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Application of Natural Fiber in Sustainable Landscape on the Basis of Landscape Ecology

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Article

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ABSTRACT

This study, which is grounded on landscape ecology, explores the application of natural fibers in sustainable garden landscapes. With bamboo and hemp fibers as experimental materials and plastic grids and concrete pavers as controls, the study examines soil physicochemical properties, plant growth, and other aspects and uses quantitative and qualitative indicators for analysis. Experimental results show that in the experimental group, the soil organic matter content is substantially increased, plant height growth is more optimal, pest and disease incidence is lower, insect species diversity is increased, and the landscape aesthetic score is higher compared with those in the control group. Natural fibers offer advantages in improving soil conditions, promoting plant growth, enhancing regional biodiversity, and optimizing landscape aesthetics. However, over a 24-month observation period, the physical durability of natural fibers is inferior to that of conventional materials, and their maintenance costs are higher. These findings provide a scientific foundation for the promotion of natural fibers in sustainable landscape design and highlight the challenges associated with their material performance.

KEYWORDS

landscape ecology, natural fiber, sustainability, landscape architecture

INTRODUCTION

Driven by global dual carbon goals and the strategy of ecological civilization construction, the landscape industry is facing two challenges: resource scarcity and ecological degradation [1]. The Paris Agreement aims to limit the global average temperature rise to within 2 °C above preindustrial levels, with efforts to limit it to 1.5 °C [2]. This target compels countries to accelerate the transformation of their energy structures, industrial upgrades, and changes in consumption patterns. As a responsible major country, China aims to achieve carbon peak by 2030 and carbon neutrality by 2060 (dual carbon goals) [3]. China has established a policy framework that includes a carbon emission statistical accounting system, a carbon trading market, and green finance. Meanwhile, ecological civilization construction, a long-term plan, requires the principles of prioritizing ecology and green development to be integrated into all aspects of economic and social development. In this context, the landscape industry, a key sector in shaping spatial environments and ecological restoration, must address the challenges of tightening natural resource constraints and the issue of development intensity approaching ecological red lines. It needs to resolve the crises of biodiversity loss and habitat fragmentation, so it must urgently explore innovative pathways for the coordinated development of low-carbon transformation and ecological restoration. Traditional garden materials, such as plastics and concrete, consume high energy during production, generate high carbon emissions, and are difficult to degrade after use, leading to soil and water pollution. The use of hard paving and monotonous vegetation in landscaping exacerbates the urban heat island effect and fragments habitats. Natural fibers, which are derived from plants, are renewable resources with biodegradability, low carbon emissions, and excellent breathability. Their application in landscaping can achieve carbon sequestration and emission reduction, and their porous structure improves soil aeration and water retention, providing habitats for microorganisms and small organisms [4]. From the perspective of landscape ecology, the use of natural fibers aligns with the need to enhance ecosystem services, which is crucial for maintaining biodiversity, enhancing landscape connectivity, and promoting the material cycle of ecosystems. These fibers are a key pathway for the green, sustainable transformation of the landscape industry.

Domestic and foreign studies on natural fibers analyzed the material’s performance and examined the areas of construction, packaging, composite materials, and so on. Arsyad analyzed the tensile, bending, and impact strengths of coconut fiber composites used in fishing boat walls and found that the higher the content of coconut fiber is, the higher the strength is [5]. Gavilanes studied and introduced lignocellulose-reinforced polymer composites on the basis of urban pruning waste, recycled high-density polyethylene, and water-based acrylic resin; the results showed that the elastic modulus of the composites increased compared with that of the pure polymer matrix [6]. Suteja investigated the development of Walikoukun fiber-reinforced epoxy composites, and dynamic mechanical analysis revealed that composites containing aluminum filler have a storage modulus as high as 2,595.09 MPa, indicating improved stiffness [7]. Wang’s research on flax fiber-reinforced polypropylene composites showed that a 45 grating orientation optimizes interface adhesion and load distribution and provides excellent overall tensile properties [8]. Saha reported that natural fiber-reinforced polymer composites, as sustainable and environment-friendly substitutes for synthetic fiber-reinforced composites, are widely employed in many industries, such as construction, automobile, and packaging [9]. In addition, Amzil stated that natural fiber has many advantages, including light weight, biodegradability, renewability, and cost effectiveness, making it a sustainable substitute for synthetic materials [10]. However, existing research focused on single material function testing or short-term effect observation and lacked systematic experiments on the basis of landscape ecology. The concrete manifestations are as follows: (1) the application of natural fiber has not been quantitatively related to ecosystem service functions, such as carbon sink capacity and biological habitat construction; (2) the comprehensive effect of natural fibers on aesthetics, ecology, and function was not evaluated from the perspective of the overall level of landscape; and (3) the determination of soil organic matter content was performed using the potassium dichromate oxidation and external heating method. In this method, first, a soil sample (0.0001 g) that has been dried and sieved through a 0.149 mm sieve is weighed accurately to 0.0001 g, placed at the bottom of a hard test tube, added with 5 mL of 0.8 mol/L potassium dichromate-sulfuric acid solution, and gently shaken to ensure thorough wetting of the soil sample. Second, the test tube is placed in an oil bath preheated to 180 °C while ensuring that the liquid level is below the oil surface, and the temperature is maintained between 170 °C and 180 °C for 5 min. During this time, the soil solution should remain boiling; when the solution color is too light, additional potassium dichromate solution is poured in. Third, after the digestion is complete, the test tube is removed and cooled to room temperature, and the digestion liquid is transferred to a 250 mL Erlenmeyer flask. The test tube is then washed with distilled water, and the wash liquid is combined to ensure that the total volume of the solution in the flask is approximately 60–70 mL. Fourth, with ferrous sulfate as the indicator, titration is performed with a standard solution of ferrous sulfate (concentration C mol/L). Fifth, when the solution changes from orange–yellow to blue–green and finally to brick red, the volume V (mL) of ferrous sulfate solution consumed is recorded. Simultaneously, a blank test is performed using a solution without the soil sample as the blank, and the volume V0 (mL) of ferrous sulfate solution consumed in the blank test is recorded. Finally, each parameter is substituted into the formula $[(V0-V) \times C \times 0.003 \times 1.724 \times 1.1] / m \times 100$ to calculate the soil organic matter content (%). In this method, potassium dichromate is used to oxidize the carbon in soil organic matter, and the remaining potassium dichromate is titrated with ferrous sulfate. In accordance with the chemical stoichiometric relationship of the redox reaction and combined correction coefficient, the content of soil organic matter is accurately measured to provide data support for evaluating soil fertility and the ecosystem carbon cycle.

