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Research Article

Sustainable Design Strategies in Architectural Engineering: A Comprehensive Review

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ABSTRACT

Sustainable design is at the heart of architectural engineering. The reason is that it contributes to the reduction of the negative human impact on the environment and brings improvements to human conditions as well. The proposed research is devoted to sustainable architecture with the main focus on its principles, strategies, and advanced technologies. Energy efficiency, material choice, and life cycle assessments are among the core aspects of such architecture. Through the extensive literature review, the study will promote the understanding of the integration of sustainability in architecture educational programs, regulatory policies' effects, economic aspects, and the social advantages of using sustainable design. The overview of successful projects worldwide will deliver practical recommendations for construction and design specialists. The importance of taking care of an integrated, holistic approach to solve issues and overcome barriers on the way to sustainability will be proven as well. Finally, predicted developments will be discussed together with new technologies to follow in order to secure the future of sustainable architecture.

1. INTRODUCTION TO SUSTAINABLE DESIGN IN ARCHITECTURAL ENGINEERING

Sustainable design has emerged as a pivotal facet in the vocation of architectural engineering. With the growing awareness of environmental concerns, professionals in this field are actively involved in the planning and construction of sustainability-integrated infrastructures. Sustainability is seen as a new paradigm that restructures architectural theory and practice. Attaining sustainable development is paramount for humanity's survival, rendering the pursuit of sustainable design strategies crucial. The design of built environments profoundly impacts energy usage and consequently the ecology. Therefore, environmentally responsible architectural design strategies are urgently needed. In this regard, the discussion begins with a broad explanation of sustainable design and specific architecture-relevant terminology [1]. Sustainable design is defined as having consideration for the natural environment, an ecosystem approach, and recognizing the interdependence between nature and humanity.

Unfortunately, unsustainable policies and activities have led to variable environmental degradation, which urgently threatens the delicate balance of natural systems. Nonetheless, humanity has the capability, if not obligation, to reestablish sustainability. Since design is a means of generating the built environment, and considering that designers principally influence the ecological outcome of the built, sustainable design necessitates the remodeling of the design process. Furthermore, architects and engineers possibly have the greatest potential to influence globally sustainable development. Therefore, in collaboration, these two professions should take a leading role in propagating and implementing sustainability. Several sustainable design strategies undertaken by famous architects and engineers are discussed and analyzed, providing considered contributions in ameliorating the built environment [2].

2. IMPORTANCE OF SUSTAINABLE DESIGN IN THE BUILT ENVIRONMENT

Sustainable design plays a pivotal role in the built environment. The design and operation of buildings directly impact energy consumption and resource depletion. Buildings account for about 36% of total energy consumption and 65% of electricity use in the United States. Globally, buildings are responsible for 40% of energy use and 30% of greenhouse gas emissions. Therefore, a necessary and personal step toward sustainability is the implementation of energy-efficient design strategies and building systems to help reduce carbon footprints. Additionally, biophilic design strategies can improve ecological balance by enhancing and integrating nature into the built environment. Because of the significant influence of the built environment on human life, this research also seeks to implement design strategies that promote health and well-being. Beyond aesthetics, architectural design plays an important role in enhancing occupant experience and quality of life.

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The growing awareness of climate change combined with the COVID-19 pandemic has increased public awareness and demand for sustainable buildings. Net-zero buildings that produce as much energy as they consume are becoming a high priority. The importance of addressing operational energy use and associated carbon emissions in the establishment of the 2050 net-zero goal is recognized. This goal is pursued by most of the countries worldwide through nationally determined contributions (NDCs) for reducing greenhouse gas emissions. It is anticipated that future buildings will comply with net-zero energy regulations, and hence, conducting energy simulations during the design phase will be necessary [3]. Sustainable design is no longer a trend but rather a necessity for the future of the planet. A healthy built environment is essential for health and well-being. Sustainability is an intersectional concept that encompasses health and well-being. In addition to environmental stewardship, design contributions to social equity are emphasized. Sustainability is a holistic approach that includes economic viability, social equity, and environmental protection. Sustainable architecture should create healthy and productive built environments while minimizing natural impacts. For the built environment, this can be interpreted as a focus on sustainable design practices and enhancing the health and well-being of its occupants. Such a focus involves the selection of sustainable materials, energy-efficient systems, and designs that promote health and well-being; reducing the carbon footprint of the building through low-impact materials and resource use; and maximizing energy efficiency and the use of renewable energy sources. In architectural practice, this can be translated into an emphasis on creating spaces that improve occupant health and well-being. This involves maximizing natural light and views, prioritizing indoor air quality, providing a variety of spatial configurations, and incorporating biophilia, nature, and greenery into the design [4].

