

Acoustic Design Systems for Sustainable Built Environments: A Comprehensive Analysis

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Abstract—Acoustic design has emerged as a critical yet frequently overlooked dimension of sustainable architecture, addressing the complex interrelationships between sound quality, environmental performance, and human well-being within built environments. The rapid expansion of urban areas and the increasing density of constructed spaces have intensified noise pollution challenges while simultaneously highlighting the importance of acoustic comfort for occupant health, productivity, and overall quality of life. These interconnected issues demand integrated design approaches that consider acoustic performance alongside energy efficiency, material sustainability, and indoor environmental quality.

This research paper undertakes a comprehensive examination of acoustic design systems and their role in creating sustainable built environments across residential, commercial, educational, and healthcare contexts. The study explores how design strategies including material selection, spatial configuration, passive acoustic techniques, and active noise control technologies contribute to enhanced sound quality while maintaining environmental responsibility. The research methodology employs qualitative approaches, drawing upon extensive secondary literature, theoretical frameworks, and analysis of contemporary sustainable building practices.

The findings indicate that thoughtful acoustic design significantly improves building sustainability by reducing energy consumption associated with mechanical noise control systems, utilizing eco-friendly and recyclable acoustic materials, and enhancing occupant satisfaction and productivity. Furthermore, acoustic comfort contributes to improved health outcomes, reduced stress levels, and enhanced cognitive performance across diverse building typologies. However, challenges related to cost considerations, technological limitations, and integration complexity remain critical areas requiring attention. The study concludes that holistic integration of acoustic design principles into sustainable architecture offers a viable pathway toward creating healthier, more comfortable, and environmentally responsible buildings capable of meeting twenty-first-century demands.

***Index Terms*—Acoustic Design, Sustainable Architecture, Sound Quality, Noise Control, Green Building Materials, Indoor Environmental Quality, Building Acoustics, Environmental Sustainability, Occupant Comfort, Passive Design Strategies**

I. INTRODUCTION

Built environments constitute the settings where contemporary populations spend the vast majority of their time, with research indicating that people in developed nations occupy indoor spaces for approximately ninety percent of their daily lives. These constructed spaces profoundly influence human experience through multiple environmental parameters including thermal comfort, air quality, lighting conditions, and acoustic characteristics. Among these factors, the acoustic environment has historically received comparatively limited attention despite its substantial impact on occupant health, cognitive function, communication effectiveness, and psychological well-being.

The acoustic qualities of buildings encompass multiple dimensions including background noise levels, reverberation characteristics, sound transmission between spaces, and the intelligibility of speech and other desired sounds. Poor acoustic conditions manifest as excessive noise intrusion from external sources, inadequate sound isolation between adjacent rooms, uncomfortable reverberation times that impair communication, and insufficient privacy for confidential conversations. These deficiencies affect building occupants across all typologies, from residential dwellings where noise disrupts sleep and relaxation to educational facilities where acoustic problems impair learning outcomes.

Simultaneously, the imperative for environmental sustainability has transformed architectural practice, driving adoption of energy-efficient systems, renewable materials, water conservation measures, and reduced carbon footprints throughout building lifecycles. Green building certification systems including Leadership in Energy and Environmental Design, Building Research Establishment Environmental Assessment Method, and comparable international frameworks have established comprehensive criteria for evaluating environmental performance. Within these frameworks, indoor environmental quality categories increasingly recognize acoustic comfort as an essential component of sustainable design, though acoustic considerations often remain secondary to energy and material concerns.

The intersection of acoustic design and sustainability presents both challenges and opportunities for contemporary architecture. Certain acoustic solutions, such as massive concrete construction that provides excellent sound isolation, may conflict with goals for reduced embodied carbon and material efficiency. Conversely, sustainable building strategies including natural ventilation, lightweight construction, and open-plan layouts can create acoustic challenges requiring careful design resolution. Navigating these tensions demands integrated approaches that optimize across multiple performance dimensions rather than treating acoustic and sustainability goals as separate or competing objectives.