EXPERIMENTAL

Materials and Methods

Materials

The natural fiber material, bamboo fiber, was made of bamboo and purchased from Anji Bamboo Products Processing Base in Zhejiang Province. Bamboo, a fast-growing and renewable resource, matures much faster than traditional wood (within 3–5 years) and can regrow naturally after felling, a characteristic that aligns well with low-carbon circular economy principles. To ensure fiber strength and toughness, the Anji facility selects bamboo that is 3–5 years old and applies standardized processing to guarantee consistent quality. The density of bamboo fiber is about 0.9–1.1 g/cm³, its tensile strength is 150–200 MPa, and it has good air permeability and hygroscopicity, which can regulate the local microclimate and mitigate the urban heat island effect. The contents of cellulose, hemicellulose, and lignin are about 60%–70%, 20%–25%, and 10%–15%, respectively. Bamboo is cut off, cooked and softened, mechanically drawn, and carbonized at a high temperature (400 °C–500 °C) to make fiber bundles with a diameter of 2–3 mm and length of 15–20 cm. These fiber bundles are used to weave footpath mats and plant support ropes because of their high strength and flexibility, which meet the mechanical stress requirements of these scenarios.

Hemp fiber, made of flax fiber, is produced in the flax planting area of Inner Mongolia. The local climate, with its large temperature differences between day and night and sufficient sunlight, endows flax fibers with high strength and stability. Moreover, flax cultivation requires minimal irrigation and chemical fertilizers, reducing the ecological footprint. The density of hemp fiber processed by professional textile mills is 1.5 g/cm³, its breaking strength is 5.5–6.5 cN/dtex, its hygroscopicity is strong, and its moisture regain can reach 12%–14%. It contains 70%–80% cellulose, 15%–20% hemicellulose, and 1%–5% pectin. After retting and degumming in the rain, the original flax stems are combed into fiber strips and woven into a linen fiber covering net with a pore size of 10 cm × 10 cm and a thickness of 5 mm for soil covering [11]. Its strong water absorption and large-pore structure can accelerate rainwater infiltration, reduce surface runoff, and provide habitats for microorganisms and small animals, thus promoting material circulation in the ecosystem.

Traditional garden materials, such as plastic grids, can be purchased from the market. These grids are 15 cm × 15 cm in size, with a filament diameter of 3 mm and a density ranging from 0.9 g/cm³ to 0.91 g/cm³. They have a tensile strength of at least 20 MPa, are chemically stable, and are resistant to acid and alkali corrosion. However, they take over 200 years to degrade. The selection of plastic grids and concrete pavers as control materials in this study is due to their extensive application in current landscape projects and high environmental costs. Concrete production, for example, accounts for about 8% of global carbon emissions. Moreover, 40 cm × 40 cm × 5 cm C25 concrete pavers produced by local prefabricated component factories were used. The pavers had a compressive strength of at least 25 MPa and were treated for slip resistance on the surface. Although traditional materials meet engineering requirements in terms of weather resistance and mechanical stability, their long-term ecological costs are high. This comparative experimental design of natural and traditional materials can systematically evaluate the balance between material performance and environmental benefits, providing scientific evidence for sustainable material selection in landscape architecture.

For the experimental plants, herbaceous plants were selected. Specifically, *Ophiopogon japonicus* (McDong) plants with a height of 10–15 cm and crown width of 8–12 cm were employed. These plants were sourced from a local nursery and planted at a density of 36 plants per m^2 for ground cover [12]. Shrubs, such as *Photinia × fraseri* (redleaf photinia), were also chosen; they had a height of 30–40 cm and crown width of 25–30 cm. Twenty plants were planted in each area to enhance landscape design and create ecological barriers. Trees, including *Osmanthus fragrans*, with a trunk diameter of 3–4 cm and tree height of 2–2.5 m were planted. Three trees were planted in each area to improve the microclimate and enhance the landscape.

Methods

For the experiment, a flat area with uniform illumination was selected in a city park and divided into two adjacent square plots (side length of 10 m and area of 100 m^2), with a 2 m wide isolation belt (paved with water-permeable bricks) between them. Before the experiment, soil samples from the two areas were analyzed to ensure the absence of statistically significant differences in soil bulk density (1.2–1.3 g/cm^3), pH (6.5–7.0), and organic matter content (1.5%–2.0%) [13]. The road structure was designed as follows. The experimental group used bamboo fiber mesh with 3 cm gravel, and the control group employed plastic mesh with permeable geotextile and 3 cm gravel. For reinforcement materials, the experimental group utilized natural fibers, including bamboo fiber bundles and ropes, and the control group used plastic mesh. In terms of soil covering, the experimental group applied fiber-reinforced nets, and the control group used horticultural nonwoven fabric [14]. Common horticultural nonwoven fabrics were covered around the roots of plants, and the covering method was similar to that of the experimental group. The differences in soil physical and chemical properties, plant growth, landscape ecological benefits, landscape aesthetic effects, material durability, and maintenance costs between the experimental and control groups were compared. Table 1 shows the specific measurement indicators and their calculation methods.