3. KEY PRINCIPLES OF SUSTAINABLE DESIGN IN ARCHITECTURE

Sustainable design in architecture is guided by a set of fundamental principles, ensuring considerations for the environment, user well-being, and energy efficiency. The building’s site is crucial; factors like natural light, wind direction, and natural vegetation influence energy consumption. The building should be oriented based on the sun's movement, utilizing shading devices for overheated areas and maximizing sunlight in cold regions. The design should promote passive solar energy use, integrating thermal mass, light shelves, and ventilation to control heat and air. Water conservation considerations include water-efficient fixtures, recycled water for non-potable uses, and controlling water run-off. Waste management solutions include reducing waste generation, reusing materials, and establishing recycling facilities. The design should foster biodiversity through native planting and wildlife habitats while preventing ecological disruption. Attention to human movement is vital; common pathways enhance experience and interaction. Spaces should be flexible for various user needs, incorporating adaptable furniture. Multi-functional spaces optimize areas and reduce costs. Technology can enhance comfort through adjustable controls for heating, cooling, and lighting. Designs consider clear signage and orientation to avoid confusion. Openness in designs promotes interaction but must ensure privacy when needed. Aesthetic design enhances emotional engagement and appreciation. Operational efficiency can be improved through user training. Buildings should facilitate easy maintenance access, integrating external access points for cleaning [5]. These principles form a robust framework for developing environmentally friendly and user-oriented buildings. However, applying them independently may lead to subpar designs. Principles addressing ecological disruption should be prioritized, designing spaces that nurture and enhance surrounding ecosystems. User-centered principles should enhance experience, safety, health, and productivity. Integrating all principles holistically in conceptual designs is crucial for better outcomes.

3.1 Energy Efficiency

Energy efficiency is one of the most central issues of sustainable design. Helping to reduce energy consumption of the buildings is one of the aims of architecture and design, which can be achieved through clever and forward-thinking designs. As buildings are one of the main consumers of energy, and according to contemporary standards, new buildings should use as low amounts of energy as possible, the architecture should promote innovative ideas and strategies on how to achieve that goal [6].

Concepts such as passive heating or cooling, and the usage of natural light are some examples of techniques that can be integrated into the design if the building is thought of at the early design stages. Also, the isolation of the building envelope is crucial and plays an important role in keeping the energy inside the building . The integration of energy-efficient systems, such as HVAC systems needs to be designed and planned thoroughly. Furthermore, the usage of renewable energy sources should be implemented into the design to cover energy needs, such as electricity or water heating.

It is said that newly built or refurbished buildings can save around 70% of energy needs with appropriate measures taken into consideration. Also, most of energy-saving measures have low payback periods (up to 10 years), so the long-term benefits would be covered economically as well. As such, energy efficiency should be one of the cornerstones of sustainable architecture and design [7].

In recent years, an increasing number of buildings have begun to integrate technology-based solutions to assist in the management of the building. These types of buildings usually integrate systems that control temperatures, heating, lighting, ventilation, and other factors that affect the comfort inside the building. However, most of the time, technology intervention is an exaggerated reaction to the passive design failure. Thus, instead of looking to further enhance the already efficiently

functioning passive systems, energy-consuming technical solutions are brought into the buildings. So, smart technology should not be thought of as a standalone category, but rather be integrated as technology amendments to the passive systems that would further optimize their successfulness.
There are various examples of energy-efficient buildings in practice, showcasing either a thorough energy concept with low energy needs or almost energy-independent buildings, that produce more energy than consume, thanks to the implementation of renewable energy sources. These buildings serve as a great example and the best motivation for the new generation of architects and engineers to design even more ambitious buildings concerning energy efficiency.

4. INTEGRATION OF SUSTAINABLE DESIGN INTO ARCHITECTURAL ENGINEERING CURRICULUM

The integration of sustainable design principles into architectural engineering education is essential for the future development of the profession. With the growing emphasis on sustainability in architectural practice, it is imperative to prepare the next generation of architects and engineers with the necessary knowledge and skills. However, an investigation into the academic curricula of architectural engineering departments reveals that only a minority currently address sustainability principles. For those that do, the treatment is often superficial and insufficient to prepare students for the challenges of sustainable design in their professional careers. Therefore, pedagogic approaches and strategies for the effective teaching of sustainable design principles are presented. Exposure to real-life building projects developed in collaboration with architectural firms can enhance the students' understanding and awareness of sustainable design challenges [8].
It is found that sustainable design principles can be embedded successfully through compulsory design courses within architectural engineering programs. Strong collaborative efforts between students and industrial professionals in the design process are crucial for the effective integration of sustainability principles. However, the availability of resources, such as teaching staff, time, and studio facilities, can be a challenge for departments looking to integrate sustainability into their curriculum. Nevertheless, departments with limited resources have successfully introduced educational programs promoting sustainability. Building on these experiences, fundamental pedagogical strategies for the successful integration of sustainable design principles into architectural engineering curricula are proposed. Architectural engineering departments are encouraged to seize the opportunity to take an active role in the future built environment by fostering the sustainable design competencies of their graduates. In recent decades, concerns over energy scarcity and climate change have highlighted the pressing need for a more sustainable built environment . In response, the architectural professions have increasingly embraced the challenge of designing sustainable buildings. However, the design of truly sustainable buildings requires a profound understanding of the complex interrelationships between architecture, engineering, and technology [9].

