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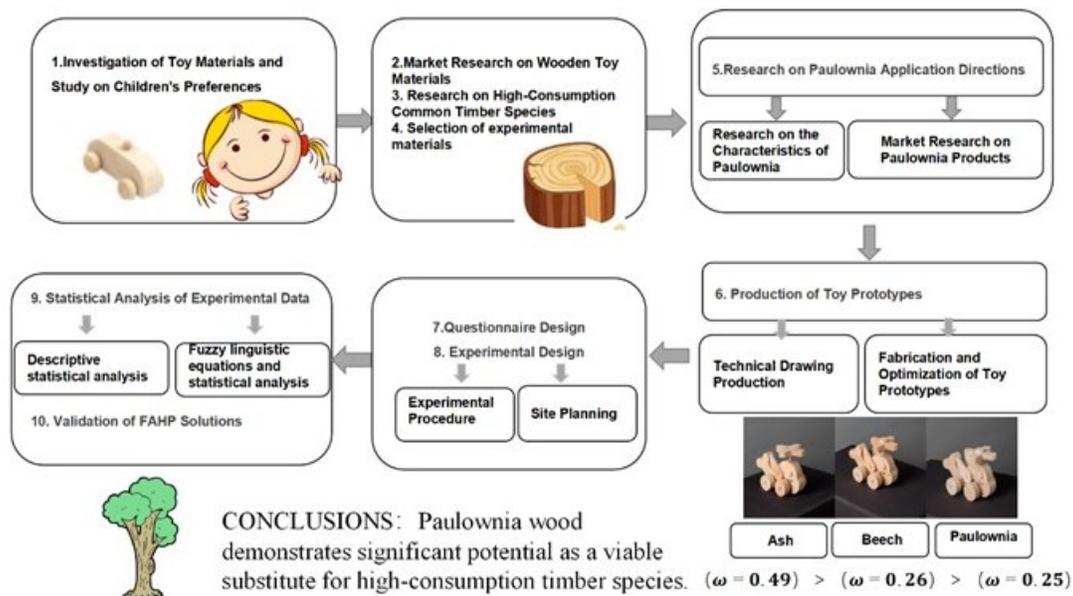
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GRAPHICAL ABSTRACT

Application of *Paulownia* Wood Based on Fuzzy Theory Decision-Making

Xiaohan Shen,[a] Junzhe Liu [iD],[a] YiXian Xiao,[b] XinYuan Shao,[c] and Xiaoli Zou [d]

This study examined parental and children's perceived value preferences regarding wooden toy materials to facilitate more efficient toy selection while evaluating whether fast-growing *Paulownia* wood can serve as a valuable alternative to high-consumption timber species to promote green toy adoption. The research employed three common wood types used in toys, furniture, and construction - ash, beech, and *Paulownia* - to fabricate experimental toy prototypes. Through on-site observations and questionnaires, parental preferences were documented across five dimensions: surface characteristics, price, usage cycle, environmental friendliness, and suitability. Results were analyzed using fuzzy theory for data recording, SPSS 27 for descriptive statistics, and fuzzy analytic hierarchy process for solution validation. Findings indicate that while *Paulownia* showed slightly weaker advantages in surface characteristics and modest benefits in usage cycle and suitability, it demonstrated significant advantages in price competitiveness and environmental performance, suggesting substantial potential for wider adoption.

INTRODUCTION

As parents worldwide have placed increasing emphasis on children's healthy development, the impact of toy production and usage on child health has garnered significant attention. A growing number of parents and manufacturers have begun prioritizing the selection and promotion of environmentally friendly toys. Wooden toys, with their traditional appeal and ecological advantages, have regained prominence in the public consciousness and become the preferred choice for many parents when purchasing children's toys.

Early intellectual stimulation plays a pivotal role in child development. As children's primary play partners, caregivers facilitate growth through interactive engagement, with the type of toy directly determining the quality of such interactions (Miao *et al.* 2025). Research demonstrates that electronic toys show significantly poorer performance in promoting parent-child interaction compared to traditional toys (Hassinger-Das *et al.* 2021). Growing research demonstrates toys' significant role in preschoolers' comprehensive cognitive development. When used as interaction mediators between caregivers and children, toys demonstrate excellent performance in promoting intellectual

growth, particularly in language acquisition, problem-solving, and creativity cultivation (Healey *et al.* 2019). Yang *et al.* (2025) found that age-appropriate toys, such as building blocks, can significantly enhance children's cognitive abilities and attentional capacities. Moreover, their structured characteristics not only improve children's focus but also foster spatial reasoning and problem-solving skills. As educational toys help children develop critical abilities such as cognitive thinking and problem-solving, the Indian government has recognized toys' developmental importance and prioritized toy promotion (especially indigenous toys) in its National Education Policy (Saikia *et al.* 2023). Wooden toys are most suitable for children aged 2 to 7 years, corresponding to the preoperational stage in Jean Piaget's theory of cognitive development (Piaget and Cook 1952). According to Piaget's theory, children in the preoperational stage exhibit four key characteristics: (1) emergence of symbolic function (language development), (2) attribution of realistic meaning to behaviors and language, (3) initial manifestations of egocentric thinking, and (4) pretend to play simulating real-world scenarios. However, over 90% of commercially available toys are plastic-based, making plastic toys a major contributor to plastic pollution. The extensive chemical substances in plastic toy materials may pose non-negligible health risks to children, necessitating more thorough investigations into plastic toys and the development of environmentally friendly alternatives (Aurisano *et al.* 2021).

In comparison, wooden toys are regarded as environmentally friendly alternatives to plastic toys due to their natural, non-toxic, and biodegradable properties. Compared with plastic toys, wooden toys involve fewer chemical substances during production, resulting in reduced environmental pollution. Bispo *et al.* (2021) demonstrated that urban forestry pruning waste possesses excellent attributes for manufacturing wooden toys, showing strong potential in environmental, economic, and social sustainability. Bispo *et al.* (2022) comprehensively analyzed the production processes of toys from urban forestry wood waste, evaluating the major challenges and strategies required for optimal performance at each stage, which provides references for producing safe and high-quality wooden toys.

However, despite significant advancements in sustainable production technologies for wooden toys, market acceptance remains a critical challenge. Saini *et al.* (2024) found that Indian buyers exhibit strong preferences for soft toys, electronic toys, and educational toys, with only 5% favoring wooden or green toys. This indicates significant untapped potential and opportunities for green toys, particularly wooden variants, in emerging markets. Notably, while wooden toys demonstrate distinct advantages in environmental protection and child safety, their production process still presents ecological concerns that cannot be overlooked. The production of wooden toys requires substantial timber resources, and improper harvesting practices may further exacerbate the depletion of already overexploited forest resources. Therefore, while promoting the growth of the wooden toy market, ensuring sustainable timber sources has become a critical issue.

This contradiction becomes particularly pronounced against the backdrop of the rapidly expanding global toy market. Market statistics indicate the global toy industry maintains considerable scale and is expected to sustain stable growth. Measured by GMV, the market size increased from RMB 631.2 billion in 2019 to RMB 773.1 billion in 2023, achieving a compound annual growth rate (CAGR) of 5.2% (China Economic Research Institute 2024). As the world's leading toy producer and exporter, China demonstrates clustered production characteristics. As shown in Fig. 1, according to the 2024 White Paper on China's Toy and Juvenile Products Industry released by the China Toy and Juvenile Products Association, China's toy exports (excluding games) reached USD 40.57 billion in 2023. Data from the Research Report on Market Status and Future Trends of China's

Traditional Toy Industry indicates that retail sales of traditional toys in China amounted to approximately RMB 98 billion in 2023, representing an 8.5% year-on-year growth and demonstrating robust market expansion (NewsBites 2024). Yunhe County in Zhejiang Province recognized as "China's Wooden Toy Capital", represents the nation's largest wooden toy production base. According to Yunhe County Government statistics, by the end of 2023, the county housed over 1,000 wooden toy manufacturers. Their products are exported to 82 countries and regions, accounting for 66% of China's and 40% of the global wooden toy market share, establishing Yunhe as China's predominant wooden toy export hub. In this thriving market, China, as the world's largest toy producer and exporter, may provide a significant research paradigm for future eco-commercial balance in wooden toys through its industrial clustering effects.
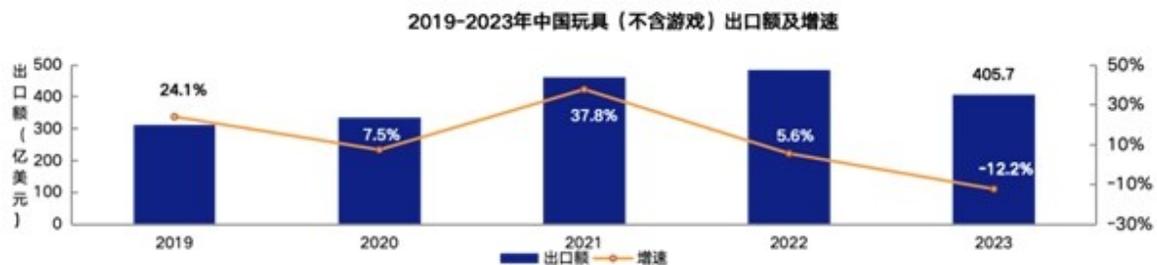

Fig. 1. China's toy exports (excluding games) value and growth rate (2019-2023). Data source: Work Report of the 7th Meeting of the 8th Council of China Toy and Juvenile Products Association