Table 1. Evaluation indexes for measuring the application effects of different materials in sustainable landscape

Dimension	Index	Computational method
Soil physical and chemical properties	Soil organic content	Determination of soil organic matter content is performed using the potassium dichromate oxidation and external heating method. First, weigh a soil sample (accurately to 0.0001 g) that has been dried and sieved through a 0.149 mm sieve, place it at the bottom of a hard test tube, add 5 mL of 0.8 mol/L potassium dichromate-sulfuric acid solution, and gently shake the test tube to ensure thorough wetting of the soil sample. Second, place the test tube in an oil bath preheated to 180 °C, ensuring that the liquid level is below the oil surface, and maintain the temperature between 170 °C and 180 °C for 5 min. During this time, the soil solution should remain boiling; when the solution color is too light, add potassium dichromate solution. After the digestion is complete, remove the test tube, cool it to room temperature, transfer the digestion liquid to a 250 mL Erlenmeyer flask, wash the test tube with distilled water, and combine the wash liquid to ensure that the total volume of the solution in the flask is approximately 60–70 mL. Third, with ferrous sulfate as the indicator, titrate with a standard solution of ferrous sulfate (concentration C mol/L). Fourth, when the solution changes from orange–yellow to blue–green and finally to brick red, record the volume V (mL) of ferrous sulfate solution consumed. Simultaneously, perform a blank test by using a solution without the soil sample as the blank, and record the volume V0 (mL) of ferrous sulfate solution consumed in the blank test. Finally, substitute each parameter into the formula $[(V0-V) \times C \times 0.003 \times 1.724 \times 1.1] / m \times 100$ to calculate the soil organic matter content (%). In this method, potassium dichromate is used to oxidize the carbon in soil organic matter, and the remaining potassium dichromate is titrated with ferrous sulfate. In accordance with the chemical stoichiometric relationship of the redox reaction and combined correction coefficient, the content of soil organic matter is accurately measured to provide data support for evaluating soil fertility and the ecosystem carbon cycle. Initial judgment is made using the manual measurement method [15].
	Soil texture	When the tactile method is used to simply identify soil texture, standardized procedures must be strictly followed to ensure the reliability of the results. The specific steps are as follows. Take about 50 g of fresh, moist soil sample and place it in your palm to check that the soil is moderately moist (the soil should be moldable but not sticky). Gently rub the soil

		to feel its texture; sandy soil will produce a noticeable sand-like friction, and clay soil will feel as fine as flour. Next, slowly press the soil sample between your thumb and index finger to observe its extensibility; sandy soil cannot form a continuous strip, silt soil can form short, easily broken strips (usually less than 2 cm in length), and clay soil can be stretched into a long, flexible strip over 5 cm in length. Afterward, hold the soil sample in your palm and squeeze it firmly; sandy soil will scatter when released, silt soil will form a loose ball, and clay soil can be molded into a compact, smooth ball. This method is based on the international standard for soil texture classification and allows for a quick judgment of soil texture types (sand, loam, clay, and their transitional types) through the intuitive perception of soil particle composition. It provides essential data for soil improvement, plant selection, and drainage system planning in landscape design and is especially suitable for onsite rapid assessment and preliminary investigation scenarios.
Plant growth status	Plants grow tall	For each plant variety, 20 individuals are randomly selected, and a multidimensional indicator scoring method is applied for establishing evaluation systems for growth (plant height, stem diameter, new branches), physiology (leaf chlorophyll content, photosynthetic rate), morphology (leaf area index, flower diameter), and stress resistance (disease index, drought tolerance score), with weights being assigned to each indicator (e.g., 30% for growth, 25% for physiology). A 5-point scale is used: 5 points for excellent (≥20% higher than the control), 3 points for moderate (similar to the control), and 1 point for poor (≥20% lower than the control). Measurements are taken using tools (ruler, caliper, chlorophyll meter, etc.) and image analysis software, and the arithmetic mean and standard deviation are calculated for each indicator. Scoring is adjusted based on standard deviation: +1 point if the standard deviation is less than 10% of the average value (stable performance) and −1 point if it exceeds 20% (large individual variation). Comprehensive scores are obtained via weighted summation to quantify the adaptability and ecological benefits of plant materials.
	Occurrence of plant diseases and insect pests	1. Level 1 (no pest or disease): the plant has a smooth surface with no disease spots, insect holes, or live pests. All physiological indicators are normal, and no control measures are required. 2. Level 2 (mild pest or disease): scattered disease spots cover less than 5% of the leaf area, with not more than 5 pests per 100 cm² leaf. These pests cause only minor damage and do not affect growth; they can be managed manually. 3. Level 3 (moderate pest or disease): Disease spots cover 10%–30% of the leaf area, causing partial yellowing of the

		leaves. There are 10–20 pests per 100 cm^2 leaf, and growth is substantially slowed down. Chemical or biological control measures are necessary. 4. Level 4 (severe pest or disease): disease spots cover more than 50% of the leaf area, causing extensive leaf drop and branch death. There are more than 30 pests per 100 cm^2 leaf, leading to abnormal plant growth. Immediate comprehensive control measures are required. 5. Level 5 (near death): disease spots cover the entire plant, causing tissue decay and plant wilting. Pests are rampant, and the plant is on the brink of death, with a low survival rate after rescue efforts.
Landscape ecological benefits	Insect species richness	In the experimental and control areas, insect collection via yellow board trapping and netting is conducted from 9:00 a.m. to 11:00 a.m. on clear, windless days (wind speed ≤ 2 m/s). For yellow board trapping, 10 yellow boards (20 cm × 30 cm) are evenly placed at plant canopy height in each area. They are installed at 9:00 a.m. and collected 24 hours later, with captured insects stored in 75% alcohol. The netting method involves randomly selecting 5 sampling points (≥3 m apart) in each area, performing 10 –1 min net sweeps at each point in a zigzag pattern across vegetation layers, and preserving insects in 75% alcohol. All specimens are transported to the lab within 24 h for species identification and counting by professional entomologists.
	Bird activity behavior	Each quarter, during clear and windless mornings from 8 a.m. to 10 a.m. and in the afternoons from 3 p.m. to 5 p.m., the line transect method is used for observation. In the experimental and control areas, a 50 m long, 5 m wide transect line is set up. Surveyors walk along these lines and use their eyes and binoculars to observe and record the types, numbers, and behaviors of birds. Bird activities are categorized into four types: foraging, nesting, roosting, and flying over. The frequency of each activity is counted to analyze how the regional ecological environment affects bird behavior.
Landscape aesthetic effect	Color harmony score	A panel of landscape experts, designers, and the general public is invited to form an evaluation team. This team conducts onsite evaluations of the experimental and control areas at the start, midpoint, and end of the experiment. The scoring system is a five-point scale, where 1 indicates color disharmony and strong visual conflict and 5 indicates harmonious color coordination and aesthetic appeal [16]. The scores from each evaluator are collected, and the average score is used as the color harmony score for that area.
	Overall style of landscape	After each onsite evaluation, evaluators are invited to use open-ended questionnaires to describe in writing the overall landscape style of the experimental and control areas, such as