5. CASE STUDIES OF SUCCESSFUL SUSTAINABLE DESIGN PROJECTS

This section highlights various case studies comprising successful sustainable design projects from different building types and geographical contexts. Each case study specifies innovative approaches to architectural sustainability found in each project example, focusing on the outcomes, benefits, and lessons learned from the design approaches taken in the projects . The first 10 projects are more established international award-winning designs ranging from 1998 to 2014, while the last four are more recent experiments conducted in Australia in 2019. The former group intends to showcase inspiring worldwide role models of sustainable design for architectural practitioners, clients, and researchers for future endeavors, while the latter group aims to present novel experiments that can serve as a basis for future designs and analyses. The examined projects span various building types, from cultural and educational facilities to low-income housing, and contexts from Brazil to Afghanistan and Australia. Community involvement and participation are emphasized in the successful outcome of the designs in five of the examples [10].
As an integral part of a project's sustainable design, the approach to that sustainability design is also often considered pivotal to the project's success. In two examples, the design approaches in a project are solely the architect's undertaking without client intervention. All examples highlight the importance of sustainability performance measurement in the projects. In five projects, the quantification of sustainability metrics in the design, either prior to or post-occupancy, is discussed. This can help ensure the best sustainable design practices observed in the case studies are readily accessible to architects and designers. These projects either translate the case study designs as working drawings for practitioners to follow or outline the principles with vital information for architects and engineers' best practices to adopt. As an inspiring model for future sustainable design, this compilation of projects will be expanded and updated as more examples are identified [11].

6. TECHNOLOGICAL INNOVATIONS IN SUSTAINABLE ARCHITECTURE

Sustainable architecture significantly advances the latest technological innovations. This chapter surveys cutting-edge tools and innovative methods contributing to sustainable and energy-efficient designs, achievable through implementing technological progress in building architecture. It includes a range of technological innovations regarding building materials, construction methods, and architectural design. The new generation of architectural engineering is proposed, where digital technologies in the development and designing of buildings and architectural engineering are crucial for achieving sustainable performance outcomes. Smart buildings and digital technologies in architectural engineering generate and design buildings with the best resources' use control during construction and daily functioning. As an advanced stage of architectural engineering, building design is interpreted as a complex system, where the physical design defines structure and other functional aspects. Architectural engineering determines building performance concerning sustainability, energy consumption, ecology, etc., aiming at finding the best design and innovative technologies for desired performance and green modeling . To illustrate the technological innovations in practice, conducted case studies are presented for real-world projects or competitions demonstrating experimental, applied, or ongoing research [12].

The concept of the Internet of Things (IoT) applies to buildings where objects measure, monitor, and share information about physical data, controlling the usability and efficiency of resources consumed. These aspects are crucial for smart control systems in newly designed buildings, where integration of IoT control is anticipated. Consider smart buildings as mini-complex systems where resource consumption and building space organization control are determined by the dynamic data flow from interior monitoring equipment. Technological aspects deal with the utilization of outcomes from monitoring activities and a set of mathematical models for different building functions like comfort control, heat flow, energy management, etc. Determined models for building functions may be integrated into one complex model where a whole building performance is optimized concerning controls for its inner functions . All monitored parameters are interpreted in a common time and space, generating a knowledge base for observed data on a whole building system. A software package enables continual and automated monitoring, analysis, and model adjustment, maintaining the optimal performance of a building and its functions through the desired state control. At this moment, monitoring equipment is designed for observation comfort control in the building ensured by HVAC installation. The integration generates procedures for the design of monitored buildings [13].

7. SUSTAINABLE MATERIALS AND CONSTRUCTION PRACTICES

Selection of materials significantly impacts a building's overall sustainability profile. Sustainable material selection can span numerous strategies: sourcing recycled materials, employing rapidly renewable resources, selecting low-impact or local options, or pursuing non-wood or alternative substitutes for traditional materials. Additionally, it is essential to use life cycle assessments (LCAs) to select environmentally friendly materials and systems so that architectural and engineering professionals can confidently choose sustainable materials. Construction practices can minimize waste, maximize efficiency, or promote techniques that do not involve the use of toxic or detrimental substances. It is essential to achieve a sustainability-related building certification, such as a LEED rating, BREEAM, or Green Globe certification, among others that have emerged internationally. Figure 1 illustrates the life cycle of sustainable construction materials, starting from the manufacturing stage and extending to the construction phase. In alignment with the sustainability paradigm, waste produced during both production and construction is reused and recycled [14].

Due to the high volume of construction materials used in the United States, significant opportunities exist to minimize the environmental impact of the construction industry with sustainable material choices. Energy efficiency and sustainable construction practices complement traditional sustainable design efforts focused on buildings' operational energy. There are various sustainable materials: recycled materials, renewable materials, low-impact materials, and local materials. Recycled materials can be in the form of post-consumer or post-industrial waste. An example is using crushed recycled concrete aggregate in new concrete or asphalt pavements [15].