Building on this potential, material selection for wooden toys has emerged as a decisive factor in balancing market demands with sustainability goals. Among viable alternatives, *Paulownia* wood—native to China—has in recent years demonstrated remarkable potential in ecological restoration, timber production, and bioenergy applications (Jakubowski 2022). This potential is due to its unique material properties and fast-growing characteristics, while simultaneously providing innovative solutions for environmentally conscious toy manufacturing. Different *Paulownia* varieties exhibit substantial variations in wood quality, among which *P. catalpifolia*, *P. fortunei*, and *P. tomentosa* are considered premium (Chang *et al.* 2014). Characterized by a lightweight texture, aesthetic grain patterns, crack resistance, and excellent acoustic properties, the wood is widely used in industrial sectors such as furniture manufacturing, musical instrument crafting, handicrafts, and architectural decoration. Li (2009) identified that *Paulownia* wood's lightweight nature (approximately 40% lighter than conventional furniture-grade woods such as oak and pine), combined with its high flexibility, dimensional stability (resistant to warping and cracking), moisture resistance, thermal insulation, and resistance to chemical degradation. These characteristics have established *Paulownia* as a highly valued material for high-end furniture in certain markets, particularly in Japanese traditional craftsmanship, where it is prized for making premium storage furniture due to its lightweight and moisture-resistant properties. Chang *et al.* (2014) conducted a systematic evaluation of seven *Paulownia* species, revealing that *P. fortunei* (white paulownia) exhibits significantly superior performance in key physical properties such as density, hardness, and cleavage strength compared to other varieties. Its density and hardness meet the durability requirements for educational toys, while its uniform grain characteristics fulfill the aesthetic needs for child-safe surface treatments.

These parameters not only provide critical criteria for material selection in wooden toy manufacturing but also offer a solid theoretical foundation and practical reference for current research. In subsequent research, Chang *et al.* (2018) further elucidated the variations in quality demands across global *Paulownia* markets. The study identified specific material requirements in premium Japanese and Western markets, including higher density, uniform grain patterns, and lighter coloration—standards that closely align with the selection criteria for high-quality wooden toys. The finding that 85% of premium *Paulownia* products are exported strongly validates the material's global recognition, while successful case studies in high-end furniture markets demonstrate its broad applicability in quality-sensitive industries.

Paulownia wood's unique characteristics offer tangible advantages in manufacturing processes, making it particularly suitable for precision-crafted products, including children's toys, musical instrument components, and furniture parts. These practical applications have driven the establishment of industrialized *Paulownia* cultivation across major manufacturing regions such as China, Japan, and the United States. A significant portion of the annual *Paulownia* timber output is directly supplied to manufacturers, forming a complete industrial supply chain. According to 2018 data, China's *Paulownia* resources reached approximately 500 million trees, with Henan Province alone accounting for 100 million trees. The standing timber volume was estimated at 50 million m³, yielding an annual production exceeding 5 million m³ (Henan Statistical Yearbook). Globally, Japan maintains about 100 million *Paulownia* trees with a standing volume of 40 million m³. In the United States, primarily distributed across the central-southern regions, cultivated *Paulownia* totals 70 million trees (40 million m³ volume), producing over 1 million m³ annually. South America's *Paulownia* resources, concentrated in Brazil, Paraguay, and Uruguay's plains and foothills, comprise roughly 300 million trees (100 million m³ standing volume), with annual timber output surpassing 3 million m³, including 1 million m³ of *Paulownia* wood (Chang *et al.* 2018).

The furniture manufacturing industry represents the primary market for *Paulownia* wood, with an annual consumption of 1.2 million m³ (Table 1). Decorative materials rank as the second-largest application, accounting for a net timber consumption of approximately 200,000 m³ (equivalent to 600,000 m³ of roundwood) when including domestic Chinese market demand. Notably, 85% of China's *Paulownia* decorative products are exported to Japan, the United States, Australia, Southeast Asia, and Europe (Chang *et al.* 2018). The international market for *Paulownia* demonstrates robust growth potential due to its advantageous characteristics as a fast-growing, renewable, and economically viable timber resource. Its rapid growth cycle and abundant supply position *Paulownia* as an environmentally sustainable alternative to conventional timbers. Large-scale utilization could significantly reduce deforestation of natural forests while meeting the timber demands of developed markets, particularly in Europe and North America.

Table 1. Market Share and Characteristics of *Paulownia* Wood Furniture

Region	Annual consumption (×10⁴ m³)	Demand preferences	Annual output value (×10⁸ RMB)
China	15	High density, high strength	15
Japan	60	Small growth rings, high whiteness	120
Europe	21	High strength, tall trunks	21
USA	24	High strength, tall trunks	24
Total	120		180

Despite the demonstrated material advantages of *Paulownia* wood and its substantial market potential, its actual penetration rate in the toy manufacturing industry remains significantly lower than theoretically projected, revealing a critical gap in translating material superiority into consumer behavior. This discrepancy may stem from a misalignment between consumers' perceived value of *Paulownia* toys and objective materials science evidence, compounded by parents' (as primary decision-makers) limited technical knowledge (Leesakulthip 2009). To address these gaps, this study employs the Fuzzy Analytic Hierarchy Process (F-AHP) to transform technical material parameters into parent-friendly decision metrics while quantifying the actual weight of environmental benefits in purchasing decisions. The resultant predictive model for wooden toy consumption provides empirical support for promoting *Paulownia* in green toy applications. To promote the position of wooden toys in the children's toy market and their environmental contributions, this study analyzes the production process, market demand, and environmental benefits of wooden toys to explore whether *Paulownia* wood possesses substitutive potential. The findings provide scientific guidance for the toy industry and consumers, thereby advancing the development of the green toy market.

Research Objectives and Scope

This study aimed to investigate parental and children's perceived value preferences toward wooden toys and evaluate the feasibility of substituting *Paulownia* wood for conventional high-consumption timber species. The research methodology involves: first identifying 10 traditional high-consumption wood types through systematic analysis, then selecting the two most representative species – ash and beech – for comparative assessment with *Paulownia* wood in terms of perceived value, followed by statistical analysis of collected data. Simultaneously, through questionnaires and expert consultations, five key factors influencing user preferences were determined: surface characteristics, price, usage cycle, environmental friendliness, and suitability. This study aims to explore the positive impact of *Paulownia* wood on the sustainable development of green toys for children. Specifically, the research will provide designers with evidence-based material selection guidelines that fully consider children's sensory needs and preferences. Through this approach, the study is expected to promote wider adoption of eco-friendly toys, thereby reducing environmental damage caused by non-degradable plastics and minimizing health risks associated with chemical substances.

The research objectives are summarized as follows:

(1) investigating parental and children's preferences by comparing perceived value characteristics of ash, beech, and *Paulownia* wood to identify significant differences;

 (2) assessing the feasibility of large-scale *Paulownia* application in toy manufacturing;

(3) applying fuzzy logic methods to analyze preference variations and similarities among the three wood types, offering actionable references for industry stakeholders, designers, and early childhood educators;

(4) focusing specifically on parental and children's value perception of wooden toy materials, with study scope limited to in-person evaluations and physical assessments involving parent-child dyads (children aged 4 to 7 years) to ensure authentic experiences and minimize visual representation biases that could compromise result accuracy.

EXPERIMENTAL

Wood Selection and Research Workflow

The procedure of this study is divided into five phases, spanning from August 20, 2024, to April 3, 2025. Wood species commonly used in furniture, toys, wooden ornaments, and architectural decoration through literature review, national statistical databases, and e-commerce platforms: ash, Manchurian ash, beech, pine, black walnut, camphorwood, poplar, redwood, American basswood, and oak (the China Forestry Statistical Yearbook 2023; China's National Bureau of Statistics 2024). From these, ash and beech were chosen as reference materials alongside *Paulownia* to fabricate three identical gear-whale toys, based on three criteria (Schlotzhauer *et al.* 2019; Dittmar *et al.* 2003; Granier *et al.* 2000; Hu and Li 2021; Feng *et al.* 2022; Hu and Yu 2023):

(1) shared end-use applications (furniture/musical instruments/construction) with substantial market consumption; (2) establishment of a scientific density gradient (low-medium-high) to examine significant material property variations; and (3) clear demonstration of *Paulownia*'s sustainability advantages through comparison with traditional materials (Table 2).

Table 2. Fundamental Logic for Wood Selection

Market Positioning Similarity	Ash and beech are both mid-range commercial woods that share identical target applications (furniture, musical instruments, decorative materials) with *Paulownia*, alongside substantial annual consumption volumes. Selecting these two species carries significant economic and environmental implications for investigating *Paulownia*'s substitutability.
Mechanical Performance Gradient	Selecting ash (bending strength: 118 MPa) and beech (110 MPa) establishes a clear performance benchmark: while *Paulownia*'s bending strength (~35 MPa) is lower, its specific strength (strength/density) is comparable. This comparison objectively evaluates *Paulownia*'s competitiveness in specific applications (*e.g.*, weight-sensitive structural components). All three kinds of wood share good workability, with *Paulownia*'s density (0.25 to 0.35 g/cm³) being significantly lower than ash (0.67 to 0.72 g/cm³) and beech (0.72 g/cm³). This material property comparison can investigate whether *Paulownia* wood possesses advantages in lightweight applications.
Sustainability Verification	*Paulownia*'s rapid growth cycle (5 to 7 years to maturity) contrasts sharply with ash (25 to 30 years) and beech (40 to 60 years). Life Cycle Assessment (LCA) demonstrates its superior environmental performance, aligning with contemporary green material development trends.

