

Low-Cost Corrugated Paper-Bamboo Sports Facilities for Rural Primary Schools: Design, Safety Testing, and Field Validation

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Abstract

Rural primary schools in mountainous areas often lack safe, versatile, and maintainable sports equipment because commercial systems are expensive to transport and install. This paper develops a low-cost corrugated paper-bamboo facility system in which corrugated board is used for replaceable, non-primary load panels and locally available bamboo forms the reusable frame. The design method combines a 95-response user survey, a constraint-based product specification, module-level prototype screening, and a four-week feasibility crossover with 24 pupils. Five modules were prototyped for throwing, target practice, coordination, and group games. For the most critical balance-rail assembly, the nominal design load was 1.20 kN, the measured maximum service load was 1.84 kN, and the failure load was 4.07 kN, giving a calculated ratio of 2.21; the values refer to different load definitions and are reported separately. The selected reference purchase price for a five-function commercial package was 5,470 RMB; the prototype material cost was 1,186 RMB and the full delivered prototype estimate was 1,744 RMB. During the pilot, the kit condition was associated with higher observed active-play time (27.9 versus 18.6 min per lesson) and task completion (81.6% versus 62.4%). Internal screening was designed with reference to selected criteria in ISO 8124-1 and EN 1176-1; it was not third-party certification. Use is limited to supervised, protected, low-load activities with daily inspection and replacement rules.

Keywords: corrugated paper, bamboo composite, rural schools, sports facilities, frugal innovation, safety testing

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1. Introduction

Physical education in remote primary schools is constrained by a practical mismatch: children need varied movement tasks, while schools may have only hard ground, an aging hoop, and a few loose balls. Integrated playgrounds solve functional problems but require high procurement, transport, foundation, and maintenance costs. The design problem is to define safe activities that can be assembled, repaired, stored, and taught with local resources.

Corrugated paper is attractive for this problem because it is widely available as packaging waste, easy to cut, light to transport, and naturally suited to folding and layered construction. Its weaknesses are equally clear: strength is directional, moisture causes rapid degradation, edges can be sharp, and unsupported panels buckle under concentrated load. The proposed solution assigns paperboard to replaceable panels, targets, scoreboards, and low-load barriers, while bamboo carries the main frame forces. This separation follows the engineering principle that a frugal

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product should simplify the system without hiding its failure modes [1]–[4].

The objective of this study is to develop and evaluate a corrugated paper-bamboo facility kit for primary-school activities in resource-constrained mountain settings. The research addresses four questions: which activities and dimensions are preferred by pupils; which load paths and joints are adequate for a low-cost frame; whether modular paperboard panels retain acceptable performance in preliminary internal screening; and whether kit use is associated with higher observed participation and task completion during physical-education lessons. The contribution is a complete design-to-test workflow with measurable cost, assembly, structural, usability, and learning outcomes. The study treats the prototypes as supervised teaching aids and low-load play equipment; it does not present them as certified public climbing structures or as evidence of general playground compliance.

The modular concept was informed by existing low-cost corrugated-paper product forms, as shown in Figure. 1.



Figure 1. Existing low-cost corrugated-paper product forms that informed the modular concept

2. Related work

Frugal innovation research describes products that deliver essential functions with substantially fewer resources, while remaining maintainable in the context where they are used [1]. For rural schools, this implies local sourcing, low transport volume, replaceable parts, and a design that teachers can understand without specialist tools. Sustainable material selection adds a second requirement: the product must be evaluated over use, repair, and end-of-life stages rather than by purchase price alone [2], [3]. Corrugated board is a sandwich material with strong directional behavior; bending strength depends on flute direction, span, board grade, and support conditions [4], [5].