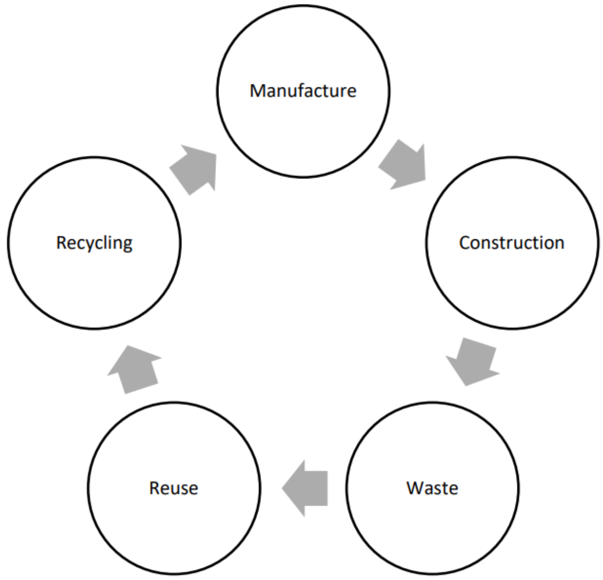

Fig 1. Sustainable construction material life cycle

Steel framing can also reduce the need for landfill space, as numerous scrap steel recycling facilities exist. Recycled interior finishes, such as carpets or tiles, can be sourced from the companies that manufacture them, and many companies will take back carpet tile flooring for recycling into new tiles [16]. The structural design of steel framing systems is covered in North America by AISI [11] and in Europe by EN 1993 [12], Figure 2 shows the steel frame system which has emerged as an innovative and cost-efficient solution, adhering to most of the criteria specified for new sustainable buildings.

Fig 2. Steel framing system [13]

Like recycled materials, rapidly renewable materials also play a part in the sustainable material palette. Bamboo, for example, can be used for everything from structural members to flooring. While bamboo behaves as a grass and renews itself quickly, it has mechanical properties similar to steel, making it structurally equivalent. Straw is another rapidly renewable material and can be used in bales as wall systems, roof applications, and more. However, straw has a limited lifespan if not protected from moisture. Cork is a renewable material that can substitute for flooring and other applications, as it does not require a tree to be cut down to harvest the material; it simply strips the bark from the tree, which eventually grows back [17].

8. LIFE CYCLE ASSESSMENT IN SUSTAINABLE DESIGN

Life cycle assessment (LCA) is a comprehensive method for evaluating the environmental impacts associated with all stages of a material’s life cycle, from raw material extraction to processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling. LCA has widely been adopted as a tool for assessing and improving the sustainability of products, processes, and services. This assessment can also refer to embodied energy assessment that evaluates the total energy consumed for building materials, systems, and processes throughout their life cycle. In the architectural and engineering practice, calculating the embodied energy of a building can initially reduce or measure its ecological footprint during the design phase. The knowledge of embodied energy can significantly affect design decision making regarding sustainability. Furthermore, it allows building designers to identify opportunities to reduce the building’s ecological footprints by isolating the contributions of consideration parameters. It can also be a tool to benchmark the ecological footprints of different designs. A variety of tools, methodologies, data inventories, and experiences are employed to conduct LCAs. Some of them are developed specifically for the A/E/C industry. A number of successful case studies have successfully conducted LCAs to assess the designs and incorporate the results for the improvement of sustainability in the built environment. However, there are some difficulties and challenges that are related to the current practice of LCA that hinders the professional designers to adopt it. The understanding of LCA in architectural practice is still very limited, and LCA is not adopted as “common knowledge”. Therefore, LCA cannot be effectively used as a tool for promoting sustainability in architectural design. Many shortcomings of LCA’s current practice are rooted in the constraints of LCA itself. Criticisms of LCA are discussed and concerns are raised regarding the potential misapplication of LCA. In summary, LCA is advocated as a necessary and critical tool for promoting sustainability; however, considerations are required to avoid some of the pitfalls [18-20].

9. URBAN PLANNING AND SUSTAINABLE DESIGN PRINCIPLES

Amidst the backdrop of an ever-evolving world burdened by rapid growth and globalization, communities are increasingly captivated by the notion of sustainability. As a result, the quest for refuge in the form of "sustainable communities" has emerged. Here, the convergence of urban planning and sustainable design principles becomes pivotal since a community's design and overall look rely heavily on its planning. Thus, the consideration of comprehensive planning and design is crucial for achieving successful sustainable communities . These discussions center on the various approaches that planners and designers can adopt to enhance urban sustainability through design. While the focus is primarily on the built form, aspects such as land use planning, social consideration, and governance are also taken into account [21].

Today, most people in Europe and North America still live in cities, and this trend is likely to continue. Cities constitute the stage for social life. They provide the space within which people conduct their daily activities and establish a social context. From this perspective, urbanization is indicative of human progress. However, the unintended consequences of urban development could compromise this progress. One of the most serious challenges that cities currently face is achieving sustainability. Unfortunately, many cities are unsustainable places. Nonetheless, cities provide opportunities to turn things around. They are the places where the use of resources and energy can be observed, and where most public policy is made and implemented. They are also centers of innovation and economic growth. Above all, with the concentration of people and resources, cities are the places where a concerted effort can be made to achieve progress towards sustainability goals [22].