Phase 2 recruited parent-child pairs (children from kindergarten/lower elementary grades) for on-site preference testing and questionnaire administration. Phase 3 conducted statistical analysis using SPSS V27. Phase 4 applied fuzzy theory to descriptive statistics and defuzzification. Phase 5 focused on result interpretation and discussion. The complete research framework and workflow are illustrated in Fig. 2.
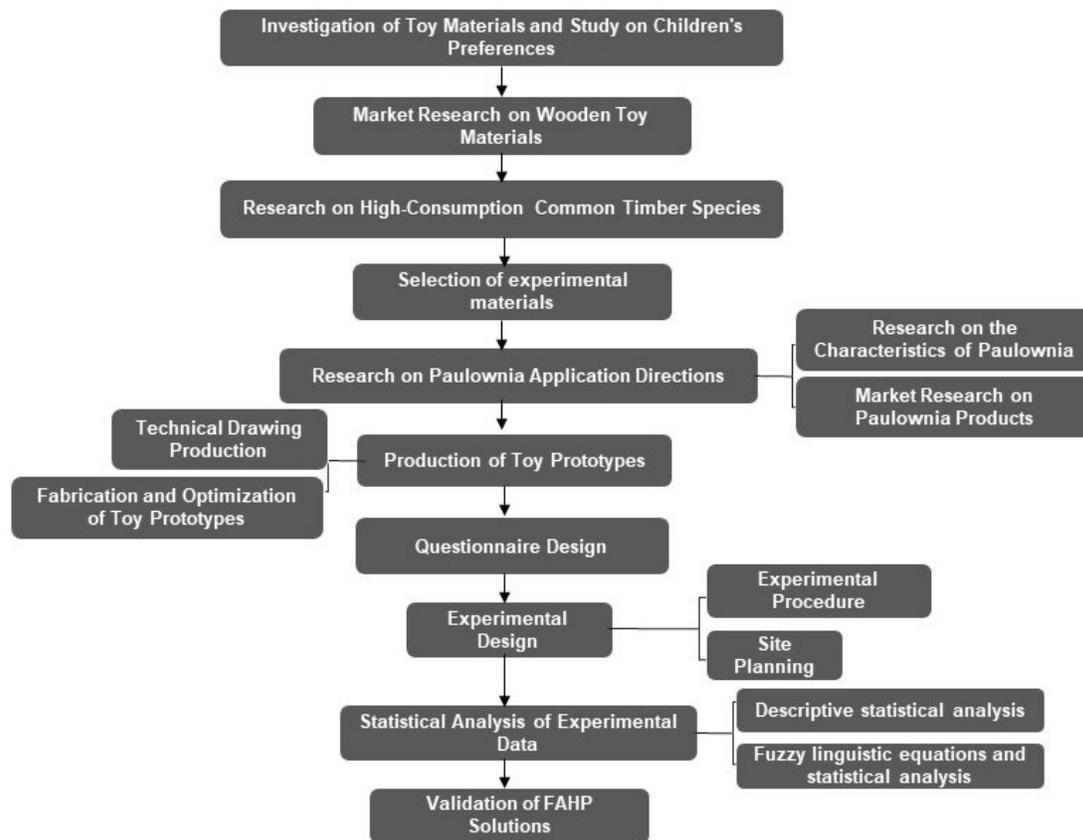
Fig 2. Research framework and flowchart

Method

Fuzzy theory

Fuzzy theory, proposed by Zadeh (1965), quantifies the ambiguity of human subjective evaluations through membership functions, overcoming the limitations of traditional precise numerical measurements. This theory employs triangular fuzzy numbers (a, b, c) to characterize linguistic variables, transforming discrete Likert scale ratings into continuous membership relationships, thereby more accurately capturing the gradational nature of psychological assessments (Li *et al.* 2017; Lin 2002).

This study applied fuzzy linguistic analysis to examine parental and children's preferences for wooden toy characteristics. A fuzzy linguistic scale based on triangular fuzzy numbers was designed to more accurately capture participants' ambiguous and uncertain perceptions.

The research utilized a five-point Likert scale questionnaire to record participants' verbal responses. Statistical analysis was then employed to characterize the relationship between underlying features and the membership degrees of linguistic terms, as illustrated in Fig. 3 (Lee 2014), which demonstrates the interrelations among fuzzy linguistic variables.
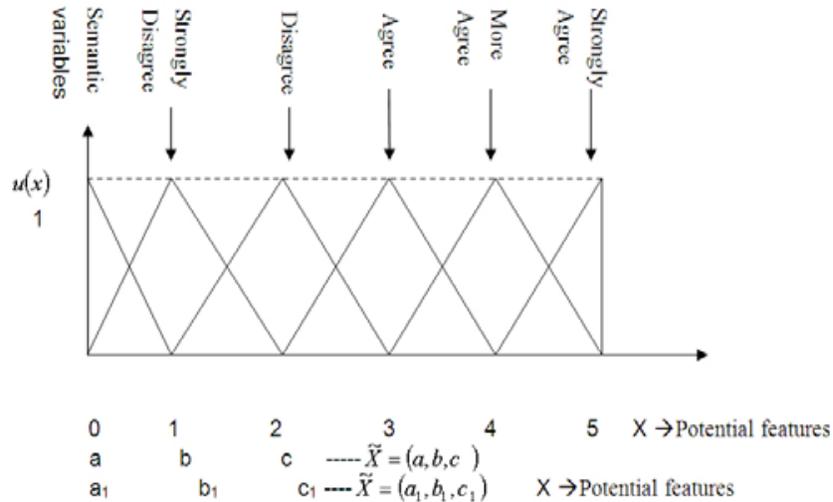
Fig. 3. Triangular membership functions for five-level linguistic variables (The figure is attributed to Lee's (2014) work)

Fuzzy analytic hierarchy process (FAHP)

In addressing complex decision-making problems, the Fuzzy Analytic Hierarchy Process (FAHP) serves as an effective framework integrating fuzzy mathematics with the traditional Analytic Hierarchy Process (AHP), providing robust solutions for multi-criteria decision-making characterized by uncertainty and subjective judgments (Noor *et al.* 2017). While conventional AHP faces limitations in accurately capturing the fuzziness of human cognition through precise numerical values, FAHP overcomes this by incorporating fuzzy set theory to extend crisp numbers in judgment matrices into fuzzy numbers, thereby better representing decision-makers' subjective preferences and uncertainty (Özdağoğlu *et al.* 2007). Kim *et al.* (2020) conducted simulations comparing artificial potential fields, AHP, and FAHP, demonstrating FAHP's superior suitability for mobile robot path planning. Yu *et al.* (2010) developed an FAHP-based evaluation model for medical resource allocation, enabling quantifiable economic feasibility assessments for medical equipment procurement and upgrades. Zhu and Ma (2012) established a four-dimensional service quality evaluation system (service attitude/competence, pricing, outcomes, and management) for private express enterprises, with FAHP validation confirming its practical value.

Defuzzification of triangular fuzzy numbers

The questionnaire in this study used a five-point Likert scale to express participants' verbal responses, where 1 represents "strongly disagree", 2 represents "disagree", 3 represents "agree", 4 represents "more agree", and 5 represents "strongly agree". However, using traditional Likert scales to measure respondents' psychological perceptions is overly simplistic because they may have ambiguous feelings toward similar linguistic descriptions. Consequently, the fuzzy linguistic scale of the questionnaire was divided into 5 levels and 50 sub-levels and defuzzified according to the four steps of the fuzziness processing system proposed by Klir and Yuan (1996): (1) fuzzification mechanism (data input); (2) fuzzy rule base (data processing); (3) fuzzy inference engine (fuzzy inference); and (4) defuzzification (data output). This study processed the fuzzy linguistic data from parent-child perceptual preference questionnaires on wooden toys through the following methodological steps:

Step 1 (fuzzification mechanism): Triangular fuzzy numbers (TFNs) were employed to quantify parental and children's linguistic evaluations of perceived value across wooden toy materials, capturing the inherent ambiguity in sensory assessments.

Step 2 (fuzzy rules): triangular fuzzy numbers were assigned to five linguistic variables: "strongly disagree", "disagree", "agree", "more agree", and "strongly agree". Using $C\rho$ to denote the anticipated triangular fuzzy numbers, the values were set as (0,0,1), (0,1,2), (1,2,3), (2,3,4), and (3,4,5), respectively. Following Lee's (2014) methodology, these values were converted by dividing by 10, resulting in transformed $C\rho$ values ranging between 0 and 1. The converted triangular fuzzy numbers $\tilde{X}$ were then defined as the following intervals:

$\tilde{X}$ = (0,0,0.1), (0,0.1,0.2), (0.1,0.2,0.3), (0.2,0.3,0.4), (0.3,0.4,0.5), (0.4,0.5,0.6), (0.5,0.6,0.7), (0.6,0.7,0.8), (0.7,0.8,0.9), (0.8,0.9,1),
representing sub-levels of the five linguistic phrases. This configuration establishes a triangular fuzzy linguistic variable system with five main levels and fifty sub-levels.

Step 3 (Fuzzy inference engine): The minimax method was applied to analyze the membership function graphs of wood perception value preferences and implement fuzzy inference for wooden toy perceptual value evaluation.

Step 4 (Defuzzification): Based on Lee's (2014) research, the fuzzy semantic average equation, this study derived the triangular fuzzy number (Fig. 6).

Moreover, the *X* defuzzification formula is as follows:

Assuming $\tilde{X}$ (t_1, t_2, t_3), $C\rho = (t_1 + 2t_2 + t_3)/4 \times 10$, the following equation is deduced from the fuzzy descriptive equation of the fuzzy linguistic questionnaire.

$$C\rho = (t_1 + 2t_2 + t_3)/4 \times 10 \tag{1}$$

It was converted then to a fuzzy linguistic mean.

$$\text{Fuzzy Linguistic Mean} = \sum_1^n (t_1 + 2t_2 + t_3)/4N \times 10 \tag{2}$$

where *N* is the number of participants.