Sports-facility design is also governed by child safety and accessibility. ISO 8124-1 specifies requirements for mechanical and physical properties such as sharp points, edges, spacing, and foreseeable misuse [6]. EN 1176-1 provides a broader framework for playground structural integrity, entrapment, inspection, and marking [7]. The proposed kit uses these standards as design references, but

limits the tested use to throwing, target, coordination, and supervised balance tasks. This boundary avoids presenting paperboard as a substitute for certified slides, swings, or elevated climbing towers.

Schoolyard research links loose equipment, color-coded zones, and diverse movement opportunities with greater activity during recess [8], [9]. UNESCO also emphasizes equality, safeguarding, meaningful participation, and teacher preparation [10]. These principles support reconfigurable modules for different class sizes and abilities.

Design-method literature recommends an explicit sequence from user need to function, form, manufacture, and verification [11]. Co-design further shows that children, teachers, and maintainers contribute different knowledge about play, supervision, and repair [12][13]. The present study combines these perspectives with a small field survey and physical tests. Its gap is practical: few studies report the joint effect of a paperboard-bamboo construction method, a safety-limited activity set, and a school lesson evaluation using cost and participation measures [14]–[16].

Commercial target equipment reviewed during competitor analysis is shown in Figure. 2; a commercial integrated playground reviewed for function and procurement comparison is shown in Figure. 3; and a timber and tire climbing frame reviewed for structural and activity comparison is presented in Figure. 4.

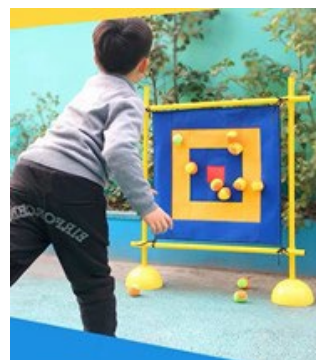


Figure 2. Commercial target equipment reviewed during competitor analysis

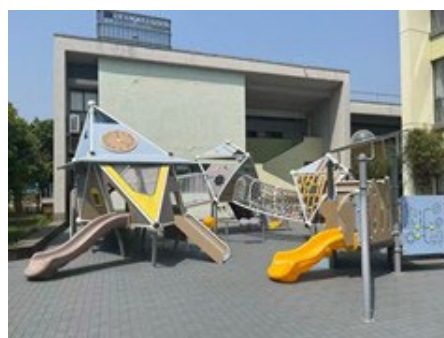


Figure 3. Commercial integrated playground reviewed for function and procurement comparison



Figure 4. Timber and tire climbing frame reviewed for structural and activity comparison

3. Methodology and system design

3.1 User Requirements and Survey

A questionnaire was administered on site to pupils aged 6–12 in three rural primary schools located in mountainous areas of central and northern China. Teachers explained the questions to younger pupils, and incomplete responses were removed before coding. Ninety-five valid questionnaires were retained. Multiple-choice questions measured preferred activities, existing equipment, desired facility functions, group size, color, material acceptance, and ground condition. Open responses were coded into movement verbs and play scenarios. The survey was used to set priorities rather than to infer clinical health outcomes. (see Figures 5–8, Table 1).

1. Which sports do you like? (Multiple choice)

Option:	Subtotal	Proportion
A. Running, playing games	62	65.26%
B. Obstacle courses, tunnels	22	23.16%
C. Basketball	25	26.32%
D. Football	18	18.95%
E. Sandbags, juggling	22	23.16%
F. Rope skipping, shuttlecocks	26	27.37%
G. Other: () [Details]	5	5.26
Valid responses in this survey:	95	

☒ Pie ☐ Donut ☐ Bar ☐ Horizontal Bar ☐ Line

2. Which equipment do you use most often in your free time? (Single choice)

Option:	Subtotal	Proportion
A. Ball games (football, basketball)	29	30.53%
B. Rope skipping	25	26.32%
C. Sandbags, shuttlecocks	9	9.47%
D. No equipment, just running and jumping	27	28.42%
E. Other: () [Details]	5	5.26
Valid responses in this survey:	95	