This research paper aims to analyze acoustic design systems and their applications in sustainable built environments, examining how design strategies can simultaneously achieve acoustic comfort and environmental responsibility. By situating the discussion within an interdisciplinary framework encompassing architectural acoustics, building science, environmental psychology, and sustainability assessment, the study seeks to provide comprehensive understanding of approaches for creating buildings that perform well acoustically while meeting rigorous sustainability standards.

II. AIM AND OBJECTIVES

The primary aim of this research is to explore and evaluate acoustic design systems that contribute to sustainable built environments by enhancing sound quality, minimizing noise pollution, and improving occupant comfort while maintaining environmental responsibility. The study seeks to examine the intersection between acoustic performance and sustainability, emphasizing the importance of integrated design approaches in achieving comprehensive building performance outcomes.

The objectives of the research encompass theoretical, practical, and evaluative dimensions addressing multiple aspects of sustainable acoustic design. The first objective is to analyze the principles of architectural acoustics in sustainable building design, examining fundamental concepts of sound behavior within enclosed spaces and their implications for design decisions.

The second objective seeks to examine the relationship between acoustic performance and environmental sustainability, exploring potential synergies and conflicts between these goals and strategies for optimization across multiple performance criteria.

The third objective focuses on identifying eco-friendly acoustic materials and technologies, surveying available products and systems that achieve acoustic objectives while meeting sustainability requirements for recycled content, low emissions, renewability, and end-of-life recyclability.

The fourth objective evaluates noise control strategies in residential, commercial, and institutional buildings, analyzing approaches appropriate to different building typologies and their relative effectiveness and sustainability implications.

The fifth objective assesses the impact of acoustic comfort on health, productivity, and well-being, synthesizing research evidence regarding the human consequences of acoustic environmental quality.

The sixth objective proposes recommendations for integrating acoustic systems into green building frameworks, suggesting approaches for more comprehensive treatment of acoustic considerations within sustainability assessment and certification systems.

Through this comprehensive set of objectives, the study endeavors to provide holistic understanding of how acoustic design can be effectively integrated into sustainable architectural practices while acknowledging implementation challenges and contextual considerations.

III. RESEARCH METHODOLOGY

This research adopts a qualitative methodology based on systematic review and critical analysis of secondary data sources. The study relies on academic journals, scholarly books, professional standards, technical reports, and case study documentation related to architectural acoustics, sustainable building design, and indoor environmental quality. This methodological approach enables comprehensive understanding of theoretical and practical aspects of the subject while enabling synthesis across diverse disciplinary perspectives.

The methodology involves in-depth literature review to identify key concepts, principles, and emerging trends associated with acoustic design and sustainability. Sources were selected based on relevance, scholarly rigor, and contribution to understanding the relationship between acoustic performance and environmental responsibility. The review encompasses literature from architectural acoustics, building physics, materials science, environmental psychology, and sustainability assessment to capture the interdisciplinary nature of the topic.

Comparative analysis is employed to examine different acoustic design approaches, highlighting advantages and limitations of various strategies in different building typologies and contexts. This comparative approach enables identification of factors that influence design success and allows for nuanced understanding of contextual considerations affecting material selection and system specification.

The research incorporates conceptual analysis to explore relationships between acoustic characteristics, environmental performance, and human experience. By synthesizing information from diverse sources, the study identifies patterns and insights that contribute to deeper understanding of integrated design approaches. Although the research does not include acoustic simulation or on-site experimental measurements, the use of well-established academic and technical sources ensures the reliability and validity of the findings.

IV. LITERATURE REVIEW

4.1 Fundamentals of Architectural Acoustics

Architectural acoustics encompasses the science and practice of controlling sound within and between building spaces to achieve desired acoustic conditions for occupants and activities. The field addresses multiple phenomena including sound absorption, reflection, transmission, and diffusion, each governed by physical principles relating to sound wave behavior and material properties.

Sound absorption occurs when acoustic energy is converted to heat through friction within porous materials or resonance mechanisms in panel and cavity systems. Absorptive treatments reduce sound levels within spaces and control reverberation, which significantly affects speech intelligibility and musical quality. The absorption coefficient, measured on a scale from zero to one, indicates the proportion of incident sound energy absorbed by a material at specific frequencies.