		modern minimalist, natural ecological, or traditional Chinese styles, and to explain their criteria and impressions. The collected textual data are then organized and categorized, and the characteristics of landscape styles in different areas, as well as public recognition, are analyzed [17].
Material durability and maintenance costs	Material breakage rate	On the 20th of each month, the materials in the experimental and control areas are inspected for appearance. The length and width of damaged areas are measured using a tape measure, and the total damaged area is calculated. The damage rate (percentage) is calculated as (damaged area / total material area) × 100. The damage rates for natural fiber and traditional garden materials are calculated separately. A line graph showing the change in damage rate over time is created to compare the durability differences between the two types of materials.
	Material aging appearance characteristics	Monthly observations of material aging appearance are conducted in conjunction with the measurement of damage rates by using a five-level classification system. Level 1 indicates no significant changes on the material surface, with good color and texture. Level 2 shows slight fading of the material surface, with no noticeable change in texture. Level 3 indicates a noticeable lightening of the material's color, with a few fine cracks appearing. Level 4 marks severe fading of the material's color accompanied with an increase in cracks, crack widening, and texture loss. Level 5 signifies extensive damage and fractures, leading to the loss of functionality. The area proportions of materials at different levels are statistically analyzed to assess the trend of material aging.

Statistical methods (SPSS 26.0 software) and the X^2 test were used for data measurement （$\overline{x} \pm s$）. The results were statistically significant, with $P < 0.05$ by T test.

RESULTS AND DISCUSSION

Physical and Chemical Properties of Soil

Figure 1 shows the statistical results on soil organic matter content in soil physical and chemical properties. The data show that no statistical difference existed between the two groups before the experiment, and the soil organic matter content in the experimental group was significantly higher (with statistical significance) than that in the control group after the experiment. In addition, the soil texture qualitative results indicate that both groups consisted of loam before the experiment. After 12 months, both groups still consisted of loam, but the water retention of the experimental group improved, and the hand feel became delicate. In the control group, soil hardening occurred locally.

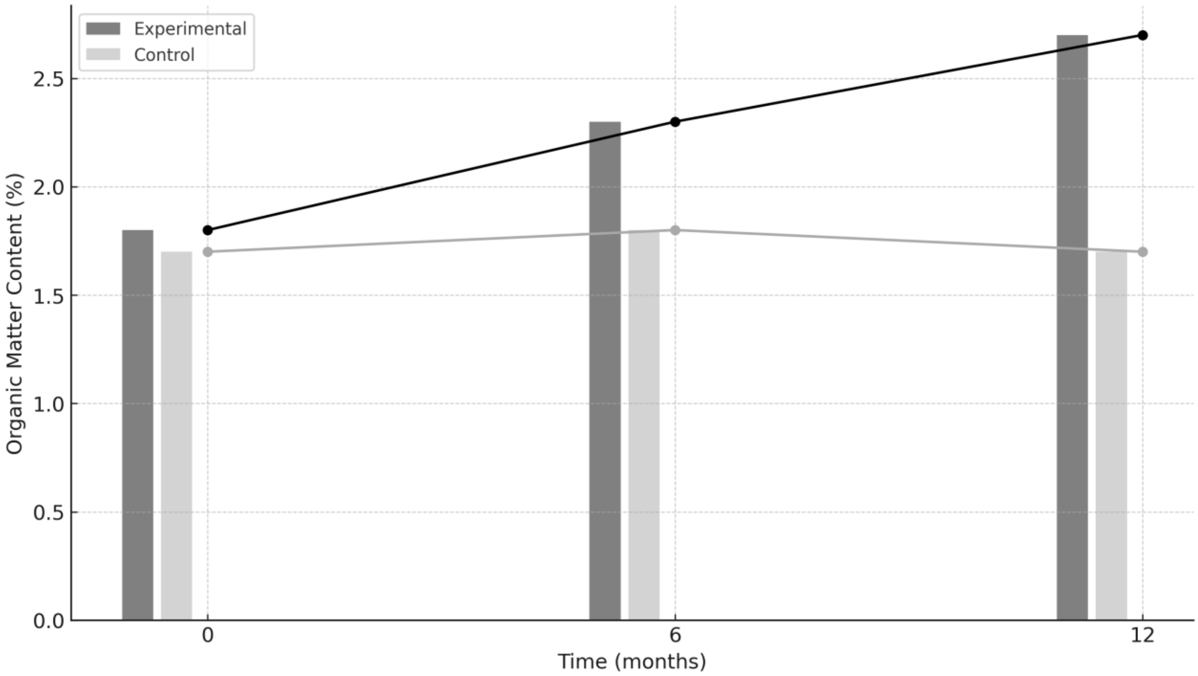

Figure 1. Comparison of soil organic matter content

Plant Growth

Plant Height Comparison Results

Figure 2 presents the comparative results on plant height. At the onset of the experiment, no significant differences were observed in the initial heights of the various plant types between the two groups. However, over the 12-month observation period, all three categories of plants in the experimental group—herbaceous species, shrubs, and trees—exhibited consistently superior growth trends compared with those in the control group.

Further analysis revealed that the natural fiber materials used in the experimental group, such as bamboo fiber mulch, substantially improved the soil’s thermal and moisture conditions. Recorded measurements indicated that these materials reduced the daily average soil temperature by 2.3 °C and increased soil moisture content by 19%. These improvements enhanced root vitality by 34%. Moreover, the cellulose degradation products released by the fibers, such as oligosaccharides, functioned as signaling molecules that stimulated auxin biosynthesis, thereby accelerating cell division at the shoot apices. By contrast, the plastic mesh used in the control group caused soil compaction and led to hypoxic conditions in the root zone, which inhibited cell elongation. Moreover, the trace amounts of plasticizers released from the conventional materials may have disrupted the hormonal balance of the plants, resulting in delayed vertical growth. The study further observed that plants grown in areas covered with hemp fiber had heights that were approximately 8% greater than those in areas covered with bamboo fiber. This difference was due to the release of potassium (1.2 mg/g) during the degradation of hemp fiber, which promoted vascular bundle development. These findings provide robust quantitative evidence for the differential effects of various landscape materials on promoting plant growth.