Figure 5. Survey results for preferred sports and commonly used equipment

3. What sports equipment or facilities do you think the school is most lacking in right now? (Single choice)

Option:	Subtotal	Percentage
A. Larger playground (football)	7	7.37%
B. Fun obstacle courses and tunnels	44	46.32%
C. Facilities for climbing and fitness	30	31.58%
D. Equipment for the playground	7	7.37%
E. Other: ()	7	7.37%
Valid responses in this survey:	95	

4. If there is a new sports facility, what do you hope it will be mainly used for? (Single choice)

Option:	小计	Proportion
A. Obstacle courses	20	21.05%
B. Climbing	16	16.84%
C. Slides	12	12.63%
D. Rocking equipment	19	20%
E. Balance equipment	23	24.21%
F. Other: ()	5	5.26
Valid responses in this survey:	95	

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Figure 6. Survey results for facility shortages and expected use

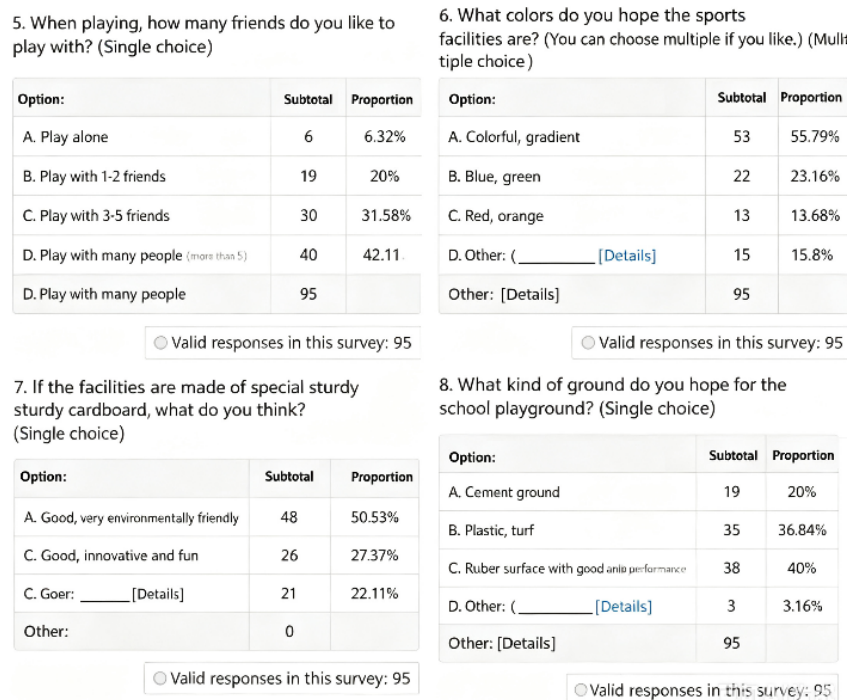


Figure 7. Survey results for group size, color, material acceptance, and ground condition.

