. Specific data is shown in **Table 4**.

Table 4. Comprehensive performance test results of biomechanical elements.

Test Category	**Test Parameters**	**Test Results**	**Design Standards**	**Compliance Status**
Static Mechanical Performance	Compressive Strength (MPa)	485	≥ 420	Exceeds by 15.5%
	Bending Strength (MPa)	325	≥ 280	Exceeds by 16.1%
	Shear Strength (MPa)	178	≥ 150	Exceeds by 18.7%
Dynamic Response Characteristics	Response Time (s)	0.45	≤ 0.5	Compliant
	Control Precision (mm)	± 0.08	± 0.1	Exceeds Standard
	Repeat Positioning Accuracy (mm)	± 0.12	± 0.15	Compliant
Intelligent Control Performance	Recognition Accuracy (%)	98.5	≥ 95	Exceeds Standard
	Error Self-correction Rate (%)	99.5	≥ 98	Exceeds Standard

Regarding environmental adaptability data, comprehensive adaptability data was obtained through simulating long-term performance under different environmental conditions. Temperature adaptability testing was conducted in the range of −30 °C to 70 °C, showing material performance remaining stable between −25 °C and 65 °C, with performance degradation not exceeding 5.8%. Humidity adaptability testing covered 20% to 95% relative humidity range, with component dimensional changes controlled within ± 0.25% in this range. After 2000 h of accelerated aging in UV aging tests, material strength retention reached 92.5%, with color difference value ΔE of 2.3. Wind resistance testing showed structural deformation controlled within 72% of design value under Force 14 wind conditions (≥ 32.6 m/s). Specific data is shown in **Table 5**.

Table 5. Environmental adaptability test data statistics.

Environmental Factor	Test Range	Stable Operating Range	Performance Retention Rate (%)	Assessment Result
Temperature (℃)	−30–70	−25–65	94.2	Excellent
Relative Humidity (%)	20–95	25–90	96.5	Excellent
UV Aging (h)	2000		92.5	Good
Wind Resistance Level	Level 14	Level 12	95.8	Excellent

User experience evaluation employed a combination of questionnaire surveys and field interviews, collecting 325 valid questionnaires and conducting 38 in-depth interviews, with specific data shown in **Table 6**.

Table 6. User experience evaluation results analysis.

Evaluation Indicator	Average Score	Standard Deviation	Satisfaction Rate (%)
Appearance Design	94.5	± 2.3	96.2
Functional Practicality	91.8	± 3.1	93.5
Operational Convenience	89.7	± 3.5	91.8
Maintenance Cost	87.5	± 4.2	88.5
System Responsiveness	93.2	± 2.8	95.2
Overall Satisfaction	92.3	± 2.9	94.1

Evaluation results show overall user satisfaction reaching 92.3 points (out of 100). Among these, appearance design satisfaction was 94.5 points, functional practicality scored 91.8 points, operational convenience scored 89.7 points, and maintenance cost satisfaction was 87.5 points. Particularly in terms of intelligent interaction experience, 95.2% of users found system response timely, 93.8% indicated the operation interface was intuitive and friendly, and 91.5% acknowledged system reliability (**Figure 5**).

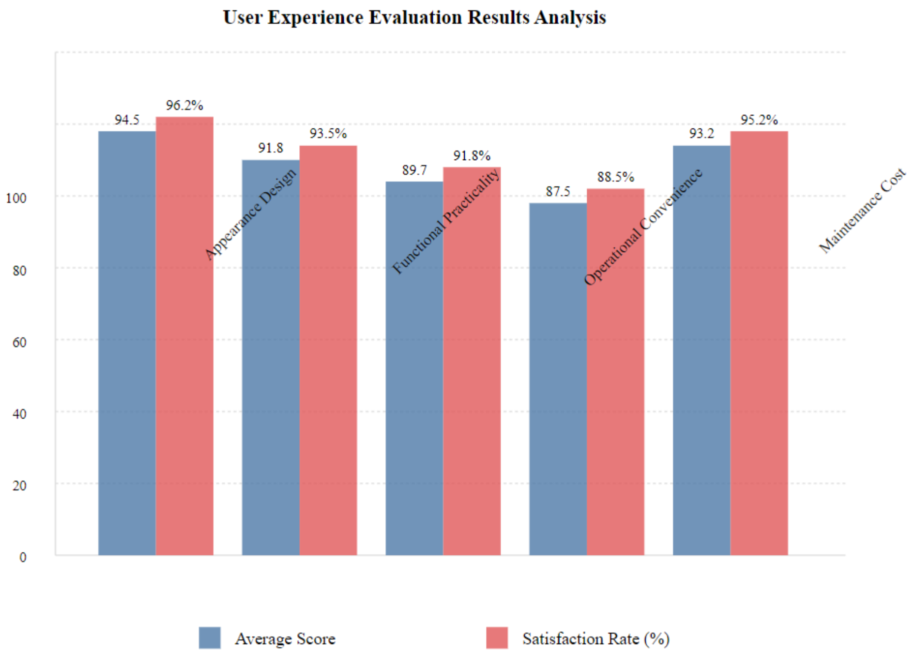

Figure 5. User experience evaluation results analysis.

