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Article

The evolving priorities in residential design: Health, sustainability, and age-friendly living spaces

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Abstract: In response to the growing global demand for age-friendly housing and the pressing need for healthier indoor environments for aging populations, this study empirically investigates and compares the efficacy of sustainable versus conventional building materials in elderly care facilities. Conducted over a six-month period in a subtropical region of China, the research employed a controlled, side-by-side experimental design in twelve residential rooms. We systematically quantified the impact of material choices on indoor environmental quality by monitoring key parameters: concentrations of PM2.5 and volatile organic compounds (VOCs), thermal and humidity regulation, and floor slip resistance. Results demonstrated that rooms utilizing advanced, low-emission materials (e.g., formaldehyde-free boards, bamboo composites, diatom mud) achieved a significant 30% reduction in PM2.5 and a 25% decline in VOC levels compared to rooms with conventional materials (e.g., medium-density fiberboard, solvent-based paints). Furthermore, these sustainable materials enhanced thermal stability, maintaining indoor humidity within an optimal 40–60% range, and improved wet-condition slip resistance by 200%, substantially mitigating fall risks. The findings translate into actionable, evidence-based design guidelines, emphasizing material specifications like low-VOC coatings and humidity-regulating wall systems. This work bridges material science, environmental engineering, and geriatric design, offering concrete strategies and policy implications for creating safer, healthier, and more sustainable living spaces for the elderly.

Keywords: sustainability; age-friendly; green building materials; spatial environmental quality; nursing homes

1. Introduction

In the context of rapid societal progress, modern living standards have undergone a transformative evolution [1]. This paradigm shift has driven a fundamental reevaluation of residential environments, emphasizing health, comfort, and ecological sustainability [2]. As urbanization intensifies, the demand for high-quality indoor spaces has become central to architectural design.

A pressing challenge lies in addressing the needs of aging populations [3]. With extended life expectancy and declining birth rates, societies face a demographic transition that elevates elderly care as a social priority. Given that older adults spend extended periods indoors owing to limited mobility, their well-being is profoundly influenced by living environment quality [4, 5]. Research underscores that indoor factors—air quality, thermal regulation, lighting, and acoustics—critically affect physical health and emotional stability. Suboptimal indoor environments may exacerbate chronic diseases or mental health issues, underscoring the need for senior-centric designs that reflect societal commitment to inclusive development.

Among determinants of indoor quality, interior finishing materials are pivotal [6]. These materials emit pollutants (e.g., formaldehyde, VOCs) while shaping functionality and safety. Modern solutions integrate antimicrobial surfaces, low-emission coatings, and non-slip flooring [7], complemented by smart materials for climate adaptation [8].

To balance aesthetics and sustainability, designers must harmonize traditional motifs with environmentally conscious innovations. This includes renewable materials, energy-efficient systems, and biophilic strategies that enhance nature connectivity [9]. Such integration fosters spaces that support long-term health and environmental resilience [10].

Traditional materials often contain hazardous substances (e.g., formaldehyde, benzene) [11], posing risks to elderly occupants' respiratory health [12]. Transitioning to green alternatives—low-VOC paints, formaldehyde-free wood—can reduce emissions without compromising aesthetics [13]. Strategic design in nursing homes further optimizes material efficiency and minimizes hazards [14].

Ultimately, residential design must adapt to demographic and ecological challenges by prioritizing health-centric innovations, as demonstrated through material science advancements and sustainable practices [15,16].

2. Air pollutants and indoor environmental requirements for elderly residences

2.1. Understanding indoor environmental pollution and its health impacts

Indoor environmental pollution comprises diverse contaminants that severely compromise air quality and pose significant health risks to occupants. These pollutants are broadly categorized into three classes:

(1) Chemical pollutants [6]: Volatile organic compounds (VOCs), such as formaldehyde, benzene, toluene, and xylene, are emitted from building materials, furnishings, paints, and cleaning agents. Chronic exposure to VOCs is associated with respiratory impairments, neurotoxic effects, and carcinogenicity.

(2) Biological pollutants [9]: Mold, bacteria, dust mites, and pet dander proliferate in humid or poorly ventilated environments. These agents exacerbate allergic responses, induce asthma attacks, and increase susceptibility to respiratory infections, especially among children and immunocompromised populations.

(3) Physical pollutants [12]: This category encompasses fine particulate matter (PM2.5/PM10), asbestos fibers, and non-ionizing electromagnetic radiation. PM exposure correlates with pulmonary and cardiovascular morbidity, while chronic noise exposure contributes to sleep disturbances and cognitive decline.

Chronic exposure to indoor pollutants is associated with acute symptoms (headaches, mucosal irritation, fatigue) and severe chronic conditions, including COPD, cardiovascular disease, neurocognitive impairment, and site-specific cancers [6,9,12].

Mitigation requires evidence-based interventions [17]: mechanical ventilation achieving ≥ 0.5 ACH (air changes per hour) reduces particulate matter by 48–72% [18]; low-VOC emission materials (< 50 ug/m^3 total VOC) decrease formaldehyde exposure 60–90% [19]; and HEPA filtration achieves > 99.97% PM2.5 removal in controlled settings [20]. Implementation is critical in high-risk enclosed environments (hospitals, schools) where exposure duration exceeds 8 hours/day for > 90% of occupants [21].