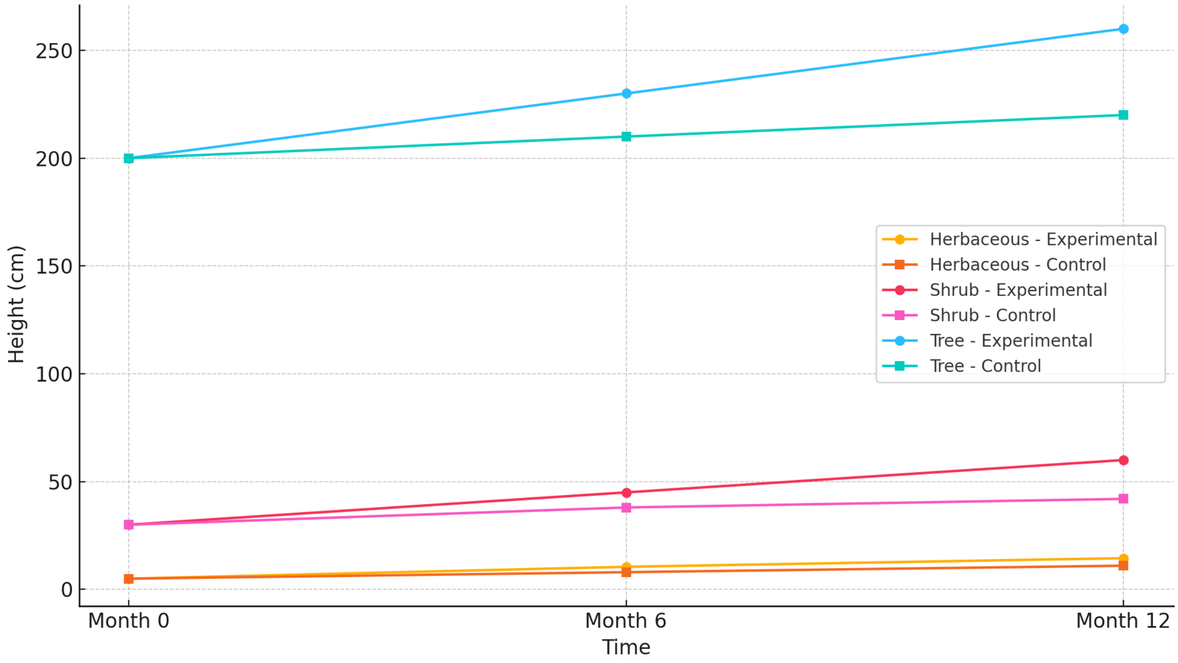

Figure 2. Comparison of plant growth height

Occurrence of plant diseases and insect pests

Figure 3 illustrates a comparative analysis of plant disease and pest severity, reflecting the proportional changes in plant health levels within the experimental and control groups over a 12-month observation period. The data reveal a clear difference in ecological resilience between the two groups. Initially, both groups maintained healthy conditions. However, by the sixth month, a marked divergence was observed, coinciding with seasonal disease outbreaks and other environmental stress events. While both groups experienced a decline in plant health, the effect was considerably more severe in the control group. These results indicate that ecosystems established using natural fibers possess a strong capacity to withstand environmental stressors. Furthermore, the 12-month data highlight notable differences in recovery potential. The experimental group exhibited markedly strong resilience, suggesting that the application of natural fibers fosters the development of robust plant communities that not only demonstrate enhanced resistance to disease and pest pressures but also possess a superior ability to recover from environmental disturbances.