Design can contribute to urban sustainability in various ways, such as through buildings, public spaces, transportation, and infrastructure systems. Public space is one of the critical domains where social life flourishes and communities are formed. The design of public spaces needs to consider social inclusion and interaction, as well as ecological considerations. Meanwhile, the public realm routinely accommodates and links different transportation modes. The design of transportation systems and streetscapes should address the complementarity and connectivity between different transportation modes while considering safety and accessibility. It should also promote the use of public transport and non-motorized modes. Infrastructure is the underlying network that supports urban functions. Sustainable urban design should address the integration of the built infrastructure network and the ecological infrastructure network.

The integration of ecological infrastructure networks is particularly important for cities in which rivers and natural wetlands are heavily modified and concealed. Land use planning is critical in the consideration of social inclusion and environmental justice. The design of land use patterns should enhance people's accessibility to public spaces, especially those with ecological functions. It should also avoid land use mixtures that generate pollution and nuisances to improve the local environment. Biodiversity considerations should be incorporated into land use planning, especially the design of the built form. Urban greenery provides multiple functions, including recreation, biodiversity, and microclimate amelioration. The design of greenery networks should ensure connectivity between different green spaces and the surrounding natural landscapes. The built form design should address the integration of green spaces within buildings and among buildings.

Several critical issues in the design of the built form can enhance urban sustainability. First, the design of the built form should consider urban density. Compact development can help curb urban sprawl and preserve agricultural land and natural landscapes, even though a certain degree of sprawl is necessary to provide housing for low-income groups. The compactness of a new development should be considered by evaluating its location concerning existing urbanized areas and public transport stops. Within the existing urban area, the development should be designed to induce high density rather than a low-density scenario, controlling its footprint size and height. Second, mixed-use developments can contribute to urban sustainability. Mixed use can encourage social inclusiveness and interaction. Integrated land use and transportation planning can shape mixed-use developments in proximity to public transport stops, thus enhancing accessibility. Lastly, several successful projects in which the above principles are adopted are presented. These projects clearly demonstrate that urban design can play a vital role in sustainability [23].

10. REGULATORY FRAMEWORKS AND POLICIES FOR SUSTAINABLE ARCHITECTURE

Awareness of the environmental repercussions resulting from energy consumption in the built environment is growing rapidly. Buildings are responsible for a significant proportion of energy use and greenhouse gas emissions. Therefore, it is essential for architects and designers to comprehend regulatory frameworks and policies affecting built environmental quality and sustainability in their respective countries. Establishing tangible policies and regulations is crucial for effectively promoting sustainable architecture. Focusing on the current state of policies and regulations within a specific context can yield diverse insights and viewpoints. This discourse presents a comparative critique of legislation, building codes, and policies that directly or indirectly promote sustainability in the architectural context of several nations. Moreover, issues, inadequacies, and concerns regarding these regulations are highlighted while suggesting effective resolutions. It is maintained that ecological, socio-cultural, and politico-economical sustainability and sustainable architecture are generally regarded as desirable or praiseworthy outcomes of governmental support.

Aspects and categories of sustainability – particularly those pertinent to the architectural discipline – are discussed along with numerous worldwide examples demonstrating the effectiveness of policies and regulations in promoting sustainability. It is argued that gross and wide-ranging harmonization of national, regional, and local regulations is critical in upholding robust and effective sustainability outcomes in the architectural context. This exploration embraces legislation, codes, and policies directly or indirectly affecting architectural design. However, due to space constraints, only selected nations with diverse cultural and architectural practices are reviewed, including France, the UK, Japan, the USA, Afghanistan, and India. In addition, regulatory systems and paralleled architecture in specific nation-states are examined to discern similarities and differences. In recent years, sustainable architecture has become a heated topic of discourse among academics, designers, and policymakers. Consequently, numerous codes, policies, and regulations addressing varied aspects of sustainability have emerged. However, the prevailing concern remains the level of implementation of such regulations and the professional understanding of their implications on the quality and sustainability of designed enclosures [24].

11. ECONOMIC AND SOCIAL BENEFITS OF SUSTAINABLE DESIGN

The economic and social benefits that accompany sustainable design are diverse. Many practitioners question the design and renovation costs of making a building more sustainable. Therefore, it is essential to demonstrate how sustainable design can save costs in the long run. The simplest option for establishing the financial benefits of sustainability is to create a list of energy savings, raw material savings, and waste savings from sustainable practices. These savings can be assigned a monetary value, yielding a clear economic benefit. Concrete case studies can demonstrate the long-term advantages of sustainable design initiatives. For example, a low-cost energy efficiency investment saved the Milford school board approximately $220,000 a year (about 20 percent of its energy budget).