Wooden Toy Consumption Influence Factors Indicators

Basic characteristics of the purchasing process

The offline purchasing process for wooden toys typically involves consumers visiting physical stores to experience products firsthand, receiving shopping guidance from the sales staff, consulting children's preferences, completing on-site payment, and either waiting for store preparation or taking immediate delivery, with its key features being the direct product experience that ensures accurate perception and the ability to incorporate children's feedback during purchase.

Consumption influence factor index determination method

Establishing an indicator system for wooden toy purchase influencing factors serves as the foundational premise of this study. First, a comprehensive review of the literature was conducted to systematically identify factors affecting wooden toy consumption. Early research (Christensen and Stockdale 1991) revealed six core criteria for parental toy selection: educational value, craftsmanship, parental appeal, versatility and child appeal, and value transmission. Notably, the study found that while educational value is universally emphasized, parents often adjust their priorities based on perceived craftsmanship during actual decision-making. Recent studies by Setiani *et al.* (2023), grounded in the Theory of Planned Behavior, further demonstrated that parental purchasing

decisions are significantly influenced by perceived behavioral control, attitudes, subjective norms, perceived value for money, and perceived product quality. Among these, perceived product quality has been deconstructed as a multidimensional concept (Lee and Jin 2019), encompassing performance, functionality, reliability, consistency, specialized design, durability, maintainability, and aesthetics. Of particular significance is the growing emphasis on environmental sustainability and health safety in toy selection. Aurisano *et al.* (2021) highlighted the potential negative environmental and child health impacts of plastic toys, thereby expanding the dimensions of perceived product quality. Tu *et al.* (2022) investigated the decision-making factors for eco-friendly toys by analyzing the complete life cycle of children's toys, based on their characteristically short usage periods and high pollution rates.

Building upon these theoretical foundations and contemporary concerns, the present research adopted a two-phase methodological approach to transform qualitative insights into measurable indicators. First, researchers applied the Analytic Hierarchy Process (AHP) to analyze five purchase stages: need recognition, search for information, alternatives evaluation, purchase decision, and post-purchase behavior, deriving a preliminary indicator framework (Oblak *et al*. 2017). The Delphi Method was subsequently employed to collect expert opinions and finalize core indicators (Brady 2015), clarifying the fundamental aspects and constituent factors of wooden toy selection. To ensure objective and accurate results, this study engaged reliable participants across multiple domains, including child psychologists, toy designers, educators, marketing professionals, and consumers. The final factors were refined by synthesizing cross-industry feedback and referencing existing literature-based indicator systems.

Judgment index establishment

Through the aforementioned methodology, five key indicators for wood material selection were identified: surface characteristics, price, durability, environmental friendliness, and suitability (Table 3).

Experimental Setup

This study was formally approved by the Ethics Review Committee of the College of Furnishings and Industrial Design at Nanjing Forestry University (Approval No. 2025028). The approval process included: (1) submission of the research protocol, anonymized questionnaire, and informed consent documents; (2) committee evaluation confirming minimal risk (non-interventional preference survey); (3) approval in accordance with China's *"Ethical Review Measures for Research Involving Human Subjects" (2023)* and the *General Data Protection Regulation (GDPR) 2018* requirements. All participants provided signed informed consent, with additional parental consent required for children. The research strictly adhered to data anonymization protocols to ensure participant privacy protection.

The experiment was divided into five components:

(1) Participants: This study included 53 parent-child dyads (each comprising one child and one parent), recruited through stratified sampling from multiple channels, including kindergartens, community centers, online parenting forums, and wooden toy stores. Eligible parents were required to be primary caregivers with prior experience in purchasing wooden toys, while children needed to be capable of completing simplified assessments with parental assistance. The sampling framework ensured diversity across

household income levels, geographical distribution (urban-rural differences), and parental educational backgrounds to capture real-world decision-making variation.

Table 3. Criteria for Judgment Index Selection

Index	Evaluation Basis
Surface Characteristics	Wooden toys directly contact children's skin, making surface characteristics critically important. *Paulownia* wood features a lightweight and soft texture that is easy to polish, providing a mild tactile sensation; ash wood displays clear grain patterns but has a harder texture that may require additional treatment to achieve ideal tactile qualities; while beech wood offers fine texture, it tends to develop micro-cracks after drying. This evaluation metric primarily examines the natural tactile properties and safety of these three wood types in their untreated state.
Price	As consumable products, cost control is particularly crucial for toys. *Paulownia* wood, being a fast-growing species, has raw material costs of only 1/3 that of ash wood and 1/4 that of beech wood. Its low-density characteristics significantly reduce processing energy consumption. In comparison, the higher prices of ash and beech woods may ultimately be passed on to consumers, potentially affecting market acceptance. This metric will quantitatively compare the full lifecycle costs of all three wood types.
Usage Cycle	In modern parenting practices, the high replacement frequency of toys means excessive durability may lead to resource underutilization. While *Paulownia* wood has a relatively lower hardness, it fully meets the strength requirements for typical toy usage, and its natural biodegradability aligns with eco-friendly principles. In contrast, the superior durability of ash and beech woods often results in these toys becoming "permanently idle" after children's interests shift. This evaluation metric specifically assesses how well each wood type matches reasonable product lifecycles.
Environmental Impact	*Paulownia* wood reaches harvest maturity in just 5 to 7 years with high carbon sequestration efficiency and readily biodegrades after disposal. In contrast, ash wood requires pesticide treatments due to pest susceptibility, while beech wood demands decades-long growth cycles. Life Cycle Assessment (LCA) results demonstrate *Paulownia*'s significantly lower carbon footprint compared to these alternative species. This metric will analyze environmental impacts across the complete product lifecycle from raw material acquisition to end-of-life disposal.
Suitability	The lightweight characteristics of *Paulownia* wood (density: 0.25-0.35 g/cm³) make it particularly suitable for young children: toys of identical volume made from *Paulownia* weigh only 1/3 of those made from ash wood, reducing drop-impact risks while improving grip comfort. Conversely, the greater weight of ash and beech wood not only hinders children's manipulation but also presents potential safety concerns. This evaluation metric focuses on assessing the alignment between wood's physical properties and children's usage requirements.

(2) Location: University research classroom

(3) Materials and props:

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bioresources.cnr.ncsu.edu

Three numbered wooden gear whale toys were used as samples, labeled from left to right as A: ash wood, B: beech wood, and C: *Paulownia* wood. All components maintained consistent thickness and received no special treatment to preserve the natural wood aroma and texture (Fig. 4).

Fig. 4. Experimental samples: (A) *Fraxinus*, (B) *Fagus*, and (C) *Paulownia*

(4) Experimental procedure and questionnaire:

The testing area was divided into two sections: the left side served as the observation and tactile evaluation zone, equipped with a sample display platform showcasing three wooden gear whale toys (made of ash, beech, and *Paulownia* wood) for parent-child pairs to freely observe and touch; the right side functioned as the questionnaire assessment area, furnished with standardized questionnaires and auxiliary tools (Fig. 5). Only one test group was permitted in the area at a time to minimize external interference. Parents provided comprehensive evaluations based on both children's feedback and their judgments across different dimensions, while researchers recorded the results on questionnaires simultaneously. The specific procedure was as follows:

(i) Pre-experiment Training:

Before the experiment, materials science researchers provided a standardized 5-minute briefing covering:

Q1 (Surface Characteristics): Demonstrated differences in wood grain, color, and luster among the three wood types (ash, beech, *Paulownia*), explaining the formation and visual traits of natural wood patterns. Participants rated their preference for each wood's surface features.

Q2 (Price): Presented market prices of the three woods; participants evaluated affordability based on their economic status.

Q3 (Usage Cycle): Illustrated methods to assess durability *via* wood hardness and density. Higher-density woods feel heavier—participants compared samples to a 100 g reference weight. Hardness was tested *via* nail-scratch resistance. Participants were prompted to consider whether excessive durability aligns with toy lifespans.

Q4 (Eco-Friendliness): Shown tree-ring comparison charts to infer attributes through tactile/visual cues. Researchers explained that faster-growing woods (lighter/softer, wider rings, rougher longitudinal texture) are more sustainable due to rapid renewability and lower environmental impact from harvesting.

Q5 (Suitability): Participants evaluated the flexibility and play experience of wooden toys to assess the materials' suitability for toy applications.

(ii) Real-Time Assessment Support:

During on-site evaluations, uniformly trained research assistants in the

questionnaire area provided rational explanations and guidance to aid participants in completing surveys.

(iii) Standardized Auxiliary Tools:

The observation area was equipped with standardized auxiliary tools, including information boards, comparative charts of the three wood types' biological characteristics, simplified explanations of environmental indicators, and reference data on the typical lifespan ranges of common toy materials. The charts visually highlighted key differences in growth patterns and cellular structures among the wood species, while the environmental indicators employed universally recognizable icons to communicate sustainability metrics. Lifespan references provided contextual benchmarks for durability assessments, displayed alongside actual wear-and-tear samples to enhance perceptual accuracy.