Sound transmission between spaces depends on the mass, stiffness, and construction continuity of separating elements including walls, floors, and ceilings. Heavier and more airtight constructions generally provide superior sound isolation, though performance is also affected by flanking transmission through connected structural elements and building services penetrations. Sound transmission class ratings quantify airborne sound isolation performance, while impact insulation class ratings address structure-borne sound from footfall and similar sources.

Reverberation time, measured as the duration for sound to decay by sixty decibels following source cessation, significantly influences acoustic quality for different activities. Longer reverberation times enhance musical richness but impair speech intelligibility, while shorter reverberation times improve clarity for verbal communication but may create acoustically dead or lifeless environments. Optimal reverberation times vary substantially depending on room function, size, and the nature of sound sources present.

4.2 Acoustic Requirements Across Building Typologies

Different building types present distinct acoustic challenges requiring tailored design responses. Residential buildings require adequate sound isolation between dwelling units to protect privacy and prevent noise disturbance, with particular attention to airborne sound transmission through party walls and impact sound transmission through floors. Background noise levels from building systems and external sources must be controlled to permit comfortable sleep and relaxation.

Educational facilities demand acoustic environments supporting speech communication between teachers and students, with appropriate reverberation control and background noise limitation essential for learning effectiveness. Research demonstrates that excessive classroom noise and reverberation significantly impair student achievement, particularly affecting younger children and those with hearing impairments or learning differences. Guidelines typically recommend maximum background noise levels of thirty-five decibels and reverberation times not exceeding six-tenths of a second in classroom spaces.

Healthcare buildings present complex acoustic requirements including speech privacy for patient consultations, noise control for patient rest and recovery, and alarm audibility for safety systems. Research links hospital noise exposure to patient outcomes including sleep disruption, elevated stress hormones, and delayed healing. Acoustic design in healthcare settings must balance competing requirements for privacy, communication, and alerting.

Office environments increasingly adopt open-plan layouts that create acoustic challenges for speech privacy and concentration. Background noise levels, absorption provision, and spatial planning significantly affect acoustic satisfaction in open offices, with research indicating that noise-related distraction constitutes the most common complaint in these settings. Design strategies including sound masking systems, absorptive treatments, and enclosed spaces for concentrated work address these challenges.

4.3 Sustainability Principles in Building Design

Sustainable building design seeks to minimize environmental impact across building lifecycles while creating healthy and comfortable environments for occupants. Core principles include energy efficiency through passive design strategies and high-performance systems, resource conservation through material selection and waste reduction, indoor environmental quality supporting occupant health and productivity, and site design respecting ecological systems.

Energy considerations encompass both operational energy for heating, cooling, lighting, and equipment, and embodied energy in building materials and construction processes. Lifecycle assessment methods quantify environmental impacts across extraction, manufacturing, transportation, construction, operation, and end-of-life phases, enabling comparison of alternatives and identification of improvement opportunities.

Material sustainability criteria include recycled content utilizing post-consumer and post-industrial waste streams, renewable materials from responsibly managed biological sources, low embodied carbon reducing climate change contributions, durability extending useful life and reducing replacement frequency, and recyclability or biodegradability at end of useful life.

Indoor environmental quality encompasses thermal comfort, air quality, lighting, and acoustic conditions, all affecting occupant health, productivity, and satisfaction. Research demonstrates that poor indoor environmental quality imposes substantial costs through increased absenteeism, reduced productivity, and health impacts, while high-quality environments generate measurable benefits for organizations and individuals.

4.4 Intersection of Acoustic and Sustainable Design

The relationship between acoustic performance and environmental sustainability presents both synergies and tensions requiring integrated design approaches. Certain acoustic strategies align naturally with sustainability goals, while others create potential conflicts demanding careful optimization.

Massive construction materials including concrete and masonry provide excellent sound isolation through their high surface density, but carry substantial embodied carbon from cement production and extraction impacts. Lightweight construction systems using timber framing and bio-based materials offer sustainability advantages but require more sophisticated detailing to achieve equivalent acoustic performance.