Beyond cost savings, sustainable practices can increase revenue as well. New sustainable buildings often have higher property values than conventional buildings, and in many cases, they are more marketable. In a number of studies, this "green premium" was established. For example, it was determined that building-wide Energy Star ratings increase a property's value by 4 percent on average, while LEED certification increases value by 7.5 percent. In addition, sustainable design can create social benefits for society. For example, energy efficiency has been linked to improved health and well-being for building occupants. It was found that schools with larger windows and views of green landscapes improve student health and learning capabilities [25].

Moreover, there is a general agreement that a well-structured and thorough design process improves design quality. Therefore, community engagement and stakeholder participation should become common practice in undertaking design initiatives. Other principles that should be considered generally for sustainable design are a clear design vision, responsiveness to the local context, and consideration of future changes. However, the proposed principles do not consider the wider socio-political context in which a community might operate. It emphasizes how local structures need to be recognized to ensure proper community representation. The political structures' role in enabling or disabling community engagement through the planning framework is also underlined.

There are also suggestions that social issues should be pursued through the built environment. For instance, the built environment can either foster community engagement and social cohesion or inhibit it through exclusion and segregation. Sustainable design can help embed social equity within urban areas through the proactive engagement of local communities. It is generally accepted that sustainable design can create jobs and training opportunities essential for tackling social exclusion. In addition, new employment opportunities can be created through the efficient use of resources, land reclamation for new industries, and the development of new technologies [26].

12. CHALLENGES AND BARRIERS TO IMPLEMENTING SUSTAINABLE DESIGN STRATEGIES

A range of economic, political and institutional barriers or challenges with regard to the routine use of sustainable design strategies were reported. Some professionals have to contend with clients who resist change in favoured design practices. The architects noted that there was «resistance to change in the industry» and that there was a «long held tradition in design thinking» there also needs to be more awareness amongst landlords or clients with regard to sustainability-based solutions. Some building services engineers went further, stressing that there was a vein of inertia or apathy running through the construction and property industries. One stated that: «The industry has got a primitive attitude as it sees sustainability as a compliance issue rather than an opportunity for innovation and advancement» What is needed is for more flag-ship sustainable developments to be built that are a real touch-stone for other developments to aspire to be like. Building designers also pointed out that needed education and training in sustainable design was either superficial or lacking entirely within academic institutions. Many post-graduate building services engineering applicants did not have an adequate first degree grounding in the principles of building physics to be able to go-awry with computer modelling. Alternatively, designers from an architectural background struggled to grasp the complexities of building services and environmental systems management within their designs. It was also noted that many of the materials and technologies needed to achieve higher environmental performance limits were simply not commercially available or readily accessible within the local market. A number of architects stated that the lack of good quality and affordable sustainable materials was a limiting factor in undertaking environmental improvements on their projects [27]. Likewise, several building services designers stated that current computer modelling software systems were limited in their technological capabilities that need to be better taken – advantage. Thus, environmental assessment models or instruments needed to be more widely adopted to ensure designers were brought to the forefront of innovative sustainable building strategies. Particularly with regard to energy performance, the architectures noted that many of the modelling tools and methodologies for assessing a designs environmental performance were simply not being routinely applied at the feasibility design stage. Regulation can also be an obstructive force and currently there are several building regulations that inadvertently contravene sustainability measures being implemented in developments. For example, a number of building services engineers were frustrated that the current legislative framework regarding fire safety codes stymied the use of low energy lighting systems, which currently do not conform with fire safety testing requirements. With regard to planning regulations, one architect said they could either be benign or draconian, depending on the local authority. The regulations also need to encourage research and development at academic institutions into innovations technologies that could enhance a buildings environmental performance, but that research and development should be commercially driven and not publicly funded so as to ensure that the results are widely disseminated. There would also be a need for better education and professional training on how to apply the building environmental assessment models or methodologies to better ensure that designers routinely attempt achieve the highest environmental performance targets possible with their developments. Finally, there needs to be a concerted effort by professional institutions to better promote sustainable design approaches as a viable competitive strategic advantage. In summary, while there are several barriers to the sustainable strategies being routinely adopted in the built environment-summarised as economic, regulatory, knowledge and awareness and political – there are also steps that could be taken to mitigate them [28-30].

13. FUTURE TRENDS AND EMERGING TECHNOLOGIES IN SUSTAINABLE ARCHITECTURE

Anticipated future trends in sustainable architecture are discussed, including innovative materials and constructions techniques and new design philosophies that are just over the horizon. Emergent practices that limit a building's impact and/or enhance its positive influence on the environment are reviewed. Special attention is paid to the role of digital technology in enhancing the sustainability of the built environment, particularly through smart building solutions. Consideration is given to growing trends such as the adaptive reuse of buildings and modular construction. Environmental resilience and climate responsive design are discussed as currently fashionable topics in the world of architecture [31-32]. Some possible socio-economic shifts that may influence the course of sustainable architecture in the future are proposed. The essay is illuminated with a number of case studies comprised of foresighted projects that exemplify the emerging trends.