Fig. 5. Experimental Setup

Experimental Procedure

The experimental process was systematically divided into five key steps, with detailed descriptions of each stage provided below (Fig. 6).
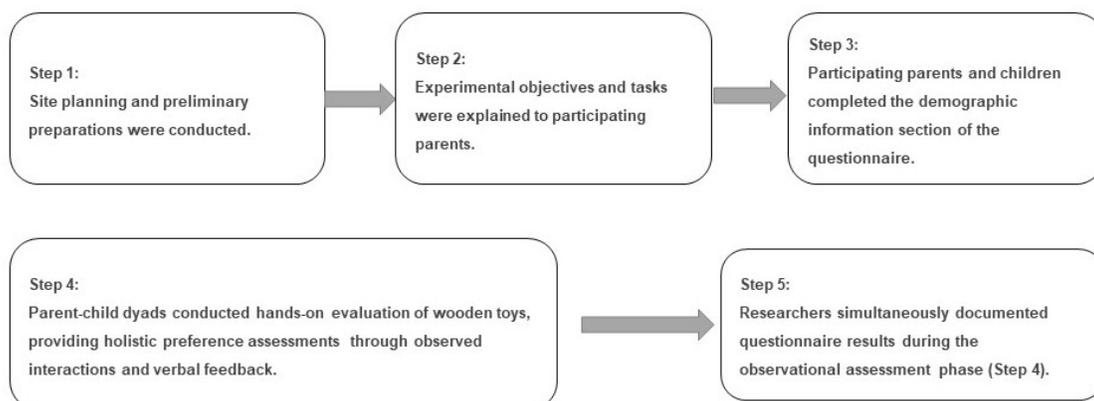

Step 1:
Site planning and preliminary preparations were conducted.

Step 2:
Experimental objectives and tasks were explained to participating parents.

Step 3:
Participating parents and children completed the demographic information section of the questionnaire.

Step 4:
Parent-child dyads conducted hands-on evaluation of wooden toys, providing holistic preference assessments through observed interactions and verbal feedback.

Step 5:
Researchers simultaneously documented questionnaire results during the observational assessment phase (Step 4).

Fig. 6. Experimental workflow

Questionnaire design

The questionnaire design in this study was mainly divided into three parts: the first part concerned the basic information of the respondents, the second part concerned consumers' preference tendencies for children's toys, and the third part concerned

consumers' views on the application of *Paulownia* wood in wooden toys. The fuzzy semantic dimensions of consumers' perceived value of furniture product design characteristics were "strongly disagree", "disagree", "agree", "more agree", and "strongly agree", respectively. The main data collection part consists of opinions and evaluations of the perceived value of the three types of wood, as shown in Table 4.

Table 4. Subjective Evaluations and Perceived Value Assessments of Wood Materials

The second part of the questionnaire: This part is for your opinions and evaluation of product design features, including distinction, integration, and interaction. Please answer the following questions according to your subjective feelings. "Strongly Agree" is Level 5, and the score ranges from 4.1 to 5, a total of 10 equal portions. "More Agree" is Level 4, and the score ranges from 3.1 to 4, a total of 10 equal portions. "Agree" is Level 3, and the score ranges from 2.1 to 3, a total of 10 equal portions. "Disagree" is Level 2, and the score ranges from 1.1 to 2, a total of 10 equal portions. "Strongly Disagree" is Level 1, and the score ranges from 0.1 to 1, a total of 10 equal portions. In total, there are 50 equal portions. Please score the level you select according to your opinions and evaluation. In the display of the fuzzy semantic scale, 4.8 and 4.4, for instance, both belong to Level 5, but they differentiate the score more delicately.					
Survey Questionnaire on Perceived Value Preferences for Wooden Toys	L1	L2	L3	L4	L5
Q1 Surface Characteristics: The color, grain, texture, and scent of the wood make me and my child feel comfortable.					
Q2 Price: The price of the wood should be within an acceptable range.					
Q3 Usage Cycle: The selected wood should match the expected lifespan of the toy.					
Q4 Environmental Friendliness: The use of wood should demonstrate environmental sustainability.					
Q5 Suitability: The physical properties of the wood (e.g., weight) should align with children's current physiological capabilities, making it easy for them to handle.					

ANALYSIS OF STATISTICAL RESULTS

Based on the results obtained from the on-site experimental observation and the questionnaire survey records, this study conducted a descriptive statistical analysis and a fuzzy linguistic analysis using SPSS (Version 27; IBM). The statistical analysis results were obtained according to the following analysis steps and content:

Reliability and Validity

Reliability analysis was performed on the evaluation scores of the five indicators for ash, beech, and *Paulownia* wood. The results demonstrated good internal consistency, with Cronbach's alpha coefficients of 0.889 for ash, 0.832 for beech, and 0.834 for *Paulownia*, all well above the conventional threshold of 0.7 for acceptable reliability (see Table 5).

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Table 5. Questionnaire Reliability Analysis

Item	Cronbach's α Value
Ash	0.889
Beech	0.832
Paulownia	0.834

Results of the Descriptive Statistical Analysis

Descriptive statistical analysis was conducted using one-sample t-tests, yielding the following results for preference mean values. As shown in Fig. 7, among the three types of wood, beech wood had the highest mean preference score for Q1 surface characteristics (M=4.01, SD=0.30, t(53)=4.00, p<0.05, Cohen's d = 0.55, 95% CI [0.26, 0.84]); beech wood also showed the highest mean preference for Q2 price (M=3.77, SD=0.30, t(53)=4.21, p<0.05, Cohen's d = 0.58, 95% CI [0.29, 0.87]); *Paulownia* wood demonstrated the highest mean preference for Q3 usage cycle (M=3.69, SD=0.40, t(53)=3.90, p<0.05, Cohen's d = 0.54, 95% CI [0.25, 0.82]); *Paulownia* wood exhibited the highest mean preference for Q4 environmental friendliness (M=3.73, SD=0.32, t(53)=4.01, p<0.05, Cohen's d = 0.55, 95% CI [0.26, 0.84]); and *Paulownia* wood displayed the highest overall mean preference for Q5 suitability (M=3.72, SD=0.34, t(53)=4.1, p<0.05, Cohen's d = 0.57, 95% CI [0.27, 0.86]).

The one-sample t-test analysis in this study revealed distinct consumer preference patterns among the three wood types across various evaluation dimensions. The statistical results demonstrate:

1. Beech wood showed significant advantages in both Q1 surface characteristics (M=4.01) and Q2 price (M=3.77) dimensions. The effect sizes (Cohen's d=0.55-0.58) reached moderate levels, with confidence interval lower bounds all exceeding 0.25, indicating these preferences have practical significance.

2. *Paulownia* wood received the highest preference ratings for Q3 usage cycle (M=3.69), Q4 environmental friendliness (M=3.73), and Q5 overall suitability (M=3.72). All dimensions showed moderate effect strengths (d=0.54-0.57) with similar 95% confidence interval ranges ([0.25,0.82] to [0.27,0.86]), demonstrating result consistency.
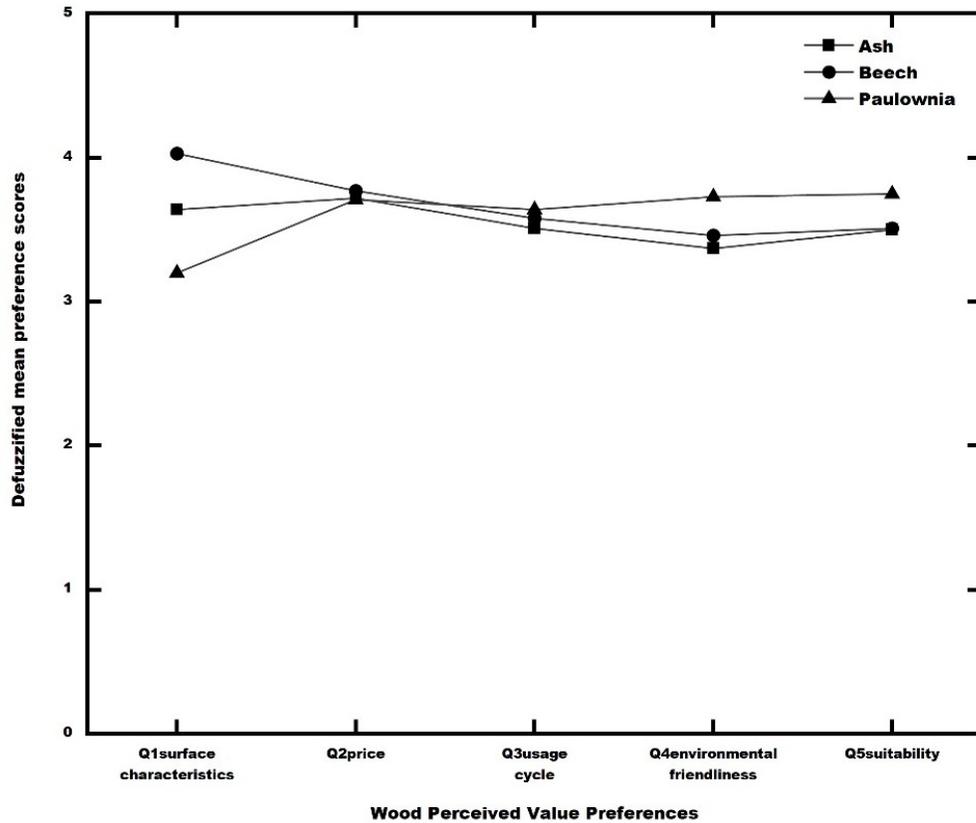
Fig. 7. The overall mean of each characteristic by one-sample t-test

3. All test results reached statistical significance ($p<0.05$), with relatively small standard deviations (0.30 to 0.40), reflecting concentrated data distributions and stable measurements. The effect size estimates all exceeded the 0.5 threshold for moderate effects, and the confidence intervals excluding zero suggest these preference differences possess both statistical and practical significance.

