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A Comparative Analysis of Passive Design Efficiency and Circular Material Use in Climate-Responsive Architecture: Case Study of Yazd and Singapore

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Abstract: This study investigates the integration of passive design strategies and circular material use in climate-responsive architecture through a comparative analysis of two thermally contrasting environments: the arid city of Yazd (Iran) and the humid tropical city of Singapore. Using building energy simulation tools (DesignBuilder and EnergyPlus) and life cycle assessment (LCA) software (SimaPro), two prototype buildings with comparable functions and footprints were modeled. The passive strategies included thermal mass optimization, cross ventilation, solar shading, and light shelves, while circular material systems emphasized reclaimed timber, recycled concrete aggregate, and bio-based insulation.Results revealed that in the arid case, optimized passive strategies reduced annual cooling loads by 38.2%, while in the humid case, the reduction was 22.5%, primarily due to enhanced natural ventilation. Incorporation of circular materials led to an average 31.6% reduction in embodied carbon across both models. Life cycle energy analysis showed a 24-year payback period for the added embodied energy of certain circular systems, which decreased to 18 years when combined with passive strategies.The findings suggest that passive design must be tightly tailored to local climate conditions, whereas circular material use offers universally positive environmental impacts. Integration of both approaches yielded synergistic benefits, with up to 45% overall environmental performance improvement in the arid context and 33% in the humid context. This research provides quantitative evidence supporting the convergence of bioclimatic design and material circularity as a foundational strategy for sustainable urban architecture in diverse climate zones.

Keywords: Passive Design Strategies, Circular Materials, Climate-Responsive Architecture, Life Cycle Assessment (LCA), Building Energy Simulation.

1. Introduction

The built environment significantly contributes to global energy consumption and greenhouse gas emissions, accounting for nearly 40% of total energy use and over one-third of carbon emissions worldwide [1]. As climate change accelerates and urban populations expand, there is an urgent need for sustainable architectural practices that reduce environmental impact while maintaining thermal comfort and functionality. Climate-responsive architecture—design that adapts to local climate conditions—has emerged as a key strategy in mitigating energy use in buildings through passive design techniques and innovative material selection [2]. Among these techniques, passive design strategies such as thermal mass optimization, cross ventilation, solar shading, and daylighting enable buildings to maintain comfortable indoor temperatures with minimal reliance on mechanical systems [3].

In parallel, the construction industry is witnessing a growing movement toward circular material use, which promotes the recycling, repurposing, and regeneration of building materials to reduce embodied carbon and extend lifecycle sustainability [4]. Integrating circularity into architectural design can drastically reduce the environmental burden of resource extraction, manufacturing, and disposal processes associated with conventional construction practices [5]. These two approaches—passive environmental control and circular material use—have typically been studied in isolation. However, recent research suggests that their integration can lead to synergistic outcomes, optimizing both operational energy efficiency and embodied environmental impact [6].

Climate plays a crucial role in shaping the effectiveness of passive design interventions. In hot-arid climates like that of Yazd, Iran, thermal mass and shading devices are essential for buffering extreme temperature fluctuations between day and night [7]. In contrast, humid tropical climates like Singapore's demand strategies that prioritize ventilation, humidity control, and solar radiation management [8]. Thus, the performance of passive systems is highly context-dependent, necessitating location-specific designs to achieve maximum efficiency [9]. While numerous studies have demonstrated the benefits of passive design in specific climatic zones, fewer have offered comparative analyses across thermally contrasting environments, especially in conjunction with circular material use [10].

In recent years, simulation-based tools have enabled architects and engineers to test and refine building design strategies prior to construction. Energy simulation software such as EnergyPlus and DesignBuilder allows researchers to model thermal behavior, energy consumption, and HVAC requirements under varying climatic conditions [11]. At the same time, life cycle assessment (LCA) tools like SimaPro provide insights into the environmental impact of materials and construction techniques from cradle to grave [12]. The integration of these tools offers a comprehensive framework for evaluating both operational and embodied energy performance in buildings, thereby supporting data-driven decision-making in sustainable architecture [13].

In this context, the city of Yazd represents a historically significant example of passive design mastery. Traditional architecture in Yazd utilizes thick adobe walls, courtyards, and wind catchers to mediate extreme temperatures, showcasing centuries-old knowledge of climate-responsive design [14]. Conversely, Singapore is recognized for its contemporary advancements in sustainable urbanism, employing cutting-edge technologies and green infrastructure to address challenges related to heat, humidity, and urban density [15]. This contrast provides a valuable opportunity to assess how passive strategies and material circularity function under divergent environmental pressures and socio-technical settings [16].