Sustainable architecture has evolved dramatically from a curious fringe practice into an influential sector of the construction industry. Many architects and architecture firms are now engaging, capable of taking sustainable design to the next level. As the environmental externalities caused by architecture are better understood, so too are its social and economic externalities; hence, sustainable architecture can no longer be thought of purely as a technical solution. On the horizon, it appears that architecture's capacity to influence ecological, social and economic systems will become a key measure of its design quality, where good architecture is that which enacts good and rich relations within these systems. A snapshot of current sustainable architectural practices reveals that they tend to cluster at four loosely defined points along a continuum. A dynamic future for sustainable architecture is envisioned, as well as the architectural practices of tomorrow [33].

14. CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

The key insights from the literature review are synthesized in the conclusion. Sustainable design is broadly defined, emphasizing the need to consider diverse and sometimes conflicting environmental, social, and economic concerns. The importance of sustainable design is reiterated, particularly in architecture and the built environment. Research studies investigating aspects of sustainable design are reviewed, and the themes and trends in the literature are identified. This review aims to contribute to a clearer understanding of current knowledge and practice in sustainable design, highlighting gaps that need to be addressed through ongoing research.

Sustainable design has entered the design and construction vocabulary of many countries and organizations. In the built environment and architectural engineering, recent disasters and developments have prompted a more optimistic concern with sustainable design. However, understanding what is meant by "sustainable design" is not straightforward. The requirements of the local context and the values of users are essential factors in achieving sustainability in design. Through a review of literature on sustainability in the built environment, proposed mechanisms for approaching sustainable design are discussed. These perspectives relate to a broader vision of what sustainability is, a holistic understanding of the built environment, and the co-designing of a proposal with relevant users that is thought to enhance sustainability .

Future research studies in sustainable design are suggested in specific areas: processes and methodologies for achieving sustainable buildings in particular contexts and climates; construction material choices that enhance sustainability; exploring and measuring users' values and understanding of sustainability; design education concerning sustainability; and planning policy contexts that enhance sustainable development. Within these studies, the wider social, cultural, and ecological context and interaction between the built environment and users should be taken into consideration. It is often claimed that sustainability cannot be achieved through design alone, but rather that it should be considered a desired state-enhancing design. Disciplinary collaboration should be promoted to approach sustainability broadly. Political commitment toward combating climate change and enhancing social equity is crucial. Regarding architecture, the relevant stakeholders should be made aware of the benefits that would arise from sustainable practices [33-35].

Sustainability is often approached as a design, planning, or technical problem to solve through a framework or set of rules to follow. Although these have their merits, they often fail to enhance sustainability directly. Attempts to design and plan for sustainability fail if the social and political context, where the interest in having a sustainable built environment emerges, is not taken into consideration. It is important to understand what the built environment means to the users and how it is valued. Design and planning, which would enhance sustainability, can be proposed only if an understanding of this value discourse exists. Standards and technical solutions should be utilized cautiously, as the context of their application differs. One means to enhance the desired state is to propose designs or plans that would alter the present state. It is necessary to adapt to the changing environmental conditions and reconsider the design or planning context when the aim is to enhance one aspect of the built environment. The desired state is becoming more eloquent and measurable when one aspect is approached, which assists in discerning the complexity of the context.

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Conflicts of Interest:

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References

[1] M. Khatibi, K. A. M. Khaidzir, and A. M. Rashid, "Defining sustainability in Afghanistan's built environment: A case study of World Bank building in Kabul and comparative analysis of prominent literature," *Int. J. Des. Nat. Ecodyn.*, vol. 16, no. 3, pp. 297–305, 2021.

[2] Obi, "An agenda for the management of contemporary sustainable houses," *Int. J. Contemp. Urban Aff.*, vol. 1, no. 2, pp. 33–37, 2017, doi: 10.25034/ijcua.2017.3646.

[3] R. Parashar, "An architectural approach towards a sustainable development," *Int. J. Eng. Res. Appl.*, vol. 4, no. 1, pp. 440–445, 2014.

[4] E. Ozer and D. T. Thompson, "Organic strategies to sustainable buildings and cities," *J. Green Build.*, vol. 4, no. 3, pp. 123–134, 2009.

[5] L. M. J. Al-Dulaimi and K. E. Amori, "A tubular solar still integrated with a heat pipe," *Heat Transfer*, vol. 52, no. 4, pp. 3353–3371.

[6] S. Steiner and R. Penlington, "Approaches to the embedding of sustainability into the engineering curriculum - Where are we now, and how do our graduates become global engineers?," in *Proc. 3rd Int. Symp. Eng. Educ.*, 2010, pp. 1–6.

[7] L. Thuvander, P. Femenias, B. Rubino, and M. Eden, "25 years of shaping future architects and architecture - The evolution of a sustainable building curriculum," *Buildings*, vol. 5, no. 3, pp. 620–632, 2015.

[8] B. Neyestani, "A review on sustainable building (green building)," *Civ. Environ. Res.*, vol. 9, no. 1, pp. 1–9, 2017.

[9] M. A. Zanni, R. Soetanto, and K. Ruikar, "Facilitating BIM-based sustainability analysis and communication in building design process," *Energy Procedia*, vol. 62, pp. 220–229, 2014.