Natural ventilation strategies reduce mechanical cooling energy but introduce external noise through openings, potentially compromising acoustic comfort in noisy locations. Design solutions including acoustic louvers, offset openings, and courtyard configurations can mitigate this conflict, though with added complexity and cost.

Open-plan spatial configurations reduce material use and enhance daylight penetration but create acoustic challenges for speech privacy and concentration. Addressing these challenges through absorptive treatments, space planning, and sound masking requires additional materials and systems with associated environmental impacts.

Recycled and bio-based acoustic materials offer opportunities to achieve acoustic objectives while meeting sustainability criteria. Products incorporating recycled textiles, agricultural fibers, and reclaimed materials increasingly provide performance comparable to conventional alternatives while offering superior environmental profiles.

V. ACOUSTIC DESIGN STRATEGIES FOR SUSTAINABLE BUILDINGS

5.1 Passive Acoustic Design Approaches

Passive acoustic design strategies utilize building form, spatial organization, and construction characteristics to achieve acoustic objectives without active systems requiring operational energy. These approaches offer inherent sustainability advantages through reduced energy consumption and mechanical system complexity.

Building orientation and site planning represent fundamental passive strategies, with positioning of noise-sensitive spaces away from external noise sources reducing transmission exposure. Courtyard configurations, building setbacks, and the use of less-sensitive spaces as acoustic buffers between noise sources and critical areas reduce acoustic challenges requiring construction-based solutions.

Spatial organization within buildings locates compatible uses adjacently while separating acoustically conflicting activities. Stacking similar functions vertically reduces impact sound issues, while clustering mechanical spaces and other noise sources enables efficient acoustic containment. Buffer spaces including corridors, storage areas, and circulation zones provide separation between noise-sensitive and noise-generating activities.

Room proportions and geometry affect internal acoustic characteristics including reverberation and sound distribution. Parallel reflective surfaces create flutter echoes and uneven sound fields, while angled or splayed surfaces improve diffusion. Room volume relative to absorption area determines reverberation time, with appropriate proportioning reducing treatment requirements.

5.2 Sustainable Acoustic Materials

Acoustic materials selection significantly influences both acoustic performance and environmental sustainability, with expanding options enabling achievement of both objectives. Material categories include absorptive treatments, barrier and isolation systems, and diffusive elements.

Natural fiber acoustic panels utilize materials including wool, cotton, hemp, flax, and wood fibers to provide sound absorption through porous mechanisms similar to synthetic alternatives. These materials offer advantages including renewability, carbon sequestration during growth, biodegradability at end of life, and low processing energy. Products incorporating recycled textile content divert waste from landfills while achieving excellent acoustic performance.

Recycled polyester acoustic panels, manufactured from post-consumer plastic bottles, provide absorptive performance comparable to virgin synthetic products while reducing petroleum consumption and plastic waste. These materials are themselves recyclable at end of useful life, supporting circular economy principles.

Wood and wood-based acoustic products including perforated panels, slatted systems, and engineered composites combine absorptive and diffusive characteristics with the sustainability advantages of renewable timber resources. Certification under Forest Stewardship Council or comparable programs ensures responsible sourcing from sustainably managed forests.

Bio-based insulation materials including cellulose from recycled paper, cotton from textile waste, and hemp fibers provide thermal and acoustic insulation while offering superior environmental profiles compared to conventional fiberglass and mineral wool products. These materials typically exhibit lower embodied energy, utilize waste streams, and present reduced health concerns during installation.

Mass-loaded vinyl barriers and acoustic sealants present sustainability challenges due to petroleum-based content and end-of-life disposal concerns. Alternative products utilizing mineral-filled polymers and bio-based formulations are emerging to address these limitations, though performance verification remains important.

5.3 Active Acoustic Technologies

Active acoustic technologies utilize electronic systems to modify acoustic conditions, offering flexibility and precision but requiring operational energy and equipment with associated environmental impacts.

Sound masking systems generate controlled background sound to reduce speech intelligibility and perception of intrusive noises, improving acoustic privacy and reducing distraction in open-plan environments. Energy-efficient systems utilizing modern loudspeaker and amplifier technologies minimize power consumption while providing effective coverage.