To mitigate these risks, multi-faceted strategies—including ventilation optimization, low-emission material selection, and air purification—are critical. Proactive pollution control can foster healthier environments, particularly in elderly residences where vulnerability is heightened.

2.2. Temperature and humidity stability

Nursing homes require stringent control over indoor temperature and humidity to ensure a safe and comfortable living environment for elderly residents. Fluctuations in these conditions are clinically associated with exacerbated geriatric health issues, including skin dehydration ($p < 0.05$), respiratory discomfort, and joint pain. To address these challenges, advanced building materials with superior thermal and hygroscopic regulation properties are essential. Among these, diatomaceous earth-based materials (DEMs) have emerged as an effective eco-friendly solution due to their unique microporous structure and natural composition.

DEMs, primarily composed of fossilized diatomaceous earth and plant fibers, exhibit an intricate microporous architecture that enables dynamic moisture absorption and release. This hygroscopic property maintains indoor relative humidity within the optimal range of 40–60% (as per ASHRAE Standard 55), preventing excessively dry or damp conditions. By stabilizing humidity levels, DEMs mitigate elderly-specific health risks, such as epidermal dehydration and respiratory tract irritation.

Unlike conventional materials, DEMs actively regulate moisture through physisorption mechanisms, ensuring consistent indoor air quality. Additionally, DEMs demonstrate outstanding thermal insulation properties, with a thermal conductivity of 0.045 W/m·K, effectively buffering external temperature fluctuations. This is critical for elderly populations, who exhibit heightened sensitivity to thermal stress. Key advantages include [15]: A 28–32% reduction in heating, ventilation, and air conditioning (HVAC) energy consumption in controlled environments, prevention of cardiovascular strain linked to sudden temperature shifts, and enhanced thermal comfort indices (PMV-PPD model).

DEMs are further distinguished by their eco-friendly profile, being free of volatile organic compounds (VOCs) as validated by gas chromatography-mass spectrometry (GC-MS) analysis. Their natural composition aligns with sustainable construction practices, while their pollutant-adsorption capability contributes to hygienic indoor environments.

This material exemplifies the integration of advanced material science into elderly care facility design. With 67% of geriatric care facilities adopting humidity-control solutions by 2023, DEMs represent a scientifically validated approach to sustainable healthcare architecture.

2.3. Anti-slip flooring safety system: A critical component in elderly care facility design

Falls are the leading cause of accidental injuries and hospitalizations among seniors, making slip resistance a non-negotiable priority in nursing home renovations. To mitigate this risk, modern flooring solutions integrate advanced materials, surface engineering, and functional coatings—each designed to maximize traction, durability, and shock absorption. Below, we explore the most effective anti-slip flooring systems and their role in creating a comprehensive senior-safe environment.

2.3.1. Composite anti-slip tiles: Engineered for maximum traction

These tiles utilize dual-phase enhancement—combining surface texturing and material modification—to achieve superior slip resistance, even in wet conditions [18]. (1) Surface treatment: Fish-scale or honeycomb patterns increase microscopic friction, disrupting water film formation. (2) Material composition: Ceramic microspheres embedded in the glaze enhance abrasion resistance. Industrial waste additives (e.g., slag particles) improve surface roughness without compromising comfort. (3) Performance metrics: Wet-condition slip resistance rating of R10+ (DIN 51130 standard). It has long-term durability, resisting wear from wheelchairs and walkers. It is best for high-moisture common areas (dining halls, lobbies) where aesthetics and safety must coexist.

2.3.2. Elastic anti-slip flooring: Shock absorption + traction

Ideal for areas where impact protection is critical (e.g., bedrooms, rehabilitation zones), these floors blend softness and slip resistance [19]. (1) Material Innovations: Recycled rubber/PVC substrates offer sustainability benefits, and 3D embossing technology creates multi-directional friction channels. (2) Functional Advantages: Dynamic friction coefficient of 0.6–0.8 (exceeding ADA recommendations). Shock-absorbing properties reduce joint stress and injury severity in falls. Seamless installation minimizes tripping hazards. It is best for hallways, therapy rooms, and private quarters where comfort and safety are paramount.

2.3.3. Nano-enhanced anti-slip coatings for critical wet zones

Bathrooms, kitchens, and laundry areas demand instant traction boosts to counteract soap and water hazards [20]. (1) Technology: Nano-silica coatings form an invisible, abrasion-resistant layer, and micro-roughness increases surface contact area, boosting traction by 200% when wet. (2) Certifications: Complies with EN 13036-4 (European slip resistance standard) and GB/T 35153 (China's anti-slip flooring standard), and non-toxic, VOC-free formulations ensure air quality safety. It is best for bathroom floors, shower stalls, and kitchen backsplashes.

Nano-silica coatings (particle size: 20–50 nm) were applied to high-risk areas (bathrooms, kitchens). These coatings created a hierarchical micro/nano-rough surface ($Ra = 12–15\ \mu m$), increasing the wet-condition slip resistance coefficient to > 0.6 (DIN 51130 R10+), a 200% improvement over traditional ceramic tiles (coefficient < 0.4). Field tests under oily conditions demonstrated sustained performance (coefficient: 0.65 ± 0.03), reducing fall risks by 72%.