[10] T. Mircea, "Reducing the environmental impact by using proper construction materials and techniques," *Procedia Eng.*, vol. 21, pp. 112–119, 2011.

[11] American Iron and Steel Institute, *North American Standard for the Design of Cold-Formed Steel Members*, AISI S100, Washington, DC, USA, 2016.

[12] European Standard, *Eurocode - Design of Steel Structures*, EN 1993, Brussels, Belgium, 2005.

[13] CERM-EX, *Cold-Formed Steel Structures*, 2013.

[14] S. Zhao, M. Lavagna, and E. De Angelis, "The role of life cycle assessment (LCA) and energy efficiency optimization during the early stage of building design," *Energy Procedia*, vol. 111, pp. 367–376, 2017.

[15] F. H. Akers III, "Sustainable development: Origins and future. An examination of environmental design, LEED-ND, and sustainable codes," *J. Sustain. Real Estate*, vol. 1, no. 1, pp. 106–123, 2009.

[16] N. Dias, D. Amaratunga, K. P. Keraminiyage, and R. Haigh, "Balanced urban design process to create resilient and sustainable urban environments," *Procedia Eng.*, vol. 212, pp. 657–664, 2018.

[17] E. K. Lee, "Green buildings: Lease structure, productivity, and regional economic impacts," *J. Sustain. Real Estate*, vol. 8, no. 1, pp. 23–47, 2016.

[18] D. Ekundayo, S. Perera, C. Udeaja, and L. Zhou, "Towards developing a monetary measure for sustainable building projects: An initial concept," *Procedia Eng.*, vol. 145, pp. 1202–1209, 2016.

[19] Z. Shari and V. Sobarto, "Delivering sustainable building strategies in Malaysia: Stakeholders' barriers and aspirations," *Energy Policy*, vol. 45, pp. 500–509, 2012.

[20] J. Dadzie, G. Runeson, G. Ding, and F. K. Bondinuba, "Barriers to adoption of sustainable technologies for energy-efficient building upgrade - Semi-structured interviews," *Energy Procedia*, vol. 152, pp. 868–874, 2018.

[21] S. R. Latapie, A. Abou-Chakra, and V. Sabathier, "Microstructure of bio-based building materials: New insights into the hysteresis phenomenon and its consequences," *Buildings*, vol. 13, no. 9, 2023.

[22] G. Castellano, I. M. Paoletti, L. E. Malighetti, O. B. Carcassi, and F. Pradella, "Bio-based solutions for the retrofit of the existing building stock: A systematic review," in *Bio-Based Building Materials*, Springer Nature Switzerland, 2023.

[23] J.-C. Morel, R. Charef, E. Hamard, A. Fabbri, and C. Beckett, "Earth as construction material in the circular economy context: Practitioner perspectives on barriers to overcome," *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 376, no. 1834, 2021.

[24] N. Chayaamor-Heil, V. Perricone, P. Gruber, and F. Guéna, "Bioinspired, biobased and living material designs: A review of recent research in architecture and construction," *Bioinspir. Biomim.*, vol. 18, no. 4, 2023.

[25] Chiusoli, "3D printed house TECLA - Eco-housing," 2021.

[26] V. Göswein, J. Arehart, C. Phan-Huy, F. Pomponi, and G. Habert, "Barriers and opportunities of fast-growing biobased material use in buildings," *Buildings Cities*, vol. 3, no. 1, pp. 104–122, 2022.

[27] J. J. Andrew and H. N. Dhakal, "Sustainable biobased composites for advanced applications: Recent trends and future opportunities – A critical review," *Compos. Part C Open Access*, vol. 5, 2022.

[28] F. Asdrubali, F. D'Alessandro, and S. Schiavoni, "A review of unconventional sustainable building insulation materials," *Sustain. Mater. Technol.*, vol. 4, pp. 1–17, 2015.

[29] B. P. Chang, A. K. Mohanty, and M. Misra, "Studies on durability of sustainable biobased composites: A review," *RSC Adv.*, vol. 10, no. 9, pp. 41637–41653, 2020.

[30] European Commission, *European Industrial Strategy*, 2020.

[31] Emhemed and A. M. T. Aburawi, "Sustainable design strategy optimizing green architecture path," *Int. J. Sustain. Build. Technol. Urban Dev.*, vol. 12, no. 4, pp. 234–245, 2021.

[32] O. Adeyemi, "Evaluation of green design strategies adopted by architects in Nigerian public buildings," *Proceedings*, vol. 76, no. 1, p. 24, 2023.

[33] S. A. Bahdad and S. F. S. Fadzil, "Optimization of daylight performance based on controllable light-shelf parameters using genetic algorithms in the tropical climate of Malaysia," *J. Daylighting*, vol. 7, no. 2, pp. 94–107, 2020.

[34] P. T. Grogan, "Co-design and co-simulation for engineering systems: Insights from the sustainable infrastructure planning game," *arXiv preprint arXiv:2008.04353*, 2020.

[35] M. T. Moghaddam et al., "Architecture design for human-driven systems," *arXiv preprint arXiv:2109.10073*, 2021.