Notably, while all dimensions showed moderate effect strengths, the relatively wide confidence interval ranges (spanning approximately 0.6) suggest that future studies could improve estimation precision by increasing sample size. Overall, these findings provide quantitative evidence for understanding consumer preference patterns regarding different wood characteristics, offering valuable insights for product development and market positioning.

Fuzzy Linguistic Statistical Analysis

This study also converted each fuzzy number into a triangular fuzzy number after defuzzification and obtained the result after the fuzzy operation and the triangular fuzzy number analysis. Table 6 shows the maximum upper limit added by fuzzy operation, the overall mean, and the minimum lower limit of the preference for the surface characteristics of each type of wood. Figure 8 presents the mean scores of the three wood types across five evaluation dimensions.
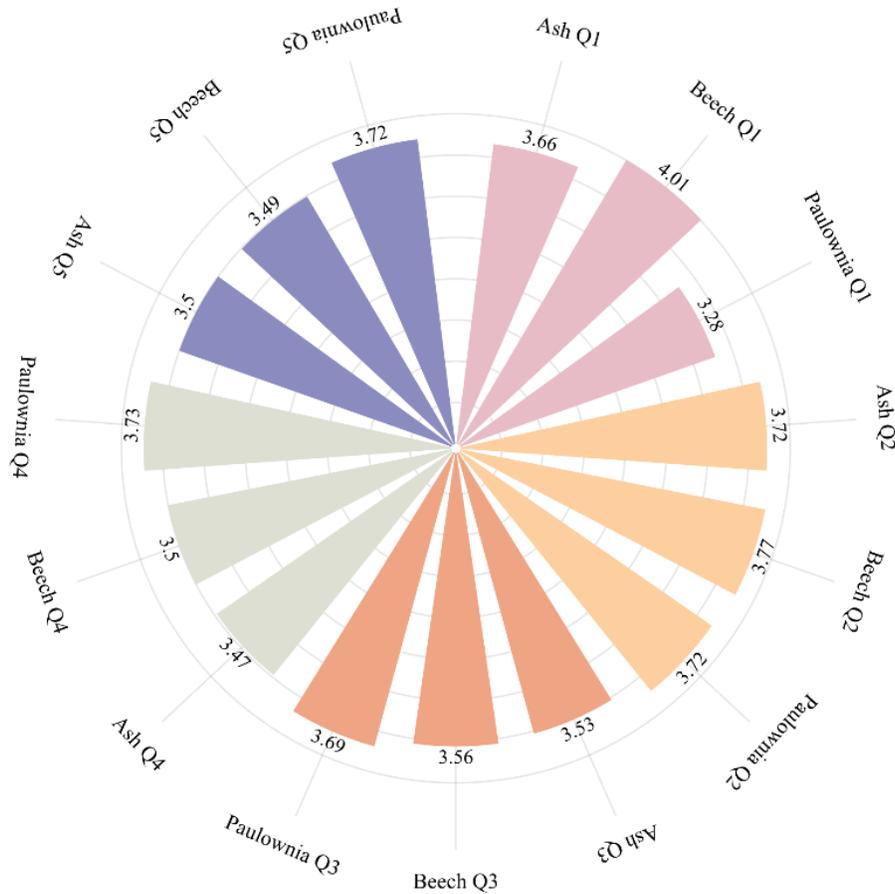
Fig. 8. Evaluation scores of Ash, Beech, and *Paulownia* across five assessment dimensions

Table 6. Fuzzy Means of Children's Preference for Wood Characteristics.

Wood Type	Ash			Beech			*Paulownia*		
Wood Perceived Value Preferences	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Q1 surface characteristics	3.2	3.66	4.4	3.5	4.01	4.7	2.8	3.28	4.2
Q2 price	3.4	3.72	4.4	3.4	3.77	4.5	3.3	3.72	4.6
Q3 usage cycle	3.0	3.53	4.3	3.0	3.56	4.4	3.0	3.69	4.5
Q4 environmental friendliness	3.1	3.47	4.2	3.1	3.50	4.2	3.2	3.73	4.4
Q5 suitability	3.0	3.50	4.3	3.0	3.49	4.3	3.2	3.72	4.5

Expert Validation

This study employed Fuzzy AHP for solution validation, incorporating the research findings obtained by Sui in 2000. The results demonstrated that the *Paulownia* wood toy solution exhibited the best comprehensive performance across all five evaluation indicators.

Triangular Fuzzy Judgment Matrix

Triangular fuzzy numbers (l, m, u), and were utilized to quantitatively represent experts' comparative judgments regarding the relative importance between two indicators. The median value m was determined based on the AHP's 1-9 scaling method, while the lower bound l and upper bound u of the triangular fuzzy numbers were established

according to the degree of fuzziness. A larger $u - l$ interval indicates fuzzier judgments, whereas a smaller $u - l$ interval reflects clearer judgments. When $u - l = 0$, the judgment becomes non-fuzzy, with $l = m = u$, equivalent to conventional judgment scale values (Tables 7 and 8).

Table 7. Meaning of Triangular Fuzzy Number Median Values (1-9 Scale)

Median Value	Interpretation
1	Indicates equal importance between two compared indicators
3	Slightly favors the former indicator over the latter
5	Demonstrates significantly stronger importance of the former indicator
7	Shows the strongly dominant importance of the former indicator
9	Represents the extreme dominance of the former indicator
2,4,6,8	Intermediate values between adjacent judgments

Table 8. Boundary Value Determination Criteria for Triangular Fuzzy Numbers

Confidence Level	$u - l$ Value	Numerical Characteristics	Score Interpretation
High	1	(max(m-1/2,1), m, min(m+1/2,9))	Expert scoring exhibits minimal fuzziness
Moderate	2	(max(m-1,1), m, min(m+1,9))	Expert scoring demonstrates intermediate fuzziness
Low	3	(max(m-3/2,1), m, min(m+3/2,9))	Expert scoring shows significant fuzziness

Triangular Fuzzy AHP Calculation Procedure

The triangular fuzzy judgment matrix was constructed as follows,

$$A = \left(a_{ij}\right)_{n \times n.} \tag{3}$$

where $a_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$; a_{ij} is a closed interval with m_{ij} as its median value.

After conducting a consistency check for the median matrix M, the maximum eigenvalue λ_{max} of the median matrix M was calculated. The λ_{max} value was substituted into the following formula to compute CI,

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

The RI table of corresponding order was used to obtain the RI value (Table 9). The CR value was calculated by Eq. 5. If $CR < 0.1$, the consistency check is passed.

$$CR = CI/RI \tag{5}$$

Table 9. Consistency Test RI chart

Matrix Order	1	2	3	4	5	6	8	9	7	10
RI	0	0	0.52	0.9	1.12	1.26	1.41	1.46	1.36	1.49

The Fuzzy Evaluation Factor Matrix E was constructed as follows,

$$E = \left(e_{ij}\right)_{n \times n} = \begin{bmatrix} 1 & 1 - \frac{u_{12}-l_{12}}{2m_{12}} & \cdots & 1 - \frac{u_{1n}-l_{1n}}{2m_{1n}} \\ 1 - \frac{u_{21}-l_{21}}{2m_{21}} & 1 & \cdots & 1 - \frac{u_{2n}-l_{2n}}{2m_{2n}} \\ \vdots & \vdots & \vdots & \vdots \\ 1 - \frac{u_{n1}-l_{n1}}{2m_{n1}} & 1 - \frac{u_{n2}-l_{n2}}{2m_{n2}} & \cdots & 1 \end{bmatrix} \quad (6)$$

where $e_{ij} = \frac{u_{ij}-l_{ij}}{2m_{ij}}$ represents the coefficient of variation (standardized dispersion ratio)

Calculation of the Adjusted Judgment Matrix Q

$$Q = M \times E = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{bmatrix} \times \begin{bmatrix} 1 & 1 - \frac{u_{12}-l_{12}}{2m_{12}} & \cdots & 1 - \frac{u_{1n}-l_{1n}}{2m_{1n}} \\ 1 - \frac{u_{21}-l_{21}}{2m_{21}} & 1 & \cdots & 1 - \frac{u_{2n}-l_{2n}}{2m_{2n}} \\ \vdots & \vdots & \vdots & \vdots \\ 1 - \frac{u_{n1}-l_{n1}}{2m_{n1}} & 1 - \frac{u_{n2}-l_{n2}}{2m_{n2}} & \cdots & 1 \end{bmatrix} \quad (7)$$

The adjusted judgment matrix Q was transformed into a diagonal-normalized matrix Q'. The indicator weights were calculated using the eigenvalue method.

Computing the nth root of all elements in each row produced Eq. 8.

$$\overline{\omega}_i = \left(\prod_{j=1}^n a_{ij}\right)^{\frac{1}{n}}, \quad i = 1,2,\cdots,n \quad (8)$$

Normalizing the weight vector $\overline{\omega}_i$ led to Eq. 9.

$$\omega_i = \frac{\overline{\omega}_i}{\sum_{i=1}^n \overline{\omega}_i}, \quad i = 1,2,\cdots,n \quad (9)$$

The final weights were derived by Eq. 10.

$$W = [\omega_1, \omega_2, \cdots, \omega_n] \quad (10)$$

Verification Process

This study employed triangular fuzzy Analytic Hierarchy Process (AHP) for triangulation validation, with three experts in industrial design (including two full professors and one associate professor) participating in the scoring. The expert selection criteria included: (1) nationally certified product engineer qualifications, (2) leadership in at least five wooden toy development projects, and (3) familiarity with wood properties and child product safety standards.