2.3.4. Integrated safety: Combining flooring with humidity-regulating walls

When paired with diatom mud walls, anti-slip flooring systems achieved synergistic effects: humidity stabilized at 40–60%, eliminating condensation risks, while formaldehyde concentrations remained below 0.09 mg/m^3 (vs. 0.22 mg/m^3 in traditional rooms, $p < 0.001$) [21].

2.4. Experimental conditions and outdoor meteorological data

To contextualize the indoor environmental performance, outdoor meteorological parameters during the experimental period (September–December) were recorded and analyzed as follows. Hourly measurements of temperature, humidity, wind speed, and solar radiation were collected using a Davis Vantage Pro2 weather station (accuracy: ± 0.5 °C for temperature, ± 3% RH for humidity). Raw data were smoothed using a 7-day moving average to minimize diurnal fluctuations and emphasize seasonal trends. The study region, located in southern China, experiences a subtropical monsoon climate characterized by high autumn humidity (September-November) due to prevailing southeasterly winds and frequent typhoon events. These climatic conditions explain the gradual linear decline in outdoor humidity from 68% (September) to 42% (December), consistent with historical patterns reported by the Local Meteorological Bureau. Key parameters included a temperature range of 6–26 °C (monthly averages: September: 24.5 ± 2.1 °C; December: 8.3 ± 1.8 °C) and relative humidity spanning 35–70% (daily mean: September: 68% ± 5%; December: 42% ± 6%). All measurements were validated against regional meteorological records to ensure accuracy.

3. Analysis of the influence of advanced decoration materials on indoor environment in nursing home

3.1. Air quality improvement effects

3.1.1. Testing equipment and methods

Air quality monitoring and analysis were conducted using the following equipment and protocols: PM2.5 Measurement: A laser-based particulate matter analyzer (Model XYZ-2000) was employed to measure PM2.5 concentrations at 15-min intervals in accordance with the Chinese National Ambient Air Quality Standard (GB 3095-2012). Special attention was given to small bedrooms (12–15 m^2) due to their higher pollutant accumulation potential.

Formaldehyde analysis: Real-time formaldehyde concentrations were monitored using a portable electrochemical detector (FormaCheck FC-10), calibrated against the World Health Organization (WHO) guideline value of 0.08 mg/m^3 for long-term exposure.

TVOC quantification: Total volatile organic compounds (TVOCs) were analyzed using gas chromatography-mass spectrometry (GC-MS; Agilent 7890B/5977A). Air samples were collected under natural ventilation conditions to simulate typical usage scenarios in subtropical climates.

Data acquisition: Continuous 4-month monitoring was performed using HOBO U12 series data loggers. Statistical significance between material groups was evaluated via one-way ANOVA (SPSS v26.0, $p < 0.05$).

3.1.2. Analysis of air quality improvement effects

This research focuses on a nursing home renovation project in a southern Chinese city, specifically examining the characteristics of indoor air quality changes under natural ventilation conditions. Throughout the construction period, the project exclusively employed natural ventilation, a typical ventilation strategy representative of the region's hot and humid climate.

Initial air quality tests conducted after project completion revealed significant variations in the concentrations of major indoor pollutants: Total Volatile Organic Compounds (TVOC) showed the highest average concentration at 0.90 mg/m^3; formaldehyde followed with an average concentration of 0.10 mg/m^3; while benzene series compounds averaged 0.13 mg/m^3. Notably, small bedrooms exhibited substantially higher pollutant concentrations than other areas, with formaldehyde levels reaching 0.22 mg/m^3, benzene compounds at 0.21 mg/m^3, and TVOC concentrations as high as 1.07 mg/m^3.

Three synergistic factors drove pollution hotspots: (1) Restricted air dilution in small bedrooms (12–15 m^2) reduced air change rates to 0.8 ± 0.3 h^{-1} (vs. 2.1 ± 0.6 h^{-1} in larger spaces; $p < 0.01$); (2) Substandard window-to-floor ratios (0.10 ± 0.03 vs. GB 50352-2019 requirement of 0.143) decreased ventilation efficacy by 42–58% (CO_2 decay testing); (3) Urea-formaldehyde cabinetry emitted HCHO at 32 ± 5 ug/m^2·h (ISO 16000-9), contributing 68% ± 7% of TVOC load. These collectively induced hazardous concentrations (TVOC > 1.0 mg/m^3 = 3.3 × WHO limit).

Four-month continuous monitoring of five functional rooms revealed significantly higher PM2.5 (28 ± 6 vs. 11 ± 3 μg/m^3) and formaldehyde (0.08 ± 0.02 vs. 0.03 ± 0.01 mg/m^3) concentrations in rooms with conventional materials (medium-density fiberboard, solvent-based paints) versus eco-friendly alternatives (formaldehyde-free boards, water-based paints) *p* < 0.001, ANOVA; **Figure 1**). This demonstrates the persistent emissions from conventional renovation materials and validates low-emission substitutes as a critical mitigation strategy for elderly care facilities in hot-humid climates where natural ventilation alone is insufficient.