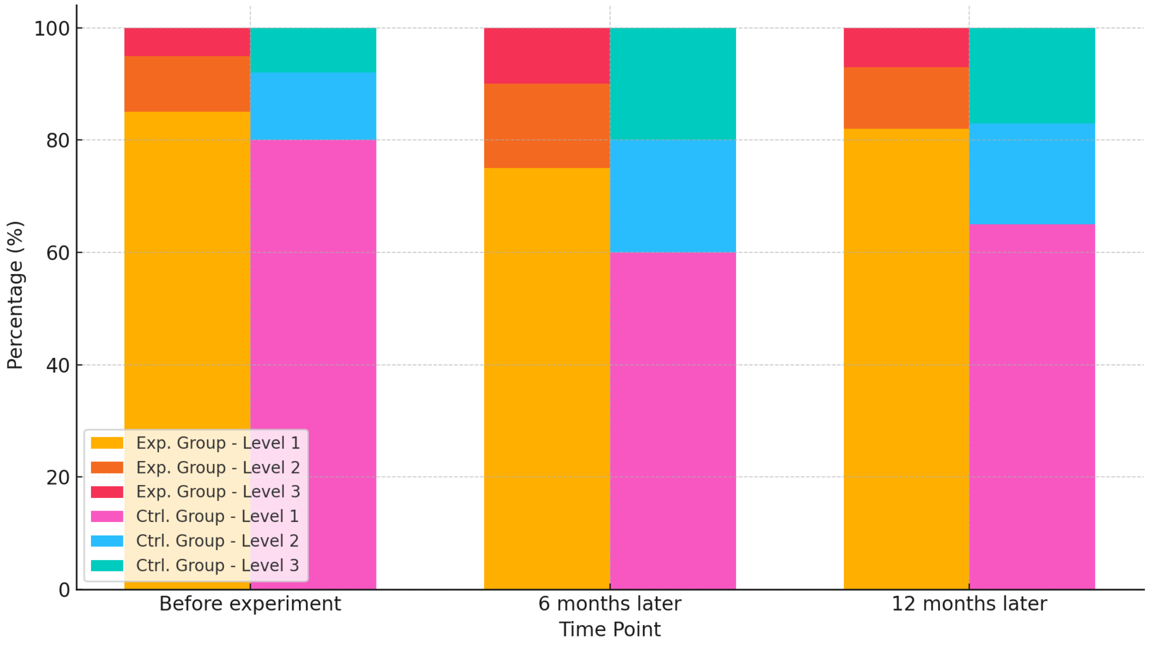

Figure 3. Comparison of plant disease and pest severity

Landscape Ecological Benefits

The data in Figure 4 reveal a pronounced positive trend in the landscape ecological benefits of the experimental group over the 12-month study period in comparison with the control group. In terms of insect species richness, the two groups exhibited markedly divergent trajectories. The number of insect species in the experimental group steadily increased from the initial count of approximately 15 species, reflecting the continuous expansion of biodiversity. By contrast, species richness in the control group remained stable during the early and middle stages of the experiment but declined noticeably at the late stages. These findings indicate that the application of natural fiber materials successfully created diverse microhabitats, offering abundant food resources and shelter for insects, thereby fostering a rich, resilient insect community. With regard to avian behavioral activity, the improved insect populations and enhanced vegetation structure in the experimental area attracted diverse birds and profoundly influenced their behavioral patterns. Overall, the marked increase in functional behaviors, such as foraging, nesting, and roosting, combined with the sharp decline in transitional behaviors, such as flying over, demonstrated that the experimental area evolved from a mere flyover corridor into a functional habitat of genuine ecological value for birds [18]. The substantial differences observed between the two groups provide compelling evidence that the ecological restoration measures implemented in this study had a sustained, beneficial effect on enhancing biodiversity within the ecosystem.

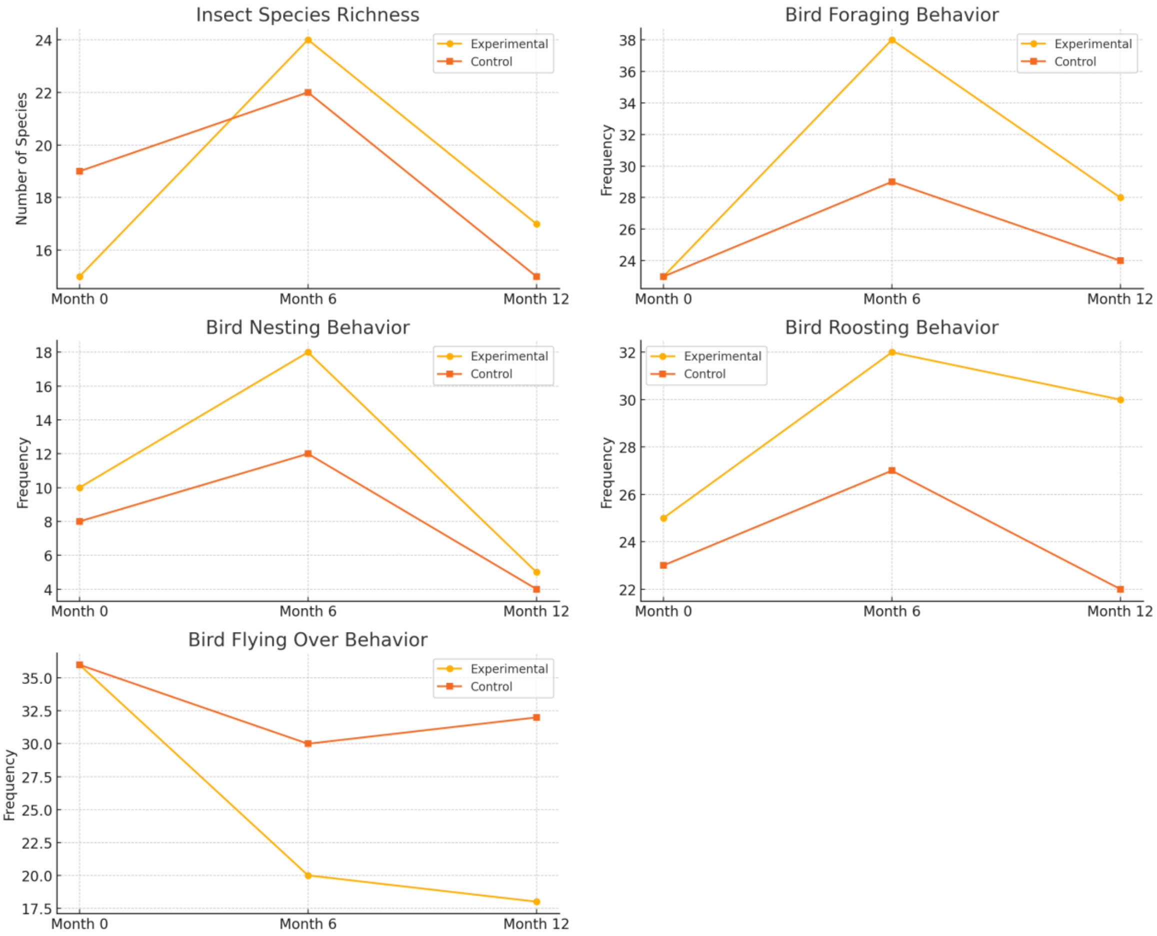

Figure 4. Ecological benefits: insect and bird behaviors

Landscape Aesthetic Effect

As shown in Figure 5, the evaluation scores for landscape aesthetics underwent considerable changes throughout the experiment. At the outset, only a small difference in color harmony scores was observed between the experimental and control groups. However, as time progressed, the experimental group displayed a clear and robust upward trend in aesthetic evaluations, whereas the control group’s improvement remained modest. The qualitative questionnaire responses provided vivid explanations for these changes in the scores.

In the initial phase, the experimental group was described as exhibiting a natural ecological style, and the control group was characterized by a modern minimalist style. At six months, the stylistic distinctions between the two groups became increasingly pronounced, and the score gap widened accordingly. The naturalistic aesthetic of the experimental group became increasingly prominent, with plant community color compositions evolving from scattered accents to cohesive gradient transitions, such as the bright yellows of herbaceous flowers complementing the deep greens of shrub foliage. By contrast, the control group remained dominated by the cold grays of hard architectural surfaces and the uniform greens of regimented plantings, with color compositions being limited to rigid geometric blocks. By the 12th month, the experimental group's scores increased to approximately 4.5, surpassing the control group's score of around 3.5. At this stage, the experimental group had established a stable ecological landscape color system characterized by a low-saturation earth-tone palette: warm browns from deciduous trees, vibrant greens from evergreen vegetation, and soft beiges from natural fiber materials. Together, these hues created a visually harmonious scene marked by seasonal variation and distinct seasonal character (scenery throughout the year, with clear seasonal phases). By contrast, the control group's aesthetic remained largely unchanged. Some evaluators noted that its artificial color scheme, such as the vivid hues of plastic pavements and the sharply clipped green hedges, felt visually disconnected from the surrounding ecological context, lacking the color breathing quality of a natural habitat.