To mitigate subjective bias, the Delphi method was implemented for three rounds of blind evaluations. The initial assessment yielded a Kendall's coefficient of concordance of 0.82, which improved to 0.91 after video conference discussions on divergent indicators, with all consistency ratios (CR) of judgment matrices maintained below 0.1. Expert weights were determined through an entropy-weighted method based on historical project accuracy rates (Experts 1-3: 92%/85%/78% respectively), integrated with positional weights (Professor: Associate Professor = 1.5:1; Professor vs. Engineer = 2:1) and professional experience (15/12/10 years), and finally optimized via TOPSIS to establish weights of 0.5, 0.3, and 0.2.

All experts were weighted based on qualifications and other criteria. If no weighting is required, all experts have equal weights.

$$W_{zj} = [w_1, w_2, \ldots, w_m] \tag{11}$$

Satisfying：

$$w_1 + w_2 + \ldots + w_m = 1 \tag{12}$$

All expert questionnaires were processed using triangular fuzzy AHP, and the resulting weights were integrated to form the weight matrix, where each row represents the weight vector obtained from an expert's matrix.

$$W_{wj} = \begin{bmatrix} w_{11} & w_{12} & \ldots & w_{1n} \\ w_{21} & w_{22} & \ldots & w_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ w_{m1} & w_{m2} & \ldots & w_{mn} \end{bmatrix} \tag{13}$$

The $1 \times m$ expert weight vector is multiplied by the $m \times n$ weight matrix to yield a $1 \times n$ weighted indicator vector.

$$W = W_{zj} \cdot W_{wj} = [W_1, W_2, \ldots, W_n] \tag{14}$$

Table 10. Expert 1's Criterion Layer Judgment Matrices

	Surface Characteristics	Price	Usage Cycle	Environmental Friendliness	Suitability
Surface Characteristics	1	3-1	5-2	1/3-1	7-2
Price	1/3-1	1	3-1	1/5-1	5-2
Usage Cycle	1/5-2	1/3-1	1	1/7-2	3-1
Environmental Friendliness	3-1	5-1	7-2	1	9-1
Suitability	1/7-2	1/5-2	1/3-1	1/9-1	1
λ_{max}= 5.237, CI = 0.059, RI = 1.12, CR = 0.053 < 0.1					

Table 11. Expert 2's Criterion Layer Judgment Matrices

	Surface Characteristics	Price	Usage Cycle	Environmental Friendliness	Suitability
Surface Characteristics	1	2-1	4-2	1/2-1	6-2
Price	1/2-1	1	3-1	1/3-1	5-2
Usage Cycle	1/4-2	1/3-1	1	1/5-2	4-1
Environmental Friendliness	2-1	3-1	5-2	1	7-1
Suitability	1/6-2	1/5-2	1/4-1	1/7-1	1
λ_{max} = 5.195, CI = 0.049, RI = 1.12, CR = 0.043 < 0.1					

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Table 12. Expert 3's Criterion Layer Judgment Matrices

	Surface Characteristics	Price	Usage Cycle	Environmental Friendliness	Suitability
Surface Characteristics	1	4-2	6-2	1/3-1	8-2
Price	1/4-2	1	3-1	1/5-1	6-2
Usage Cycle	1/6-2	1/3-1	1	1/7-2	4-1
Environmental Friendliness	3-1	5-1	7-1	1	9-2
Suitability	1/8-2	1/6-2	1/4-1	1/9-2	1
λ_{max}= 5.382, CI = 0.095, RI = 1.12, CR = 0.085 < 0.1					

Calculation results of the criterion layer judgment matrix and weight vectors (ω)

The consistency check passed for the criterion layer judgment matrix of Experts 1, 2, and 3 (Tables 10, 11, and 12).

The judgment matrices provided by the three experts were processed using a weighted average method based on expert weights, yielding the following calculated results for the criterion layer weight vector, as shown in Table 13.

Table 13. Calculation Results of Criterion Layer Weight Vectors

	Surface Characteristics	Price	Usage Cycle	Environmental Friendliness	Suitability
Expert 1	0.284721686	0.166430939	0.08190036	0.435638044	0.031308971
Expert 2	0.275896241	0.201698722	0.11961089	0.366620232	0.036173915
Expert 3	0.31086087	0.169214521	0.091773564	0.401331862	0.026819182
Weighted result of the weight vectors: (ω):	0.287	0.178	0.095	0.408	0.032

Calculation results of the alternative layer judgment matrix and weight vectors (υ)

For Expert 1, 2, and 3, all alternative layer judgment matrices passed the consistency check (Tables 14, 15, and 16).

Table 14. Expert 1's Alternative Layer Judgment Matrices

Variable	Species	Ash	Beech	*Paulownia*
Surface Characteristics	Ash	1	1/2-1	2-1
	Beech	2-1	1	3-1
	Paulownia	1/2-1	1/3-1	1
Price	Ash	1	2-1	1/3-2
	Beech	1/2-1	1	1/4-1
	Paulownia	3-2	4-1	1
Usage Cycle	Ash	1	2-1	1/2-1
	Beech	1/2-1	1	1/3-2
	Paulownia	2-1	3-2	1
Environmental Friendliness	Ash	1	2-2	1/4-1
	Beech	1/2-2	1	1/5-2
	Paulownia	4-1	5-2	1
Suitability	Ash	1	2-1	1/2-2
	Beech	1/2-1	1	1/3-1
	Paulownia	2-2	3-1	1

Table 15. Expert 2's Alternative Layer Judgment Matrices

Variable	Species	Ash	Beech	*Paulownia*
Surface Characteristics	Ash	1	1/3-1	3-2
	Beech	3-1	1	4-1
	Paulownia	1/3-1	1/4-1	1
Price	Ash	1	1-2	1/2-1
	Beech	1-2	1	1/3-1
	Paulownia	2-1	3-1	1
Usage Cycle	Ash	1	1-2	1/2-1
	Beech	1-2	1	1/3-1
	Paulownia	2-1	3-1	1
Environmental Friendliness	Ash	1	1-1	1/3-2
	Beech	1-1	1	1/4-1
	Paulownia	3-2	4-1	1
Suitability	Ash	1	1-2	1/2-1
	Beech	1-2	1	1/2-2
	Paulownia	2-1	2-2	1

Table 16. Expert 3's Alternative Layer Judgment Matrices

Variable	Species	Ash	Beech	*Paulownia*
Surface Characteristics	Ash	1	1/2-1	2-2
	Beech	2-1	1	3-1
	Paulownia	1/2-1	1/3-1	1
Price	Ash	1	2-1	1/3-2
	Beech	1/2-1	1	1/5-1
	Paulownia	3-2	5-1	1
Usage Cycle	Ash	1	1-1	1/2-2
	Beech	1-1	1	1/3-1
	Paulownia	2-2	3-1	1
Environmental Friendliness	Ash	1	2-1	1/3-2
	Beech	1/2-1	1	1/6-1
	Paulownia	3-2	6-1	1
Suitability	Ash	1	1-1	1/2-2
	Beech	1-1	1	1/2-1
	Paulownia	2-2	2-1	1

The judgment matrices provided by the three experts were processed using a weighted average method based on expert weights, yielding the following calculated results for the alternative layer weight vector (Table 17).

Table 17. Calculation Results of Criterion Layer Weight Vectors

Species	Surface Characteristics	Price	Usage Cycle	Environmental Friendliness	Suitability
Ash	0.31	0.217	0.269	0.212	0.280
Beech	0.542	0.128	0.188	0.125	0.206
Paulownia	0.148	0.656	0.543	0.663	0.513

Optimization results

Using the AHP-based alternative prioritization method, the global weight vector (M) of alternatives was obtained by multiplying the criterion layer weight vector (ω) with the alternative layer weight matrix (υ).

$$M = \omega \times v, \text{ where } M_j = \sum_{i=1}^{n} \omega_i \cdot v_{ij'} \tag{15}$$

Following the maximum membership principle, the alternatives are prioritized as: *Paulownia* > Beech > Ash, indicating *Paulownia* as the optimal solution (Table 18).

Table 18. Final Results

	Criterion Layer Weight Vectors	Ash	Beech	*Paulownia*
Surface characteristics	0.287	0.31	0.542	0.148
Price	0.178	0.245	0.156	0.599
Usage cycle	0.095	0.269	0.188	0.543
Environmental friendliness	0.408	0.207	0.132	0.661
Suitability	0.032	0.280	0.206	0.513
Optimization Results		0.251551	0.26163	0.486787

DISCUSSION

This study comprehensively evaluated parents' perceived value preferences for ash, beech, and *Paulownia* wooden toys using triangular fuzzy numbers and FAHP. The findings align with prior research on the acceptance of bamboo-based children's toys (Das and Kalita 2023) while providing new empirical evidence regarding material alternatives, particularly in the context of "bamboo as a substitute for plastic"(Chen *et al.* 2025). The results demonstrate that *Paulownia* wood exhibits significant advantages in sustainability and functionality, particularly in environmental attributes and cost-effectiveness, offering strong support for the application of fast-growing materials in toy manufacturing.

Triangular fuzzy number results reveal that parents tended to prioritize "sensory experience" over "sustainability" in trade-off scenarios, whereas fuzzy AHP indicated that professionals favored the latter. This discrepancy highlights the gap between theoretical assessments and actual consumer behavior. Although *Paulownia* wood slightly underperformed traditional woods in surface texture and aesthetics, its superior environmental performance and cost advantages align with current trends in sustainable consumption research. This finding challenges conventional industry perceptions of fast-growing materials, demonstrating that with appropriate processing improvements, *Paulownia* can fully meet the functional requirements of toy production.