Active noise cancellation applies to specific situations including mechanical equipment enclosures and personal listening devices, though broad-area application in architectural spaces remains limited. Research continues toward practical active systems for building applications.

Electronic sound reinforcement improves speech intelligibility in large or reverberant spaces, reducing the acoustic treatment required to achieve acceptable conditions. Energy consumption of reinforcement systems varies widely depending on scale and technology, with modern digital systems offering improved efficiency.

VI. APPLICATIONS ACROSS BUILDING TYPOLOGIES

6.1 Residential Buildings

Residential acoustic design prioritizes privacy between dwelling units, control of external noise intrusion, and management of building system noise to support comfortable living. Sustainable approaches address these requirements while minimizing environmental impact.

Party wall and floor constructions achieving required sound isolation through optimized rather than excessive mass reduce material consumption and embodied carbon. Resilient mounting systems and discontinuous construction techniques improve performance without proportional

mass increases, while attention to construction quality prevents flanking transmission that defeats theoretical performance.

Window and facade systems addressing external noise transmission increasingly utilize vacuum or triple glazing configurations that simultaneously improve thermal and acoustic performance. Properly sealed construction prevents air infiltration that compromises both energy efficiency and sound isolation.

Mechanical system selection and placement significantly affects residential acoustic comfort, with quiet equipment and vibration isolation reducing transmission to living spaces. Heat pump and ventilation systems designed for acoustic performance prevent noise complaints that might otherwise discourage adoption of energy-efficient technologies.

6.2 Educational Facilities

Educational facilities require acoustic environments supporting learning through clear speech communication and freedom from distracting noise. Sustainable design achieves these requirements while minimizing environmental impact and creating healthy learning environments. Classroom acoustic treatments utilizing sustainable absorptive materials control reverberation to support speech intelligibility. Ceiling systems, wall panels, and furniture incorporating natural and recycled fibers achieve required absorption while meeting sustainability criteria. Appropriate treatment quantities prevent over-specification that wastes resources.

Partition systems separating classrooms and other learning spaces require sufficient sound isolation to prevent speech intelligibility between rooms. Construction systems utilizing sustainable materials and efficient designs achieve performance requirements while minimizing embodied carbon and construction waste.

Mechanical system design for educational facilities must achieve low background noise levels without excessive energy consumption. Properly sized ductwork, quiet equipment selection, and strategic placement enable compliance with classroom noise criteria while maintaining energy efficiency.

6.3 Healthcare Environments

Healthcare acoustic design addresses complex requirements for patient privacy, rest, and recovery alongside communication and alerting needs. Sustainable approaches recognize the demonstrated connections between acoustic environment, health outcomes, and operational effectiveness.

Patient room acoustic isolation prevents speech intelligibility between rooms, protecting privacy during sensitive consultations. Construction systems achieving required performance through optimized design rather than excessive mass reduce environmental impact while meeting regulatory and certification requirements.

Absorptive treatments in corridors and common areas reduce overall noise levels contributing to patient stress and sleep disruption. Cleanable acoustic materials developed for healthcare applications enable effective absorption in spaces requiring infection control, with sustainable options increasingly available.

Sound masking in healthcare settings improves speech privacy where construction-based isolation proves impractical or insufficient. Modern systems achieve effective coverage with minimal energy consumption while integrating with building management for optimized operation.

6.4 Office Environments

Office acoustic design addresses the challenges of open-plan configurations increasingly common in commercial buildings, balancing collaboration with concentration and privacy. Sustainable approaches recognize that acoustic dissatisfaction drives productivity losses exceeding the environmental costs of effective acoustic treatment.

Absorptive ceiling systems constitute the primary acoustic treatment in open offices, controlling reverberation and reducing sound propagation between workstations. Products utilizing recycled content and bio-based materials achieve required performance while meeting sustainability criteria. Appropriate absorption quantities balance acoustic effectiveness against material consumption.

Furniture-integrated acoustic treatments including panel systems, screens, and shelving with absorptive linings provide additional absorption at desk level where it most effectively reduces speech transmission between adjacent workstations. Sustainable furniture materials and finishes enable acoustic optimization within comprehensive sustainability programs.