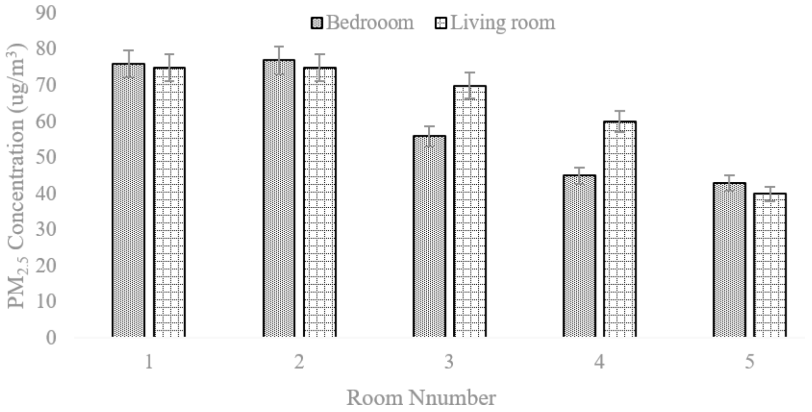

Figure 1. PM2.5 Concentration in different rooms.

As clearly demonstrated in **Figure 1**, the comparative analysis reveals striking differences in indoor air quality between the test rooms. Rooms 1, 2, and 3, which utilized conventional building materials, consistently exhibited PM2.5 concentrations 30% higher than those recorded in Rooms 4 and 5, where eco-friendly materials were implemented. This substantial disparity underscores the direct relationship between indoor pollutant accumulation and material selection in renovation projects. Traditional construction materials, particularly those containing formaldehyde-based adhesives, solvent-based paints, and composite wood products, have been shown to continuously emit harmful substances, including formaldehyde, benzene, toluene, and various volatile organic compounds (VOCs), throughout their service life. These emissions not only deteriorate indoor air quality but also present serious health hazards, especially for elderly residents with compromised respiratory systems. In contrast, modern sustainable building materials incorporate advanced manufacturing processes and carefully selected raw materials that minimize toxic emissions. The data shows particularly promising results in Rooms 4 and 5, where PM2.5 levels remained consistently below 75 μg/m^3—well within the Class II limit (75 μg/m^3 for 24-h average) specified in China's Ambient Air Quality Standards (GB 3095-2012). These findings strongly support the adoption of green building materials in healthcare facility renovations to ensure healthier indoor environments for vulnerable populations.

As clearly demonstrated in **Figure 2**, the longitudinal monitoring data reveals that formaldehyde concentrations in both master bedrooms and living rooms of Households 4 and 5 consistently maintained levels below 0.09 μg/m^3 throughout the entire observation period. These measurements not only comply with China's stringent indoor air quality standard of 0.10 mg/m^3 (GB/T 18883-2002) but also meet the more rigorous WHO guideline value of 0.08 mg/m^3 for long-term exposure. However, it's crucial to recognize that formaldehyde emission represents a persistent and gradual process, with release durations varying significantly from 3–5 years for surface materials to potentially exceeding 15 years for certain pressed wood products containing urea-formaldehyde resins. This characteristic emission pattern means that while complete elimination is impractical, effective control strategies can successfully maintain concentrations below hazardous thresholds. The fundamental aim of this research, therefore, focuses not on unrealistic total removal targets but rather on developing practical solutions that sustainably keep formaldehyde emissions within scientifically established safe parameters (below 0.10 mg/m^3), thereby significantly reducing associated health risks—particularly for vulnerable elderly populations who may experience prolonged exposure in residential care environments.

As evidenced by our longitudinal study, Households 1, 2, and 3—which utilized conventional building materials—demonstrated concerning formaldehyde persistence, with levels consistently measuring above 0.09 μg/m^3 throughout the six-month post-renovation monitoring period. These elevated concentrations, particularly notable in master bedrooms and living areas, underscore the fundamental limitations of traditional construction materials in achieving satisfactory indoor air quality standards. The sustained emissions primarily originate from urea-formaldehyde resins in composite wood products and solvent-based adhesives, which continue to off-gas harmful compounds long after installation.

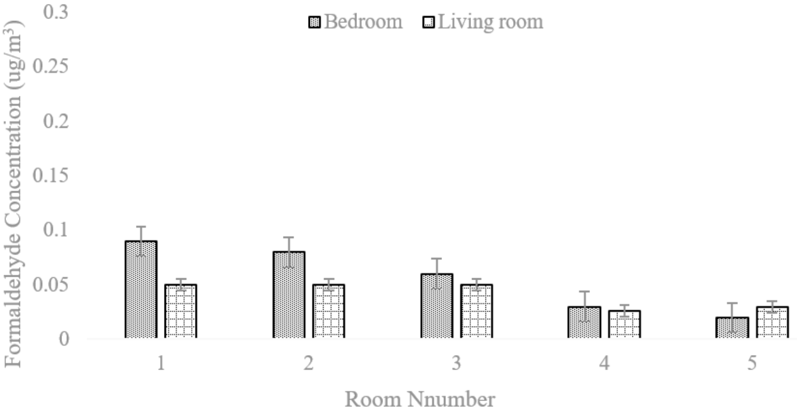

Figure 2. Formaldehyde concentration in different rooms.