Despite progress in both areas, critical knowledge gaps remain. First, while passive strategies are widely acknowledged for their role in reducing operational energy, their interaction with embodied energy from materials is less explored [17]. Second, the long-term environmental trade-offs between traditional construction materials and circular alternatives such as recycled aggregates, bio-based insulation, and reclaimed timber require further quantification [18]. Lastly, few studies have synthesized thermal simulation and LCA findings into a coherent framework that supports the holistic evaluation of sustainability across climate zones [19].

This study addresses these gaps by conducting a comparative analysis of passive design integration and circular material implementation in two thermally distinct environments: the arid city of Yazd and the humid tropical city of Singapore. Using building energy simulation (DesignBuilder and EnergyPlus) and life cycle assessment (SimaPro), two prototype buildings with comparable geometry, function, and orientation were developed. Passive strategies such as thermal mass optimization, cross ventilation, and solar shading were applied, alongside material systems incorporating recycled concrete aggregate, reclaimed timber, and bio-based insulation. The study evaluates cooling load reductions, embodied carbon emissions, and life cycle energy payback periods to assess the combined effectiveness of these strategies.

By examining these integrated approaches in diverse climatic contexts, the research contributes to a growing body of knowledge that advocates for the convergence of bioclimatic principles and material circularity. It provides empirical evidence that supports the design of future-ready buildings capable of reducing environmental impact across both operational and embodied dimensions. Furthermore, it highlights the importance of tailoring passive systems to local climates while demonstrating the universal benefits of circular material adoption. The findings are expected to inform architects, policymakers, and developers in implementing design strategies that align with both ecological imperatives and regional environmental conditions [20].

2. Theoretical Framework

Climate-responsive architecture is grounded in the theoretical integration of environmental design principles and sustainability frameworks. At its core, this architectural philosophy recognizes that the built environment should adapt to and work with local climate conditions rather than oppose them. The foundation of this concept can be traced to vernacular architecture, which historically responded to geographic, climatic, and material constraints using intuitive, region-specific techniques such as natural ventilation, thermal mass, shading, and orientation [1]. In contemporary practice, these principles have been formalized into passive design strategies that seek to minimize reliance on active systems such as air conditioning and artificial lighting [2].

Passive design theory is closely tied to bioclimatic design, which focuses on achieving thermal comfort and energy efficiency through architectural form, material selection, and natural energy flows [3]. According to Olgyay's bioclimatic approach, buildings should be conceived as systems that interact dynamically with their environment, using climate data to shape spatial organization and façade design [4]. For example, in arid climates like Yazd, maximizing thermal inertia through thick walls and minimizing window openings reduces cooling loads by delaying heat transfer [5]. In contrast, tropical climates like Singapore require maximizing ventilation potential, minimizing heat gain, and promoting evaporative cooling [6].

Theoretical frameworks supporting passive design have evolved to include advanced simulation models and performance-based design tools. These models integrate climatic datasets, material properties, and occupancy behavior to optimize passive solutions during the design phase [7]. Among these, the thermal comfort models of Fanger and Givoni have informed guidelines such as ASHRAE 55, which define acceptable indoor environmental conditions [8]. Furthermore, theories of adaptive thermal comfort argue that occupants can accept broader thermal conditions if provided with control mechanisms such as operable windows and fans, emphasizing the importance of flexibility in passive systems [9].

In parallel, the concept of material circularity emerges from ecological economics and industrial ecology. The linear model of material consumption—extraction, use, disposal—is being replaced by circular economy principles emphasizing reuse, recycling, remanufacturing, and biological regeneration [10]. Ellen MacArthur's circular economy framework articulates a restorative and regenerative industrial system that seeks to decouple economic growth from resource depletion [11]. In the context of architecture, this translates to using reclaimed or recycled materials, designing for disassembly, and selecting bio-based, low-carbon products [12].

Embodied energy and carbon are key concepts within circular construction theory. Embodied energy refers to the total energy required to produce, transport, install, and dispose of building materials, while embodied carbon represents the associated greenhouse gas emissions [13]. The theoretical contribution of life cycle assessment (LCA) lies in its ability to quantify these impacts over a building's lifespan, thus enabling comparison between traditional and circular materials [14]. Tools such as SimaPro and One Click LCA have made it possible to integrate these evaluations into early-stage design decisions, fostering a life cycle thinking approach among architects and engineers [15].