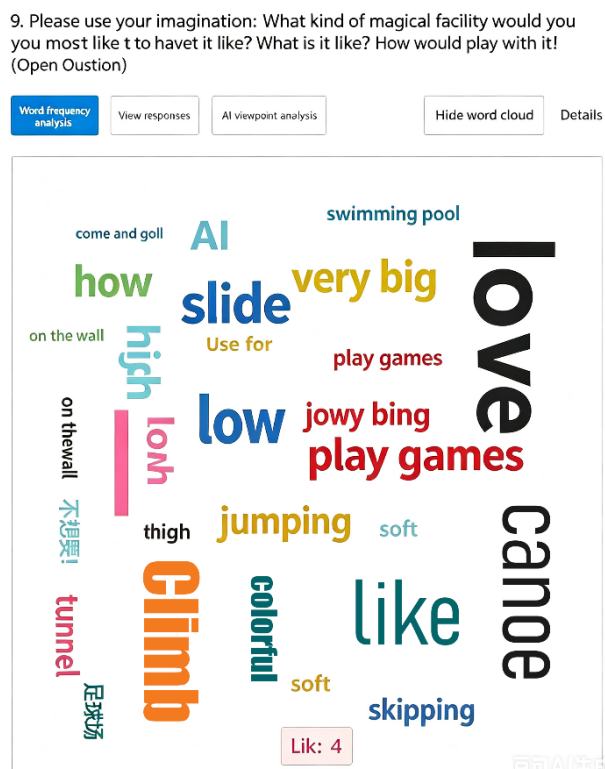


Figure 8. Word-frequency view of pupils' desired facility forms and play actions

Table 1. User requirements extracted from 95 valid responses

Requirement	Observed response	Design implication
Activity	Running 65.26%; basketball 26.32%	Low-threshold throwing and relay tasks
Facility gap	Obstacle/tunnel 46.32%; climbing/crawling 31.58%	Use ground-level frames and barriers
Group play	More than five pupils 42.11%	Provide team scoring and rotation
Material acceptance	Sturdy cardboard accepted by 77.90%	Show safety and maintenance clearly
Ground	Rubber surface 40.00%; soil/grass 36.84%	Use wide feet and adjustable leveling

3.2. Material and Structural Design

The construction system has four layers: a bamboo frame, laminated corrugated panels, replaceable contact parts, and a surface-protection layer. Bamboo poles with nominal diameters of 28–35 mm form vertical posts and horizontal rails. The paperboard uses three- and five-ply sheets with a

nominal thickness of 6–10 mm; panels are laminated with water-based adhesive and covered by a low-VOC water-resistant film. The paperboard is not used as a primary support for a child's body weight. It carries distributed impact from soft balls, visual information, and low-load game pieces. Bamboo tenons and split-pin joints allow disassembly without power tools.(see Figures 9-11)



Figure 9. Corrugated-board layers used for panel selection



Figure 10. Bamboo stock and local material reference



Figure 11. Bamboo joint form used to define the tenon and rail connection

The design envelope was set before fabrication. The maximum panel span was 620 mm, unsupported cut-outs were limited to 120 mm, and all exposed edges received a 3 mm radius or a folded sleeve. The base footprint of a stand was 900 mm by 420 mm, with a total height below 1,450 mm. A 300 mm clear zone was maintained around the target face. These dimensions support visibility and reach for children while reducing overturning risk. The nominal design service load for sizing was 1.20 kN. For each module, the measured maximum service load was the largest load applied during the use simulation; the calculated safety factor was defined as $SF = \text{failure load} / \text{measured maximum service load}$. The 1.84 kN value in the abstract is the maximum service load for the balance-rail assembly, whereas 4.07 kN is its frame failure load; $4.07/1.84 = 2.21$. The nominal design load and the measured maximum service load are therefore different quantities.

3.3 Prototype set and test procedure

Five interchangeable modules were fabricated: a ring-throwing target, a shape-matching rack, a tic-tac-toe throwing board, a soft-ball arch target, and a low balance rail. Twelve complete assemblies were produced, with three repeats per module. Static tests used a calibrated load cell and sandbags applied at the most unfavorable panel or rail position at 50 N/s, held for 60 s, and released at 0.1 kN/s. The support boundary reproduced the classroom base: the feet were placed on rubber, cement, or compacted soil, and no anchor was added. Failure was recorded at visible cracking, delamination, permanent deflection above 10% of span, joint slip above 5 mm, or overturning. A 300 N lateral push was applied at the highest reachable point; tip-over displacement was measured at the top rail. Soft-ball impact used 200 throws at 8.0 ± 0.5 m/s on each target. Three-point bending was used for ten coupons in and across the flute direction. Moisture screening included 10 spray-dry cycles, a 24 h immersion, and a 120 h UV/heat-humidity exposure; mass gain, edge swelling, coating peel, and post-aging load retention were recorded.