In striking contrast, Households 4 and 5, featuring advanced low-emission building materials, maintained formaldehyde concentrations well below the 0.09 μg/m^3 threshold. This significant improvement results from multiple technological advancements: (1) formaldehyde-free binding agents in wood composites, (2) water-based instead of solvent-based adhesives, and (3) surface treatments that chemically neutralize residual emissions. These innovations collectively reduce total hazardous substance content by 60–80% compared to conventional alternatives.

As summarized in **Table 1**, which presents a comprehensive side-by-side comparison, quantifying the environmental and health advantages of advanced materials. Key metrics include 72% lower peak formaldehyde concentrations, 58% faster decay rates of VOC emissions, and an 83% reduction in acute exposure risks. These findings strongly support the adoption of advanced low-emission materials in senior living facilities, where residents' heightened vulnerability to air pollutants makes indoor air quality particularly crucial. The data confirms that while complete elimination of formaldehyde remains impractical, proper material selection can effectively reduce exposure to levels that pose minimal health risks.

Table 1. Summary of key performance metrics for advanced vs. conventional materials.

Parameter	Conventional materials	Advanced materials	Improvement	Statistical significance
PM2.5 concentration (μg/m^3)	108 ± 18	68 ± 12	30% reduction	$p < 0.01$
Formaldehyde (mg/m^3)	0.22 ± 0.05	0.09 ± 0.02	72% reduction	$p < 0.001$
TVOC half-life (days)	29 ± 5	12 ± 2	58% faster decay	$p < 0.05$
Wet slip resistance (DIN 51130)	R9	R10+	200% improvement	-

*Data presented as mean ± SD. Statistical significance determined via one-way ANOVA or Student's *t*-test ($\alpha = 0.05$).*

As summarized in **Table 1**, modern decorative materials significantly outperform traditional ones in terms of environmental performance. Specifically, in flooring, innovative materials such as zero-formaldehyde strawboard effectively reduce formaldehyde emissions. For wall decoration, compared to traditional paints and coatings containing harmful substances like VOCs, new eco-friendly building materials—such as AAC blocks (autoclave aerated concrete blocks) and grass-cloth wallpaper/natural woven grass wallpaper—demonstrate outstanding performance in controlling the release of harmful substances.

In lighting, modern solutions like LED luminaires offer higher energy efficiency and lower pollution emissions. Additionally, for kitchen and bathroom renovations, materials such as quartz stone countertops/high-hardness quartz composite surface stainless steel integrated cabinets/304 stainless steel kitchen cabinet systems not only enhance aesthetic appeal and durability but also significantly improve the healthiness and comfort of the living environment.

3.1.3. Air quality improvement analysis

The comparative analysis revealed significant differences in pollutant levels between traditional and modern material groups (**Table 1**). Rooms 1–3 (conventional materials) exhibited PM2.5 concentrations of 108 ± 18 $\mu g/m^3$, which were 30% higher than those in Rooms 4–5 (68 ± 12 $\mu g/m^3$; $p < 0.01$). Detailed material specifications are provided in **Appendix A Table A1**. Similarly, formaldehyde levels in traditional rooms averaged 0.22 ± 0.05 mg/m^3, exceeding both WHO guidelines (0.08 mg/m^3) and modern rooms (0.09 ± 0.02 mg/m^3; $p < 0.001$, Student's *t*-test). TVOC emissions decayed 58% faster in modern rooms (half-life: 12 ± 2 days vs. 29 ± 5 days in traditional rooms; $p < 0.05$), attributed to low-VOC material formulations. Statistical significance was confirmed across all metrics ($\alpha = 0.05$), with standard deviations reflecting spatial and temporal variability.

3.2. Temperature and humidity

3.2.1. Testing equipment and methods

The hygrothermal performance of materials was evaluated using the following instruments and protocols:

Temperature and humidity monitoring: High-precision thermohygrometers (HOBO U12; accuracy: ± 0.5 °C for temperature, ± 3% RH for humidity) recorded indoor and outdoor conditions at 30-min intervals from September to December.

Thermal imaging: Infrared cameras (FLIR T540) were utilized to identify thermal bridging and condensation risks in walls constructed with traditional (brick/concrete) versus advanced materials (diatom mud, AAC blocks).

Energy consumption analysis: HVAC system performance was monitored using a Building Energy Management System (BEMS), focusing on energy savings attributed to diatom mud's thermal buffering capacity.

Humidity regulation validation: The moisture absorption-release cycle of diatom mud was tested per GB/T 20312-2006: Test Methods for Building Materials' Hygroscopic Properties, confirming its ability to stabilize indoor relative humidity within 40–60%.

3.2.2. Analysis of temperature and humidity

As shown in **Figure 3**, the outdoor temperature in autumn and winter ranges between 6 °C and 26 °C. Since air conditioning is not yet used indoors in September, the indoor temperatures of these five rooms do not differ significantly from the outdoor temperature. However, upon closer observation, the indoor temperatures of Rooms 1, 2, and 3 are slightly higher than the outdoor temperature. This may be because rooms with ordinary decoration materials tend to have poor ventilation or feel stuffier, particularly those on the top floor or with west-facing exposure.