In summary, as the plant communities underwent natural succession and the natural materials gradually blended with the environment, the landscape in the experimental group became increasingly harmonious in terms of color, texture, and overall style, developing a dynamic and evolving aesthetic. As a result, it received much higher aesthetic evaluations than the control group that utilized conventional materials.

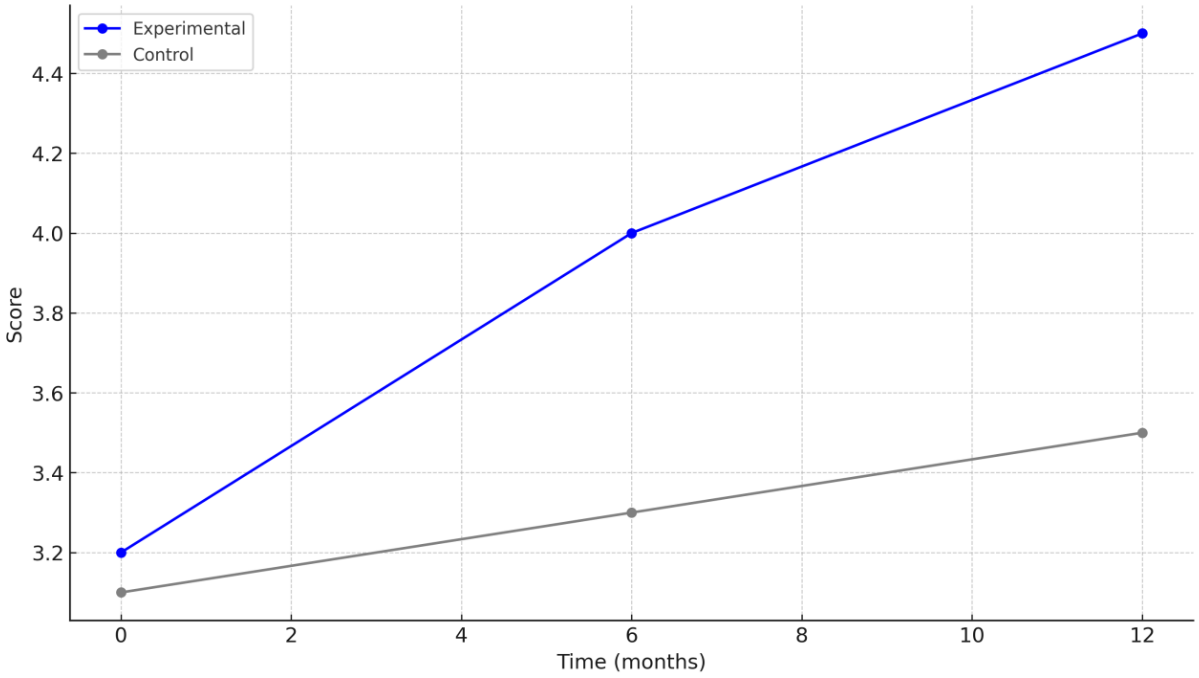

Figure 5. Color harmony score comparison

Material Durability and Maintenance Costs

The monitoring results for material durability and maintenance costs are presented in Figures 6 and 7. At the beginning of the experiment, both groups of materials exhibited no signs of damage. By the 12 month, the damage rate in the experimental group (natural fibers) reached 5.2% compared with 3.1% in the control group (conventional materials). As time progressed, the rate of material degradation accelerated. By the 24th month, the damage rate in the experimental group increased to 15.8%, which was much higher than the 7.6% observed in the control group. These data clearly demonstrate that over the 24-month observation period, the physical durability of natural fiber materials was inferior to that of traditional materials.

Meanwhile, maintenance costs were directly correlated with the extent of material degradation. At 12 months, the maintenance costs for the experimental and control groups were 18.3 and 11.5 yuan per square meter, respectively. By the 24th month, extensive structural deterioration in the fiber materials caused the maintenance costs in the experimental group to surge to 35.2 yuan per square meter, which was nearly double the control group's 18.7 yuan per square meter. These findings indicate that natural fiber materials require frequent repairs and high maintenance investments during the early and middle stages of application. Although natural fibers have clear ecological and aesthetic advantages, their low durability and elevated maintenance costs are practical challenges that must be addressed before their large-scale adoption. These shortcomings are primarily attributed to the susceptibility of natural materials to biodegradation and physical aging when exposed to outdoor environmental factors, such as moisture, ultraviolet radiation, and microbial activity [19].

This insight highlights the importance of future research efforts aimed at modifying natural fibers to enhance their durability, thereby improving their long-term performance in landscape applications.