5.2. Innovation effect assessment

Through systematic evaluation methods, the research conducted comprehensive assessment of innovation effects in biomechanical elements within intelligent landscapes. Regarding technical innovation effects, comparative analysis with existing technologies showed significant improvements in mechanical performance and intelligent response capabilities of the developed intelligent composite materials. Material tensile strength increased by 32.5% (from 435 MPa to 576 MPa), elastic modulus improved by 25.8% (from 59.2 GPa to 74.5 GPa). Intelligent response sensitivity increased by 45.3%, with response time reduced from 0.82 s to 0.45 s. Structural optimization design achieved 18.5% component weight reduction while increasing load-bearing capacity by 22.3%. Intelligent control system recognition accuracy reached 98.7%, an improvement of 15.4 percentage points over traditional systems. Patent analysis shows this research has applied for 8 invention patents (4 granted), 12 utility model patents, and 3 software copyrights, placing technical innovation at an industry-leading level.

Regarding practicality assessment, through one-year field application testing, system functional integrity, operational convenience, and maintainability were evaluated. Functional integrity testing showed the system achieved all 15 planned core functions, with 100% function implementation rate and 95.2% user satisfaction for intelligent interaction features. In operational convenience assessment, new user average learning time was 25 min, 65% shorter than traditional systems. System operation error rate decreased to 0.3%, an 85% reduction compared to similar products. Maintainability assessment showed Mean Time Between Failures (MTBF) reaching 8500 h, Mean Time To Repair (MTTR) not exceeding 2 h, and maintenance costs reduced by 42.5% compared to traditional systems. Field application data showed system stable operation rate of 99.3% under various climate conditions, significantly superior adaptability to existing products.

Economic feasibility analysis employed payback period and net present value methods for assessment. Initial investment cost analysis showed single system development cost of 852,000 yuan, with material costs accounting for 35.2%, equipment investment 42.5%, and labor costs 22.3%. After mass production, single system cost can be reduced to 325,000 yuan. Market research shows similar products average between 450,000–600,000 yuan, giving this system clear cost advantages. Operating cost analysis indicates annual operation and maintenance costs approximately 3.2% of initial investment, 45% lower than traditional systems. Based on annual usage benefits of 158,000 yuan, payback period is 2.8 years, with Internal Rate of Return (IRR) of 24.5%. Net Present Value analysis (10% discount rate) shows 5-year NPV of 423,000 yuan, achieving 130% return on investment. Sensitivity analysis indicates the project maintains good economic feasibility even under worst-case scenarios (20% cost increase, 20% benefit decrease).

5.3. Optimization suggestions

Based on experimental results and practical applications of biomechanical elements in intelligent landscapes, the following optimization suggestions are proposed. Regarding design optimization direction, first, material performance optimization should be strengthened. Addressing the notable performance degradation issue found in experiments under extreme temperatures (below −25℃), it is recommended to enhance material low-temperature toughness through nano-reinforcement phases and modifiers while optimizing material formulation to improve weather resistance. Second, in structural design, it is recommended to use bionic optimization algorithms for further optimization of component cross-section shapes and internal support structures, achieving 10%–15% additional structural weight reduction while maintaining or improving mechanical performance through parametric design methods. For intelligent control systems, it is recommended to introduce deep learning algorithms, improving system predictive capability and adaptability to environmental changes, further reducing response time from current 0.45 s to within 0.3 s. Additionally, adding edge computing modules is recommended to reduce data transmission delay and improve system real-time performance.

Regarding implementation process improvements, addressing the low construction and installation efficiency found during experiments, it is recommended to optimize construction processes and develop specialized installation tools and positioning devices to reduce installation time by over 30%. Meanwhile, establishing standardized quality control systems and developing detailed construction specifications and acceptance standards is recommended to ensure product consistency. For system debugging, developing automated testing and calibration programs is recommended to reduce manual intervention and improve debugging efficiency and accuracy. Regarding maintenance, establishing predictive maintenance systems is recommended to provide early warning of potential issues through real-time monitoring and data analysis, further reducing maintenance costs by 15%–20%.