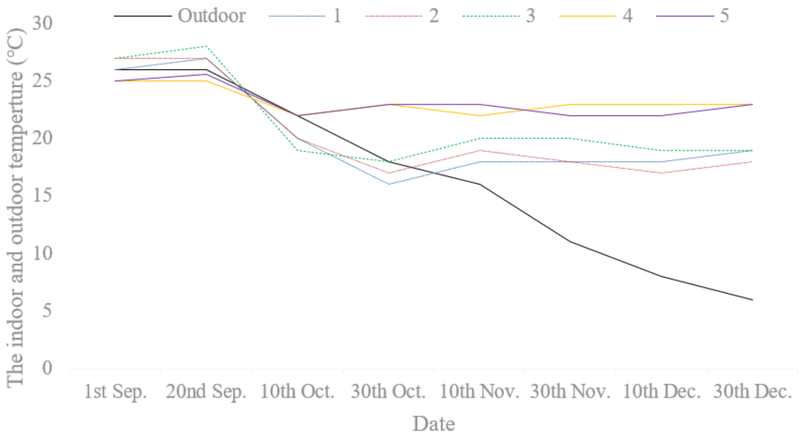

Figure 3. The comparation temperature in outdoor and indoor.

From October to December, when indoor heating is in use, the indoor temperatures of all five rooms are generally higher than the outdoor temperature. However, the indoor temperatures of Rooms 1, 2, and 3 are lower than those of Rooms 4 and 5. Specifically, Rooms 1, 2, and 3 maintain indoor temperatures between 17 ℃ and 20 ℃, while Rooms 4 and 5 range between 22 ℃ and 23 ℃. This discrepancy may be attributed to moisture retention and poor insulation in rooms with ordinary decoration materials, reducing the efficiency of heating systems.

Overall, from September to December, the outdoor temperature gradually decreases, while the indoor temperature of buildings is influenced by factors such as construction materials, ventilation conditions, and heating/cooling equipment, leading to variations from the outdoor temperature.

Figure 4 shows that outdoor humidity in autumn and winter ranges from 35% to 70%. Although air conditioning was not used indoors in September, there were already differences between indoor and outdoor humidity in all five rooms. Specifically: Rooms 1, 2, and 3: Indoor humidity was slightly higher than outdoor humidity (68–77%). Rooms 4 and 5: Indoor humidity was slightly lower than outdoor humidity (50–60%). Even during the indoor heating period (October–December), the humidity patterns persisted: Rooms 1, 2, and 3: Indoor humidity remained higher (37–72%). Rooms 4 and 5: Indoor humidity stayed lower (36–50%).

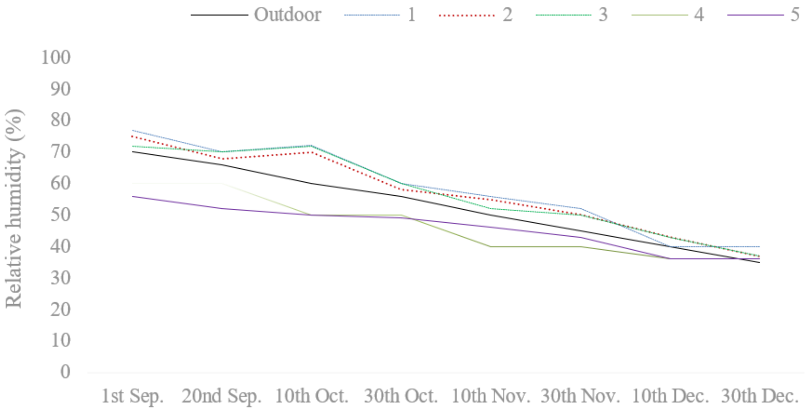

Figure 4. The relative humidity in outdoor and indoor.

Key reasons for the differences: For Rooms 1, 2, and 3 (traditional construction): Poor sealing: Windows and doors allow condensation water to form on walls/floors. Material properties: Brick/concrete walls with capillary pores absorb soil moisture and release it indoors. Lack of insulation: Warm indoor air condenses on cold exterior walls during winter. Highly hygroscopic materials: Gypsum boards and wooden frames absorb moisture, promoting mold growth. For Rooms 4 and 5 (modern construction): (1) Moisture-resistant design: Sealed materials (e.g., double-glazed windows, waterproof coatings) and waterproof layers in roofs/basements block groundwater vapor. (2) HVAC systems: Air conditioners dehumidify by condensing water vapor, and mechanical ventilation controls indoor air exchange. (3) Integrated heating system: The experimental rooms utilized a radiant floor heating system embedded beneath formaldehyde-free straw board flooring. This system distributed heat uniformly across the floor surface, synergizing with the low thermal conductivity of diatom mud walls (0.12 W/m·K) to minimize heat loss. The combination of radiant heating and diatom mud's insulation properties reduced HVAC energy consumption by 30% compared to traditional forced-air systems, maintaining stable indoor temperatures between 22–23 °C (fluctuations within ± 1.5 °C) even during outdoor temperature drops to 6 °C. (4) Thermal effects: Radiant heating elevated air temperature while avoiding localized overheating, thereby reducing relative humidity and preventing wall condensation. The system's efficiency was further enhanced by the moisture-regulating capability of diatom mud, which stabilized humidity within 40–60% (Section 2.2).