The widespread use of *Paulownia* in construction, furniture, and musical instruments provides a practical foundation for its application in the toy industry and the promotion of green toys. For toy manufacturers, this study outlines a clear sustainable transition pathway: emphasizing *Paulownia*'s eco-friendly advantages (*e.g.*, carbon labeling) in pricing strategies and developing lightweight designs for younger children to mitigate its load-bearing limitations. Retailers can leverage parents' high sensitivity to environmental benefits by positioning *Paulownia* toys as entry-level "green parenting" products to accelerate market penetration.

This study had several limitations. First, it primarily relied on subjective evaluation methods (*e.g.*, questionnaires and expert ratings) to measure parents' perceived value of wooden toys and did not incorporate direct feedback from children. While this approach mimics real-world decision-making and captures subjective preferences, it may be

susceptible to social desirability bias and inconsistencies in subjective judgments. Second, the data framework was constructed from 53 participant responses and three expert evaluations. Although fuzzy methods effectively handle uncertainty in assessments, the limited sample size may affect the robustness of the fuzzy number boundaries, thereby influencing the reliability of the final weight assignments. Third, since the sample was drawn from a single region in China, the cultural representativeness and geographical generalizability of the findings are constrained, potentially limiting direct applicability to other regions or broader consumer groups. Finally, the study does not examine performance variations among *Paulownia* species, long-term durability, or global market acceptance—factors that may impact the practical application of the conclusions.

To enhance the study's rigor and applicability, future work should focus on the following: (1) integrating objective measurements (*e.g.*, mechanical testing, wear experiments) with subjective evaluations to reduce methodological bias and employing larger sample sizes to improve the robustness of fuzzy AHP results; (2) expanding the sample to include respondents from diverse cultural backgrounds (*e.g.*, European, North American, and Southeast Asian markets) and consumption tiers to validate cross-cultural applicability; (3) investigating physical property differences among *Paulownia* species and conducting longitudinal studies to assess durability in real-world usage; and (4) initiating multinational consumer perception studies to compare acceptance levels of sustainable toy materials across markets. Addressing supply chain readiness, processing compatibility, and international certification barriers will be critical for industrial-scale adoption, facilitating *Paulownia*'s transition from a "promising material" to a "practical alternative."

Despite these limitations, this study quantified consumers' compromise thresholds for sustainable materials using fuzzy theory, providing an actionable decision-making framework for green toy promotion—one that extends beyond material selection to balance "eco-friendliness, cost, and performance" in other children's products. From a practical standpoint, the findings offer key insights: manufacturers can optimize material selection strategies, educators can develop sustainability programs, and policymakers may consider incorporating the results into industry standards. These applications will advance the toy industry toward greater sustainability.

It must be emphasized that large-scale adoption of *Paulownia* requires interdisciplinary collaboration to address non-technical barriers. This study focuses on front-end perceived value validation, which, combined with future research on supply chains, processing, and certification, forms a comprehensive assessment framework for substitution potential.

CONCLUSIONS

1. This study systematically evaluated parents' perceived value of three wood types using triangular fuzzy numbers and fuzzy analytic hierarchy process (FAHP). The data analysis revealed that beech wood demonstrated optimal performance in both surface characteristics (Q1: M=4.01) and price (Q2: M=3.77) dimensions, with effect sizes reaching moderate levels (d=0.55 to 0.58), confirming the advantages of traditional woods in sensory experience. In contrast, *Paulownia* wood showed outstanding performance in environmental friendliness (Q4: M=3.73) and overall suitability (Q5: M=3.72) dimensions (d=0.55-0.57), demonstrating its potential as a sustainable alternative material.

2. Fuzzy AHP results indicated generally consistent validation of *Paulownia*'s potential between experts and general consumers, despite minor discrepancies in indicator weight assignments.

3. The findings indicate that *Paulownia* wood not only possesses significant environmental advantages that meet the growing demand for green consumption, but also offers cost benefits (19 to 22% lower than traditional woods), giving it considerable market appeal. However, process improvements are needed to compensate for its deficiencies in surface texture to further enhance its market competitiveness. These findings provide important empirical evidence for material selection in wooden toy manufacturing.

4. While this study established fundamental preference evaluations among the three wood types, it did not account for the effects of surface treatments (e.g., varnish coating) on performance. Future research should address *Paulownia's* limitations through three key avenues: (1) material property enhancement (e.g., evaluating how different finishing processes affect sensory experience and durability), (2) processing technology optimization, and (3) comparative testing of different *Paulownia* varieties. These findings aim to provide more comprehensive, actionable insights for toy manufacturers and designers.

ACKNOWLEDGMENTS

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APPENDIX

Triangular Fuzzy Numbers

Lin (2002) demonstrated that within fuzzy theory frameworks, linguistic variables can be quantified using fuzzy numbers, enabling the articulation of multiple membership relationships through phrases like "this AND that" – an approach termed fuzzy linguistic variables. For measuring semantic meanings with fuzzy theory, triangular fuzzy numbers (TFNs) are most frequently employed, characterized by triangular membership functions defined by three parameters: minimum (a), most plausible (b), and maximum (c) values. Given real numbers satisfying $a \leqslant b \leqslant c$, the membership function can be graphically represented as shown in Fig. A1.

$$u(x) = \begin{cases} 0 & , \quad x \in [0,a] \\ x-a & , \quad x \in (a,b) \\ 1 & , \quad x = b \\ c-x & , \quad x \in (b,c) \\ 0 & , \quad x \in [c,\infty] \end{cases}$$
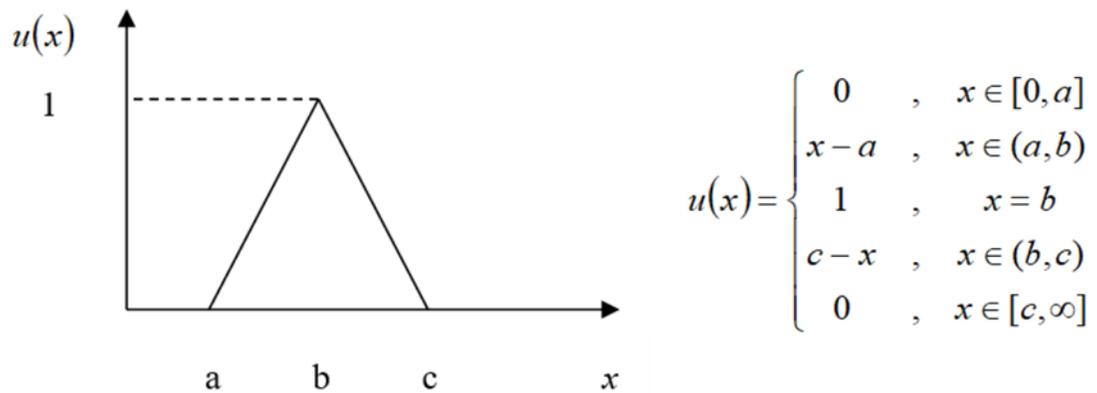
Fig. A1. The function of triangular fuzzy number

Ethical Approval Statement

IEC of College of Furnishings and Industrial Design Nanjing Forestry University
Statement of Ethical Review of Research Projects

Project Title	Application of Paulownia Wood Based on Fuzzy Theory Decision-Making		
Unit	Department of Industrial and Interaction Design	Supervisor	Junzhe Liu
Brief Description	1、1.This study investigates the preference differences between parents and children for three types of wooden toy materials (ash, beech, and paulownia) across five dimensions through questionnaires and on-site observations, aiming to evaluate the potential of fast-growing paulownia wood as a sustainable alternative material. The triangular fuzzy number-based questionnaire used in this study is solely for academic research purposes. 2.In this research, participants will be clearly informed of the study's objectives and data usage prior to the experiment. Throughout the experiment, staff will accompany participants to ensure children do not participate alone. The procedure only involves on-site observation of wooden toys and questionnaire completion.		
Sample Size	53 copies	Project Duration	10 days
Contact names / phone number	Xiaohan Shen/18851681630		
Project Information	Funding source: ☐Corporation ☐Government ☐Academic Group ☐This unit ☑Self-finance Research involving human biospecimens: ☐Yes (☐Newly collected biological specimens ☐Previously preserved biological specimens) ☑No Research involves over-the-counter drug use: ☐Yes (Please provide the Pharmacy Management and Pharmacotherapeutics Committee's endorsement) ☑No Research involving stem cell clinical studies: ☐Yes ☑No		
Project Material	☑ Participant Information Sheet/s ☑ Informed Consent/s ☐ Project design document/s ☐ Recruitment Advertisement ☑ Questionnaire/Survey ☐ Interview	Recruitment Process	Recruitment method: ☐Advertisement ☐ Personal contact ☐Database ☐Intermediary ☑Other Participant Characteristics: ☑Healthy ☐ Patient ☐Vulnerable ☐Gravida
I confirm that there is no conflict of interest between me and the research project, that the information involved in the research application has been reviewed by me, and that I guarantee that all the information in the course of the implementation of the research is true and accurate, and that it complies with the requirements of the scientific research project as well as the relevant national laws and regulations.			
Supervisor Signature / Date	*Junzhe Liu*	2025.01.27	
Competent authority review comments	After consideration by our Institutional Review Board, the experimental design and protocol of the study are scientifically sound, fair and impartial, and will not cause harm or risk to the participants . Participants were recruited based on the principle of voluntary and informed consent, and the rights and privacy of the participants were protected, and the content of the study was free from conflict of interest as well as violation of moral ethics and legal prohibitions. Conclusion: The Institutional Review Board agreed that the work on the project was proceeding as planned. Sign (Signature) Date：		