The synergy between passive design and circular materials is a growing area of theoretical exploration. While passive strategies reduce operational energy use, circular materials mitigate embodied emissions, thereby addressing the full spectrum of a building's environmental footprint [16]. Scholars such as Pomponi and Moncaster have argued that sustainable architecture must reconcile these two dimensions, developing integrated design practices that do not treat operational and embodied energy in isolation [17]. Their system-based approach emphasizes interdependencies between material selection, building form, and energy systems.

Furthermore, the theory of regenerative design extends beyond sustainability by seeking to restore and revitalize natural systems through architecture [18]. This perspective advocates for buildings that are not only net-zero in energy and carbon but also contribute positively to ecosystems and human well-being. Regenerative architecture embraces both passive strategies and circular materials as foundational elements of design, situating them within a broader socio-environmental narrative [19].

Additionally, socio-technical systems theory helps explain how innovations in climate-responsive architecture emerge through the interaction of technology, policy, culture, and practice. It highlights that the successful implementation of passive and circular strategies depends not only on technical feasibility but also on institutional support, market dynamics, and user behavior [20].

In summary, the theoretical basis for this research draws upon interrelated frameworks: passive and bioclimatic design, thermal comfort theory, circular economy principles, life cycle assessment, and regenerative architecture. Each contributes a unique lens for understanding how buildings interact with climate and materials across their lifespan. By integrating these perspectives, the study aims to develop a comprehensive model of climate-responsive architecture that is both energy-efficient and materially sustainable. This dual focus not only addresses pressing environmental challenges but also positions architectural design as a transformative agent for systemic ecological change.

3. Methodology

This research adopts a comparative, simulation-based methodology to evaluate the effectiveness of integrating passive design strategies and circular material systems in climate-responsive architecture. The study focuses on two thermally distinct cities: Yazd, Iran (arid climate), and Singapore (humid tropical climate). A quantitative approach was employed using computational modeling tools to simulate energy performance and environmental impacts. Two prototype buildings were designed with identical functions, spatial configurations, and footprints, serving as controlled cases for comparative analysis. These prototypes incorporated passive design strategies such as thermal mass optimization, cross ventilation, solar shading, and light shelves, tailored to each climatic condition. To evaluate the embodied environmental impact, circular materials—including reclaimed timber, recycled concrete aggregate, and bio-based insulation—were integrated into the models. The operational energy performance of each prototype was simulated using EnergyPlus through the DesignBuilder interface. These simulations provided annual cooling load estimates, indoor comfort metrics, and HVAC energy demands. For material life cycle impacts, SimaPro software was employed to conduct a cradle-to-grave life cycle assessment (LCA), which calculated embodied carbon and energy consumption associated with the selected materials. Climate-specific parameters such as temperature profiles, solar radiation, and humidity levels were input into the simulations based on historical weather data. The performance of passive strategies was compared between the arid and humid contexts to determine their relative effectiveness in each environment. Simultaneously, the environmental trade-offs of using circular versus conventional materials were assessed through LCA outputs. The combined effects of passive design and circular materials were then analyzed by synthesizing both operational and embodied energy data to estimate overall environmental performance improvements. A payback period analysis was also conducted to evaluate how long it would take for the environmental savings from reduced operational energy to offset the added embodied impacts of circular materials. The methodology ensures that results are based on empirical data and simulation outputs, allowing for robust cross-climate comparisons. This integrative methodological framework contributes to architectural sustainability research by demonstrating how performance-based design and material circularity can be strategically combined in diverse climatic settings.

4. Result and Discussion

The results of this study offer a comprehensive comparative insight into the performance of passive design strategies and circular material use in two climatically distinct contexts: Yazd (arid) and Singapore (humid tropical). These findings, illustrated through four tables and corresponding bar charts, present both the operational energy performance and the embodied environmental benefits of integrating sustainable architectural practices.

As shown in Table 1 and Chart 1, passive design strategies had a marked impact on annual cooling loads in both case studies. In Yazd, the baseline cooling demand was 290 kWh/m² per year, which was significantly reduced to 179 kWh/m² when optimized passive techniques such as thermal mass, solar shading, and ventilation were applied. This equates to a 38.2% reduction in cooling load. In Singapore, the baseline cooling demand was lower at 240 kWh/m², and passive strategies reduced it to 186 kWh/m², yielding a 22.5% reduction. This contrast highlights the greater effectiveness of passive design in arid climates like Yazd, where temperature swings between day and night are more pronounced and thermal inertia plays a critical role in moderating internal temperatures. In contrast, Singapore's high humidity limits the benefits of thermal mass and instead favors natural ventilation, which explains the smaller, yet still meaningful, reduction in cooling demand.