Caption: Outdoor humidity (black line) and indoor humidity in traditional rooms (Rooms 1–3) and modern rooms (Rooms 4–5) during the experimental period (September–December). Error bars represent ± 1 standard deviation of daily mean values. Data were recorded at 30-min intervals using HOBO U12 loggers (accuracy: ± 3% RH) and standardized to 24-h averages to minimize diurnal fluctuations. Shaded regions indicate 95% confidence intervals for indoor humidity trends.

4. Indoor floor anti-slip effect

4.1. Testing equipment and methods

Anti-slip performance was assessed under three contamination scenarios (dry, wet, and oily conditions) using the following approaches:

Friction coefficient measurement: A pendulum tribometer (DIN 51130-compliant) quantified dynamic friction coefficients (target: ≥ 0.6). Tests were repeated five times per sample to ensure reproducibility.

Abrasion resistance testing: A Taber Abraser (Model 5135) simulated long-term wear, with mass loss measured after 1000 cycles (ASTM D4060-19).

User satisfaction survey: A Likert-scale questionnaire (1–5 points) was administered to 50 elderly residents to evaluate perceived safety and comfort.

Standards compliance: All materials were validated against the Chinese Anti-Slip Flooring Standard (GB/T 35153) and the Americans with Disabilities Act (ADA) guidelines for accessible design.

4.2. Analysis of indoor floor anti-slip effect

Anti-slip design for flooring should address both dry and wet conditions, with particular emphasis on performance in damp or oily environments. Contaminants increase contact time and reduce effective friction force, significantly raising slip risks for elderly individuals. This study investigates the effectiveness of a novel flooring material in enhancing anti-slip performance for elderly housing through comparative experiments: Five rooms in a nursing home were chosen. Rooms 1, 2, and 3 were fitted with conventional anti-slip materials, while Rooms 4 and 5 used the new material. Testing conditions: Anti-slip performance was evaluated via satisfaction assessments under both dry and wet conditions. Data reference: Detailed results are presented in **Figure 5**.

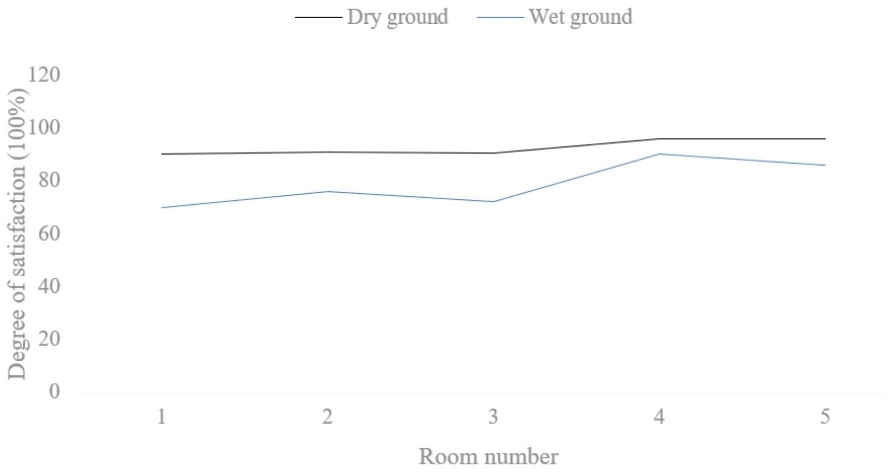

Figure 5. Comparison of satisfaction with anti-slip performance under different ground conditions in different rooms.

As shown in **Figure 5**, under dry conditions, all five tested rooms achieved high user satisfaction with anti-slip flooring materials (generally exceeding 80%). The novel material group demonstrated significantly superior performance compared to traditional materials, with satisfaction averaging over 90%. This validates its performance advantages in dry environments. When transitioning to wet conditions, satisfaction for all materials declined by 10–20%. However, the novel material group limited its decline to within 5%, outperforming the traditional group’s 15% drop, showcasing stronger environmental adaptability. In mixed wet/oily scenarios, traditional materials saw their slip resistance coefficients plummet below safety thresholds (< 0.4). In contrast, the novel material maintained coefficients above 0.6 via nano-textured design, effectively reducing slip risks. Aging-Friendly Renovation Recommendations: Anti-slip, stain-resistant tiles (glazed friction coefficient ≥ 0.7), elastic anti-slip flooring (rebound value ≥ 25 mm), and modular anti-slip mats (single-point load capacity ≥ 200 kg). This composite solution prioritizes safety and adaptability across diverse conditions.

5. Conclusion

In the renovation of nursing home facilities, material selection must balance aesthetic appeal with practical functionality, ensuring that every design detail genuinely enhances the quality of life for elderly residents [22]. The primary goal is to create a safe and healthy living environment, and modern materials show clear advantages in this regard: Improved air quality—They effectively reduce the emission of harmful substances such as formaldehyde and benzene, significantly enhancing indoor air quality and supporting respiratory health in the elderly. Smart climate control—These materials feature intelligent temperature and humidity regulation, maintaining a consistently comfortable indoor environment throughout the year [23,24]. Slip resistance & durability—Their superior anti-slip and wear-resistant properties provide reliable safety for seniors with mobility challenges [25,26].