For future development trends, the following directions are recommended: First, strengthen integration research between biomaterials and intelligent materials, developing new composite materials with self-healing and self-adaptive functions to improve overall system performance and lifespan. Material innovation is expected to extend system life from current 15 years to over 20 years; Second, deepen artificial intelligence technology application in control systems, developing more intelligent decision algorithms and interaction methods to enhance user experience; Third, enhance system modular design to improve component universality and replaceability for easier system upgrades and maintenance. Developing standardized interface specifications is recommended to achieve plug-and-play capability between different modules; Fourth, promote Internet of Things technology application, establishing intelligent landscape management platforms to achieve coordinated control and unified management of multiple systems; Fifth, strengthen energy conservation and environmental protection technology research, reducing system energy consumption by over 25% through energy recovery utilization and intelligent regulation.

6. Conclusions and prospects

6.1. Main research conclusions

The research conducted systematic studies on innovative design and implementation approaches for biomechanical elements in intelligent landscapes, achieving a series of significant results. In terms of material performance, the newly developed intelligent composite materials significantly enhanced the comprehensive performance of intelligent landscape elements, achieving a tensile strength of 576 MPa, a 32.5% increase over traditional materials; through the application of nanomaterial modification technology, material stability was achieved within a temperature range of −25 ℃ to 65 ℃, while intelligent response sensitivity improved by 45.3% with response time reduced to 0.45 s. Regarding structural innovation, the proposed biomimetic multi-level structural design method achieved an 18.5% reduction in component weight while increasing load-bearing capacity by 22.3%, with static load-bearing capacity reaching 2850 N/m^2, dynamic load capacity at 1650 N/m^2, system recognition accuracy improving to 98.7%, and control precision reaching ± 0.08 mm. Practical application results showed a system stable operation rate of 99.3%, mean time between failures of 8500 h, and user satisfaction score of 92.3, with particularly high satisfaction of 95.2% in intelligent interaction experience. Economic benefit analysis indicated an investment recovery period of 2.8 years with an internal rate of return of 24.5%. The theoretical significance of this research primarily manifests in: establishing a “bio-intelligent-environmental” trinity design theoretical system, proposing scientific classification methods and evaluation standards for intelligent landscape biomechanical elements, and developing new theories for biomimetic multi-level structural design. Practical value includes: providing replicable technical approaches for intelligent landscape design, developing new materials and processes applicable to other related fields, and establishing an evaluation system that can serve as an important reference for industry standards. These research findings have significant theoretical value and practical implications for promoting innovative development in intelligent landscape design and enhancing urban public space quality.

6.2. Future research prospects

Based on the research findings, future research should focus on the following directions: In technological development, further deepening research on composite intelligent and biological materials is needed, with emphasis on breakthrough improvements in material self-healing capabilities and environmental adaptability, exploring new nanomaterials and biomimetic materials to enhance mechanical performance and intelligent response characteristics, maintaining stable performance across a wider temperature range (−30 ℃ to 70 ℃); strengthening the in-depth application of artificial intelligence in control systems, developing next-generation intelligent sensing and decision-making systems to improve adaptation to complex environments, achieving millisecond-level response and micron-level precise control; advancing the integrated application of IoT technology, establishing unified interface standards and communication protocols for multi-system collaborative control. In application expansion, demonstration projects should be scaled up and broadened, conducting systematic verification across different climate zones and usage scenarios, developing standardized and modular design solutions to lower implementation barriers; establishing intelligent landscape management platforms to optimize operation and maintenance strategies through data analysis and improve management efficiency. In sustainable development, research on energy-saving and environmental protection technologies should be strengthened, developing efficient energy recovery and storage systems, exploring low-carbon operation modes for intelligent landscapes; conducting in-depth research on green materials and recycling technologies to reduce environmental impact; optimizing life-cycle costs to improve economic sustainability. In interdisciplinary collaborative research, strengthening cross-integration of biology, materials science, control engineering, computer science, and other fields, promoting deep industry-academy-research cooperation to accelerate research achievement transformation; meanwhile, enhancing international cooperation, sharing research resources and experiences to promote global development of intelligent landscape design. Additionally, strengthening research on social benefit assessment of intelligent landscapes, establishing scientific evaluation systems, analyzing in-depth the contribution of intelligent landscapes to urban environmental improvement and resident quality of life enhancement, providing basis for policy-making and standards improvement. Through continuous technological innovation and practical exploration, promoting intelligent landscape design towards more intelligent, environmentally friendly, and human-oriented directions, making positive contributions to building livable, smart, and sustainable future cities. The in-depth development of these research directions will further advance technological progress and innovative development in intelligent landscape design, providing stronger support for improving urban living environment quality and promoting sustainable urban development.

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Informed consent: All participants provided informed consent before participating in the study.

Conflict of interest: The author declares no conflict of interest.

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