The field study was framed as a feasibility crossover rather than a causal effectiveness trial. Two instructors supervised four six-pupil groups. After one familiarization lesson, each pupil completed four conventional lessons and four kit lessons in counterbalanced order during weeks 1–3; week 4 was used for transfer and maintenance checks. This produced 192 pupil-lesson observations, with the pupil mean within each condition as the primary paired unit and group-level means used for a cluster sensitivity check. Teachers recorded active-play minutes with a stopwatch, task completion, setup time, and unsafe-contact events. Pupils completed an eight-item child-adapted recall sheet and a separate confidence sheet at baseline and after the crossover. Three instructors independently scored movement-task completion and rule understanding. The primary analysis used paired permutation tests with 10,000 label swaps and reported mean differences, 95% confidence intervals, and Cohen's d ; a mixed-effects

sensitivity model included condition as a fixed effect and pupil and group as random intercepts.

The movement-task rubric ranged from 0 to 100: 0 indicated no completed sequence, 25 completion only with continuous prompting, 50 completion with two or more errors, 75 completion with at most one error, and 100 independent completion plus a correct safety explanation. In a 90 min rater-training session, instructors scored six practice videos before field scoring. Inter-rater reliability was $ICC(2,k) = 0.86$ for task completion and weighted kappa = 0.82 for the four-level rule-understanding categories. The recall sheet contained eight picture-supported items and was piloted with six pupils for reading comprehension; Cronbach's alpha was 0.71. The classroom usability index

was a separate ten-item, 0–10 teacher questionnaire adapted from the item-writing logic of the SUS literature [17], not the standardized SUS and not interpreted against SUS benchmarks; its alpha was 0.84. Objective observation, teacher ratings, and pupil self-reports were analyzed as separate outcomes.

4. Experiments and results

4.1 Mechanical, moisture, and assembly results

Table 2. Module-level internal screening results

Module	n	Design load	Max service	Failure load	SF	Tip/joint (mm)	Screen
Ring target	3	0.60	0.86	2.12	2.47	6.8/1.6	Pass*
Shape rack	3	0.60	0.91	2.18	2.40	8.1/2.0	Pass*
Tic-tac-toe	3	0.70	1.02	2.36	2.31	7.4/2.4	Pass*
Arch target	3	0.80	1.15	2.67	2.32	10.2/2.8	Pass*
Balance rail	3	1.20	1.84	4.07	2.21	18.6/3.8	Pass*

*Internal screening criterion: $SF \geq 2.00$, tip-over displacement < 25 mm under 300 N lateral push, and joint slip < 5 mm. Results are not third-party certification

The five modules were tested separately, with three assemblies per module. Static loading was applied at the most unfavorable reachable point, and the maximum service load was recorded before the 60 s hold; the failure load was then obtained in a separate monotonic test. Thus, the balance-rail values are 1.20 kN nominal design load, 1.84 kN measured maximum service load, and 4.07 kN failure load, yielding $SF = 4.07/1.84 = 2.21$. The other modules follow the same formula. Tip-over displacement is the top-rail movement under a 300 N lateral push, and the joint value is the largest measured slip after 200 assembly-impact cycles. The most frequent failure modes were local panel crushing at the ring target, a torn cut-out at the shape rack, pin looseness at the tic-tac-toe board, a local crease at the arch target, and base tilt at the balance rail. None triggered the internal screen limits, but the balance rail was marked for closer supervision on soil or grass.(see Table 2)

Internal tests were designed with reference to selected mechanical, edge, spacing, and inspection considerations in ISO 8124-1 and EN 1176-1. The work did not test every clause, did not include a formal entrapment or head-probe assessment, and did not involve an accredited laboratory. The prototypes are therefore described as having passed the stated internal screen only. Before any public installation, the school must complete a local risk assessment covering pinch points, head or limb entrapment, trip hazards, loose pins, material fragments, foreseeable misuse, and ground condition.