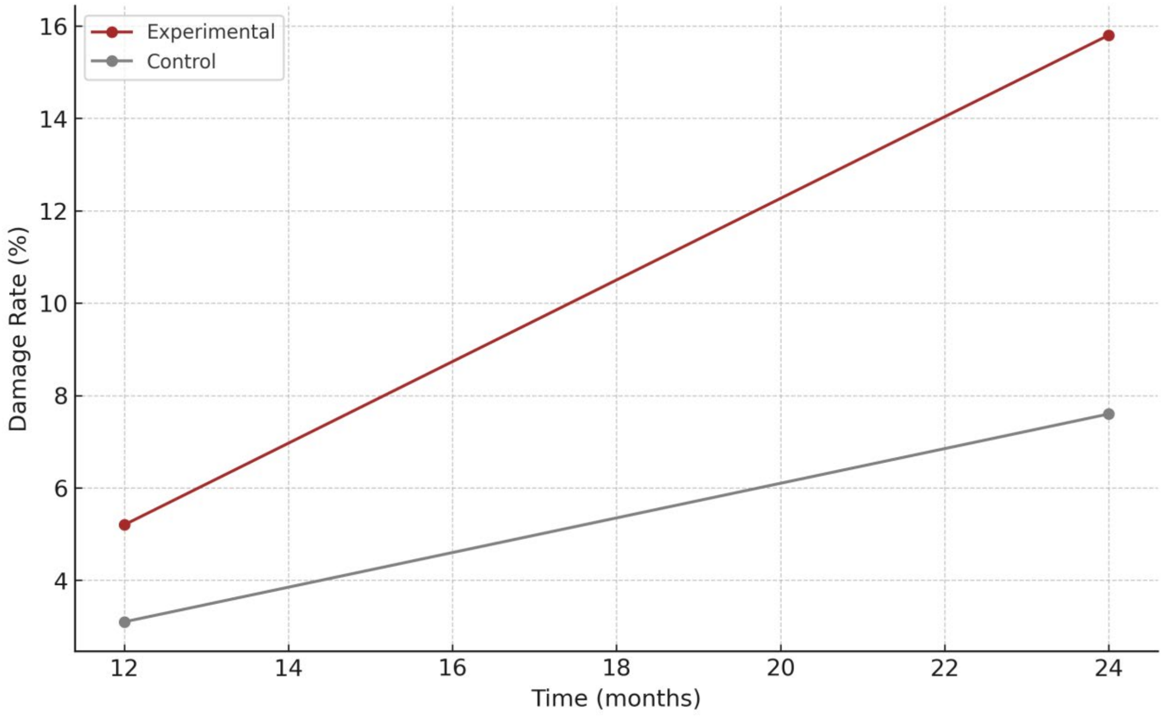

Figure 6. Material damage rate over time

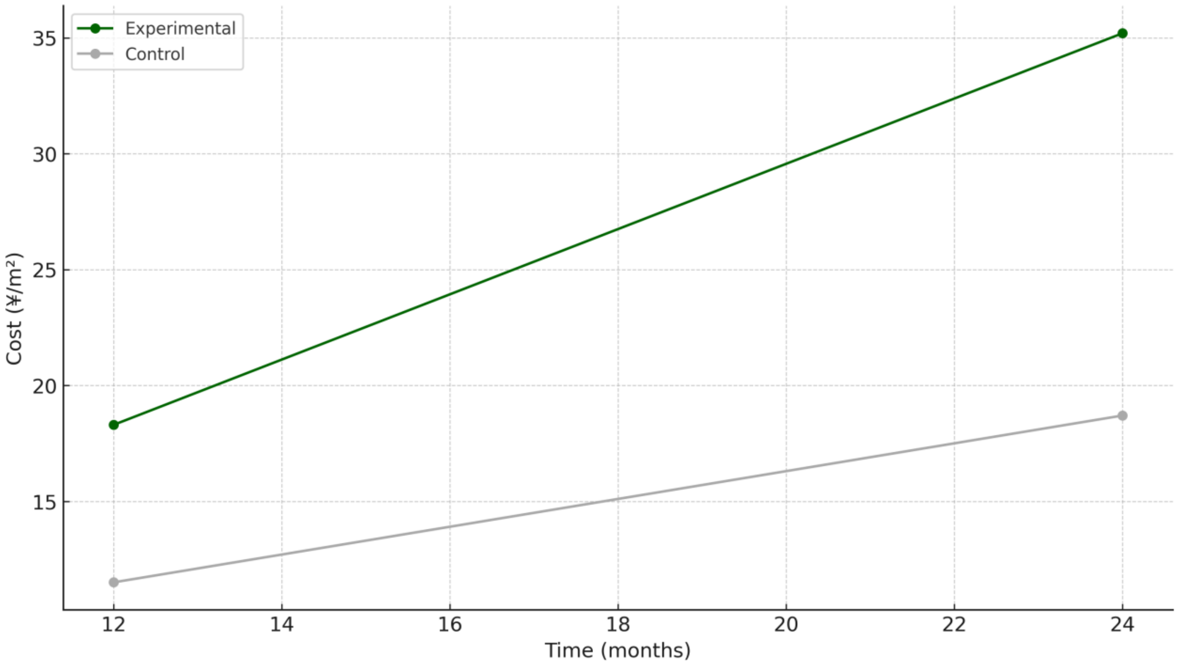

Figure 7. Maintenance cost over time

CONCLUSION

This study confirms that the application of natural fibers can substantially enhance the sustainability of landscape design. Ecologically, natural fibers help improve soil conditions, promote plant growth, and enrich biodiversity. Aesthetically, their natural texture enhances the harmony and visual appeal of the landscape.

However, this study also highlights functional challenges: over the 24-month observation period, the natural fibers exhibited lower physical durability compared with the conventional materials, resulting in increased maintenance costs.

Although this study provides valuable insights, it has limitations. The experimental period was too short to fully assess the long-term performance of natural fiber materials and their ecological effects. The single-location setting limited the consideration of varying climate zones, soil types, and geographic factors, reducing the generalizability of the results. Moreover, the focus on macrolevel indicators overlooked key interactions between natural fibers and soil microbial communities and their effects on ecosystem material and energy cycles. The absence of cost–benefit analysis and lifecycle assessment constrained the evaluation of economic feasibility and practical applicability.

To address these gaps, future research should establish multilevel experimental designs, including gradient studies, to optimize natural fiber application. Improvements should target the compatibility of natural fiber-reinforced composites and the sustainable production of building materials to mitigate ecosystem degradation [20]. Priority areas include developing low-cost, salt-tolerant water-absorbent resins via microwave-synthesized fiber grafting terpolymers [21]; exploring degradable mulch films that are based on hemp fibers and nonwoven fabrics [22]; and applying chemically modified natural fibers with diverse resin matrices to enhance thermoplastic composites in landscaping [23]. Integrating natural fibers with regional traditional garden techniques; enhancing material properties through physical, chemical, and biological modifications; and employing intelligent technologies to develop self-regulating products are also recommended.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Peng Li and Ye Pan designed the study; all authors conducted the study; Ye Pan and Peng Li collected and analyzed the data. Ye Pan and Peng Li participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

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Conflict of Interest

The authors declare no conflict of interest.

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