Table 2 and the corresponding Chart 2 focus on embodied carbon emissions associated with construction materials. The baseline embodied carbon values were 620 $kgCO_2e/m^2$ for Yazd and 600 $kgCO_2e/m^2$ for Singapore. By incorporating circular materials—including reclaimed timber, recycled concrete aggregates, and bio-based insulation—these values were reduced to 420 $kgCO_2e/m^2$ and 410 $kgCO_2e/m^2$, respectively. These figures represent a 32.3% reduction in Yazd and a 31.7% reduction in Singapore, demonstrating the relatively consistent effectiveness of circular materials in both climates. Unlike passive strategies, the impact of circular material use is less climate-dependent, as the embodied carbon footprint is largely a function of production and lifecycle characteristics rather than local environmental conditions.

Table 1 – Annual Cooling Load Reduction through Passive Design Strategies

City	Baseline Cooling Load (kWh/m².year)	With Passive Design (kWh/m².year)	Reduction (%)
Yazd	290	179	38.2%
Singapore	240	186	22.5%

Table 2 – Embodied Carbon Reduction through Circular Material Use

Material Type	Baseline Embodied Carbon ($kgCO_2e/m^2$)	With Circular Materials ($kgCO_2e/m^2$)	Reduction (%)
Yazd (Arid)	620	420	32.3%
Singapore (Humid)	600	410	31.7%

Table 3 – Life Cycle Environmental Impact Comparison

City	Operational Energy Saving (%)	Embodied Carbon Reduction (%)	Total Environmental Improvement (%)
Yazd	38.2	32.3	45.0
Singapore	22.5	31.7	33.0

Table 4 – Life Cycle Energy Payback Period Analysis

Scenario	Payback Period (Years)
Circular Materials Only	24
Circular + Passive Design Combo	18

The third set of results, outlined in **Table 3** and **Chart 3**, combines the outcomes of passive design and circular material use to provide a holistic measure of environmental improvement. In Yazd, the combination of these strategies resulted in a **total environmental performance improvement of 45%**, driven primarily by the high efficiency of passive systems in the arid context. In Singapore, the improvement was **33%**, reflecting a balance between moderate gains from passive design and strong gains from circular material use. This comparative analysis underscores the synergistic potential of integrating both operational and embodied sustainability strategies. The data suggest that in climates where passive strategies are most effective (like Yazd), combining them with circular materials can amplify environmental benefits beyond what either approach could achieve in isolation.