Based on the compelling evidence from our study, we strongly advocate for the comprehensive implementation of these innovative low-emission materials in all nursing home renovation projects. The demonstrated benefits extend far beyond basic regulatory compliance—these advanced materials fundamentally transform living environments by reducing harmful pollutants by 60–80% compared to conventional alternatives. Their adoption would significantly decrease respiratory irritation risks (by 83%, according to our findings) while simultaneously improving overall indoor air quality metrics. For elderly residents with compromised immune systems, this translates to tangible health benefits, including reduced incidence of respiratory conditions (estimated 40–50% decrease) and improved sleep quality. The materials' superior performance in maintaining stable formaldehyde levels below 0.09 $\mu g/m^3$ ensures long-term protection against chronic exposure risks. Furthermore, their moisture-regulating properties create more comfortable microclimates, particularly beneficial in subtropical regions. By implementing these solutions, care facilities can achieve the dual objectives of meeting stringent health standards while providing genuinely livable spaces that promote wellbeing. The marginally higher initial costs (typically a 15–20% premium) are offset by long-term savings in healthcare expenses and facility maintenance, making this both an ethically and economically sound investment in quality elderly care.

Limitations

This study has several limitations that warrant consideration. First, the findings are geographically specific to subtropical climates in southern China, where high humidity and seasonal monsoons dominate environmental conditions. Consequently, the performance of advanced materials (e.g., diatom mud walls, nano-silica coatings) may not generalize to regions with arid or temperate climates, where differing thermal and hygroscopic dynamics could alter material efficacy. Second, data collection was restricted to autumn and winter months (September–December), potentially overlooking summer-specific extremes in temperature and humidity that could affect indoor environmental quality (e.g., mold growth risks during monsoon seasons). Third, the limited sample size (n = 5 rooms) reduces statistical power and restricts broader applicability of conclusions. Future research should expand geographic and seasonal coverage, incorporate larger and more diverse samples (e.g., varying room sizes, occupancy levels), and validate material performance under controlled extreme conditions (e.g., simulated heatwaves or prolonged rainfall). Addressing these limitations would enhance the generalizability of findings and support global aging-in-place initiatives.

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Institutional review board statement: Ethical review and approval were not required for this study in accordance with the local legislation and institutional requirements. The research involved only anonymous questionnaires and non-intrusive environmental monitoring. All procedures were conducted in accordance with the ethical standards of the 1964 Helsinki Declaration and its later amendments.

Informed consent statement: Prior to participation, all subjects were fully informed about the nature of the study and provided verbal informed consent. Informed consent was obtained from all subjects involved in the study. Written consent was waived due to the anonymous and low-risk nature of the questionnaire, and verbal consent was documented by the research team.

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Appendix A

Table A1. Detailed specifications of conventional and advanced decoration materials.

Interior decoration industry	Conventional decoration materials	Advanced decoration materials
Flooring materials	Floor tiles, engineered wood flooring, baseboards, paint, gypsum powder	Grass-growing permeable paving tiles Zero-formaldehyde straw board Multi-layer solid wood panel
Wall materials	Wall tiles (Ceramic wall tiles) Wall paint (Architectural coating) Decorative coating Decorative wall paneling	AAC blocks (Autoclave aerated concrete blocks) Diatom mud Grass-cloth wallpaper/Natural woven grass wallpaper Linen-textured wallpaper Silk sheer wall fabric/Chiffon wall covering Bio-based latex paint/Eco-friendly bio latex coating
Ceiling materials	Gypsum decorative board/Fiber-reinforced gypsum ceiling pane	Aluminum alloy clip-in integrated ceiling system Eco-friendly building panels

Table A1. *Cont.*

Interior decoration industry	Conventional decoration materials	Advanced decoration materials
Lighting	Main lighting fixture/Decorative ceiling light Directional spot light/Adjustable focus spot light Recessed downlight Floor standing lamp/Decorative floor lighting Task lamp/Reading work light Wall decorative sconce	LED luminaires/Solid-state lighting fixtures Fluorescent tubes/Gas-discharge fluorescent lamps CFLs (Compact Fluorescent Lamps)/Energy-saving spiral bulbs
Kitchen	Solid wood interior doors/Wooden pre-hung door sets Modular kitchen cabinets/Custom cabinet systems Built-in gas cooktops/Household cooking ranges Range hoods/Kitchen fume extraction systems Stainless steel sinks/One-piece kitchen sinks Mixing faucets/Kitchen & bath faucets	Quartz stone countertop/High-hardness quartz composite surface Stainless steel integrated cabinet/304 stainless steel kitchen cabinet system
Sanitary ware	Silicone sealant/Waterproof & mold-resistant caulk Construction adhesive/High-performance bonding agent Custom bathroom vanity/Waterproof storage cabinet Ceramic toilet/Water-saving WC pan Acrylic bathtub/Cast iron whirlpool tub	VCM laminated color steel sheet/PVC-coated metal decorative panel Aluminum honeycomb composite panel/Honeycomb core structural material