Sound masking systems provide consistent background sound that reduces speech intelligibility and perception of intrusive conversations, significantly improving acoustic satisfaction in open offices. Energy consumption of modern systems remains modest relative to the productivity benefits enabled by improved acoustic conditions.

VII. INTEGRATION WITH GREEN BUILDING FRAMEWORKS

Green building certification systems increasingly recognize acoustic comfort as a component of comprehensive sustainability, though treatment varies substantially among frameworks and rating systems.

Leadership in Energy and Environmental Design includes acoustic performance credits within indoor environmental quality categories, addressing background noise levels, sound isolation, and reverberation control. Credit requirements align with professional acoustic standards while remaining achievable through standard good practice.

Building Research Establishment Environmental Assessment Method addresses acoustic performance through health and wellbeing categories, with criteria addressing sound insulation, background noise, and room acoustics tailored to different building typologies. The methodology enables quantification of acoustic performance within comprehensive environmental assessment. International WELL Building Standard emphasizes acoustic comfort as a fundamental component of healthy buildings, with extensive criteria addressing sound mapping, comfort parameters, masking, and privacy. The standard's health-focused framework positions acoustic performance alongside other environmental factors affecting occupant well-being.

Enhanced integration of acoustic considerations within sustainability frameworks would recognize the demonstrated connections between acoustic environment, health outcomes, and productivity. Quantification of acoustic comfort benefits through health and productivity metrics would enable more accurate assessment of acoustic investments within sustainability business cases.

VIII. CHALLENGES AND FUTURE DIRECTIONS

Despite growing recognition of acoustic importance in sustainable buildings, several challenges affect implementation and outcomes in contemporary practice.

Cost considerations influence acoustic specification decisions, with initial cost pressures potentially driving selection of conventional materials over sustainable alternatives. Lifecycle cost analysis incorporating durability, health benefits, and end-of-life implications would enable more informed comparisons, though such analysis requires data and methodologies not universally available.

Knowledge gaps between acoustic specialists and sustainability consultants may result in suboptimal integration of acoustic and environmental considerations. Interdisciplinary education and collaboration would improve outcomes through earlier integration of acoustic expertise in design processes.

Material innovation continues to expand options for sustainable acoustic products, with emerging developments in bio-based composites, agricultural fiber utilization, and closed-loop recycling systems. Performance verification through standardized testing enables comparison of alternatives and supports informed specification decisions.

Measurement and verification of acoustic conditions in completed buildings enables assessment of design effectiveness and identification of improvement opportunities. Post-occupancy acoustic evaluation, while less common than energy monitoring, provides valuable feedback for future projects and ongoing building management.

IX. CONCLUSION

Acoustic design represents an essential yet frequently underemphasized dimension of sustainable architecture, with significant implications for environmental performance, occupant health, and building functionality. The acoustic environment profoundly affects human experience, influencing sleep quality, cognitive function, communication effectiveness, and psychological well-being across residential, educational, healthcare, and workplace settings.

Integration of acoustic considerations within sustainable building design requires recognition of both synergies and tensions between acoustic and environmental objectives. Passive design strategies including building orientation, spatial organization, and room geometry achieve acoustic objectives through fundamental design decisions rather than added systems. Sustainable acoustic materials incorporating natural fibers, recycled content, and bio-based constituents provide

performance comparable to conventional alternatives while offering superior environmental profiles.

Challenges related to cost considerations, knowledge integration, and material availability affect implementation, though expanding options and growing recognition of acoustic importance support continued progress. Enhanced treatment of acoustic performance within green building certification systems would accelerate adoption of integrated design approaches and enable more comprehensive sustainability outcomes.

The evidence supports acoustic design as a legitimate and important component of sustainable architecture, warranting attention comparable to that afforded energy efficiency, material sustainability, and other environmental considerations. Buildings achieving acoustic comfort through sustainable means serve occupants well while meeting environmental responsibilities, demonstrating that these objectives complement rather than compete when addressed through integrated design approaches.

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