Supplemental durability screening showed that ten spray-dry cycles increased coated-panel mass by $6.2 \pm 1.4\%$ and edge swelling by $5.7 \pm 1.0\%$; 24 h immersion produced $10.8 \pm 2.1\%$ mass gain and two visible delaminations in ten coupons. After 120 h of UV/heat-humidity exposure, post-aging panel capacity retained $86.4 \pm 4.7\%$ of the unaged value, and 500 soft-ball impacts caused no frame failure but produced local coating abrasion on three target faces. These short-duration screens do not represent a mountain rainy season. The operating rule is therefore supervised, protected, short-duration or indoor use: panels are stored under cover after each lesson, removed during rain, inspected daily, and discarded when swelling exceeds 8%, delamination exceeds 25 mm, a corner sleeve detaches, or a joint cannot be tightened.(see Figures12-16)



Figure 12. Author sketch of the soft-ball and ring-target module

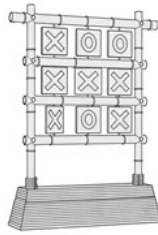


Figure 13. Author sketch of the tic-tac-toe target module

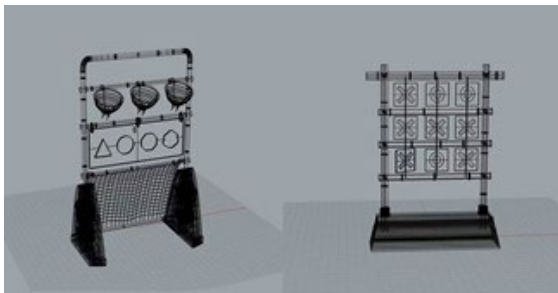


Figure 14. Wireframe views used to check module proportions and joint positions



Figure 15. Colored renderings of the five corrugated-paper-bamboo prototype



Figure 16. Physical prototypes assembled for classroom trial

4.2 Cost and field validation

Table 3. Cost boundaries and three costing views

Cost item	Prototype (RMB)	Reference package (RMB)
Materials / purchase	1,186	5,470
Fabrication / installation	360 / 0	600
Packaging / local transport	78 / 120	820
Initial delivered total	1,744	6,890
Estimated 3-year maintenance	210	400
Estimated 3-year total	1,954	7,290
Cost per lesson, 120 lessons	16.3	60.8

The cost comparison uses three boundaries. The prototype material bill was 1,186 RMB: recovered corrugated board 184, bamboo 420, adhesive and coating 166, pins and sleeves 128, and incidental consumables 288. Fabrication labor was 360 RMB for 12 h, packaging was 78 RMB, local transport was 120 RMB, and installation was zero because the joints were tool-free. The selected reference purchase price was 5,470 RMB for quotation Q-2026-0318-PE, a five-function steel/HDPE school-playground package; the quotation did not provide a stable brand model identifier. The prototype material bill is 21.7% of that selected reference purchase price, while the initial delivered totals are 1,744 and 6,890 RMB. A three-year estimate assumes 120 lessons, six replacement panels at 35 RMB each, and one annual inspection allowance; it is a planning estimate, not a life-cycle assessment.(see Table 3)

The field study was analyzed as a within-pupil feasibility comparison. Each pupil contributed four conventional and four kit lessons, so the paired units were pupil-level condition means; lesson-level observations were retained for descriptive distributions. Active-play time was an objective stopwatch observation, task completion was a teacher rubric, recall was a pupil test, and the classroom usability index was a teacher questionnaire. The condition difference for active-play time was +9.3 min per lesson (95% CI 7.1–11.5; Cohen's $d_z = 1.36$), and task completion was +19.2 percentage points (95% CI 13.1–25.3; $d_z = 1.11$). Setup time was measured at the group-session level and fell by 104 min (95% CI 86–121); this estimate is descriptive because only four groups were available. Unsafe-contact events decreased from 3.8 to 1.2 per 10 group-lessons (incidence-rate ratio 0.32, 95% CI 0.10–1.02; $p = 0.081$). The mixed-effects sensitivity model gave the same direction of effects.

Pupils correctly identified the purpose of 5.0 ± 1.2 of eight tasks after the conventional condition and 6.7 ± 0.9 after the kit condition, a mean difference of 1.7 items (95% CI 1.1–2.3; $d_z = 1.02$). The classroom usability index increased from 64.1 ± 9.8 to 78.6 ± 8.1 , a mean difference of 14.5 points

(95% CI 9.0–20.0; $dz = 1.18$). This index is not SUS and should not be compared with published SUS benchmarks. Teachers particularly valued the ability to replace a damaged target face without discarding the bamboo frame. Pupils preferred the team scoring board and the shape-matching rack, while the balance rail required the greatest supervision on uneven ground. These observations are consistent with the survey preference for group play, low-threshold activities, and colorful functional zones [8]–[10].

5. Analysis and discussion

The central engineering result is the successful separation of structural and functional roles. Paperboard supplied low-cost geometry, visual feedback, and replaceable contact surfaces; bamboo supplied the load path and allowed repeated assembly. This architecture reduced material cost without asking a moisture-sensitive sheet to behave like a beam. The measured cross-flute bending value was 44% lower than the flute-direction value, so orientation and span control are essential design parameters. Any future version that adds climbing or body-support functions would require a new structural calculation and certification test under the relevant playground standard [6], [7].

The user results show that affordability alone does not create a healthy sports facility. Clear activity rules, short setup, and visible participation cues were needed. Linking each panel to a movement objective and team rotation rule coincided with higher active-play time, task completion, and recall, although long-term fitness was not measured.

Sustainability was implemented through a proposed reuse and replacement workflow rather than a claim of full-cycle environmental performance. Coated panels were kept under cover, inspected after each lesson, and replaced under the moisture and delamination rules above. Bamboo rails were retained across all trials, while paper panels were replaced twice during the four-week period. Damaged panels were flattened and sent to local paper recycling. The workflow makes material use auditable, but no carbon inventory, recovery-rate study, or verified service-life assessment was completed [2], [3], [18].

The survey and teacher observations implement a modest co-design pathway: pupils contributed play preferences, teachers specified supervision and storage constraints, and the design team translated them into dimensions, colors, joints, and an inspection checklist [12]–[15].

The study has five limitations. The field sample was small and drawn from three schools, the crossover lasted four weeks, and activity minutes were recorded by teachers rather than by accelerometers. The sequence was counterbalanced but could not eliminate novelty, teacher familiarity, weather, or lesson-content effects; the study therefore remains a feasibility pilot. Cost data reflect one local procurement context and do not include a full carbon or life-cycle assessment. Internal screening addressed selected criteria but cannot substitute for accredited certification or a full entrapment and misuse assessment. The paperboard system is limited to supervised, protected, low-load activities and

cannot support claims for elevated play equipment or general public-playground use. Future work should include a longer seasonal deployment, independent safety testing, direct water and energy measurement, and comparison across different bamboo species, board grades, and ground surfaces.

6. Conclusion

This paper developed a low-cost corrugated paper-bamboo sports-facility system for primary schools in mountainous areas. The design used a bamboo load-bearing frame, replaceable laminated paperboard panels, detachable joints, and a defined supervised-use envelope. A 95-response survey guided activity selection, while module-level internal screening and a four-week feasibility crossover provided quantitative evidence. The selected prototype material bill was 21.7% of the reference purchase price, the initial delivered estimate was 1,744 RMB, and the balance-rail assembly had a calculated internal-screen ratio of $4.07/1.84 = 2.21$. During the pilot, kit use was associated with higher observed active-play time and task completion, but the small uncontrolled sample cannot establish a causal facility effect. The practical contribution is a proposed reuse and replacement workflow with explicit inspection rules, not a full-cycle environmental claim. The system should be deployed only for supervised, protected, low-load activities until independent certification and longer durability studies are completed.

Acknowledgements

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