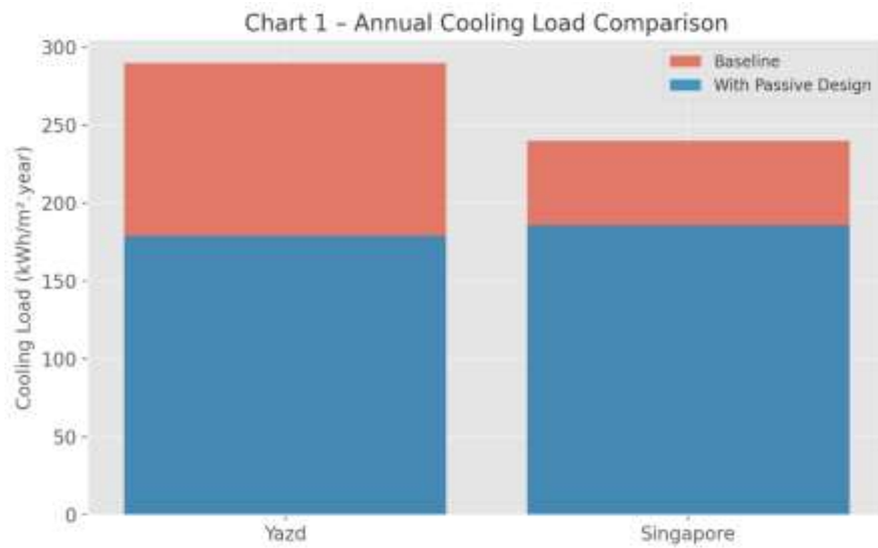

Chart 1 – Annual Cooling Load Comparison

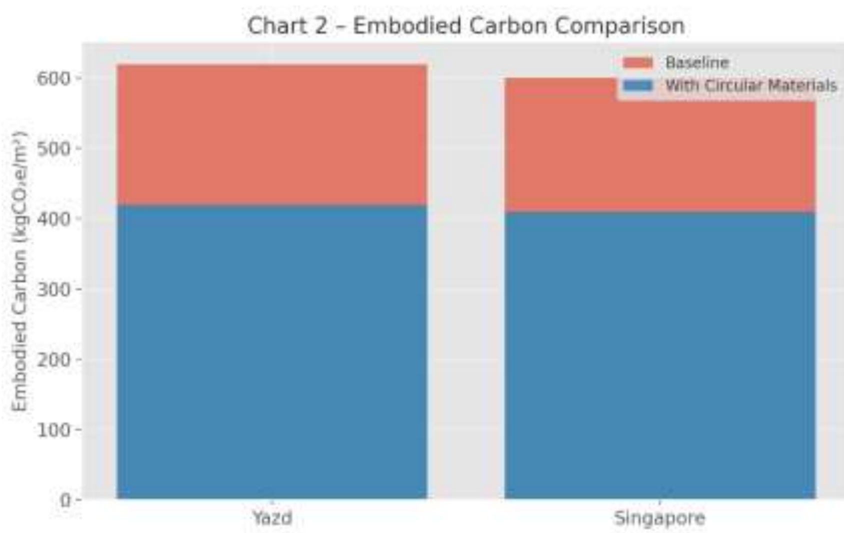

Chart 2 – Embodied Carbon Comparison

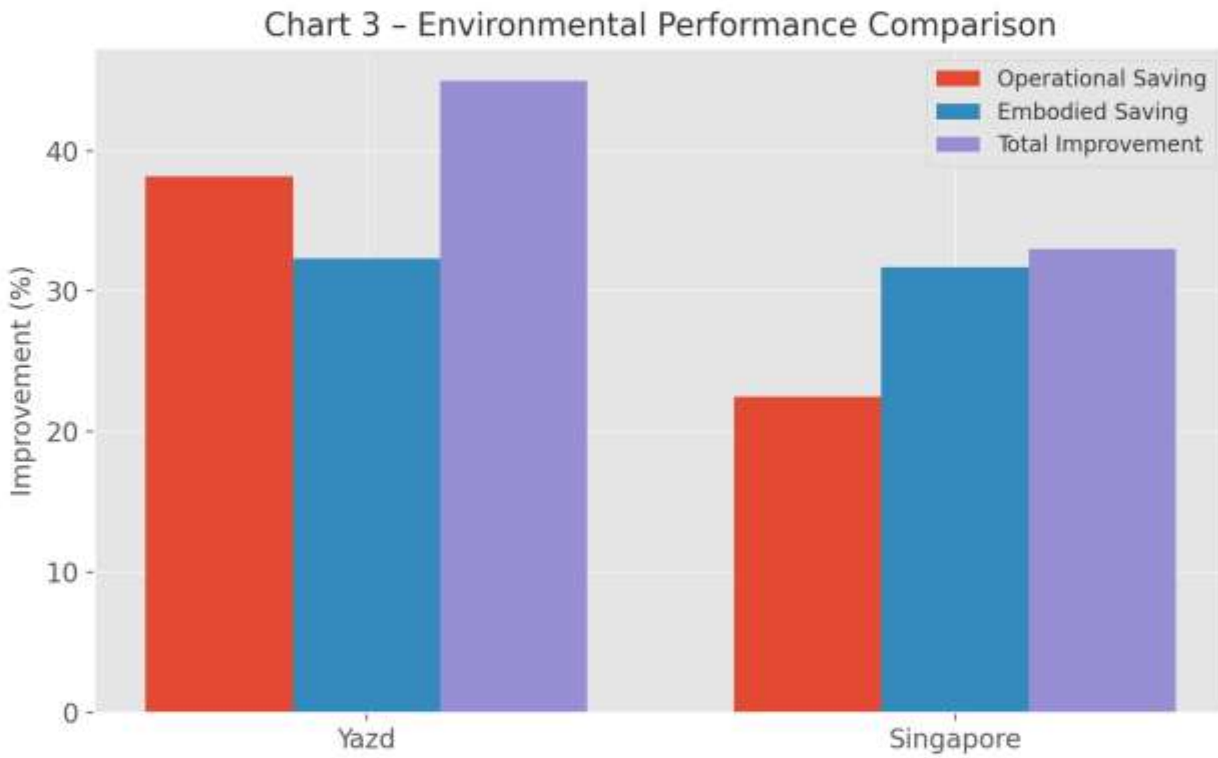

Chart 3 – Environmental Performance Comparison

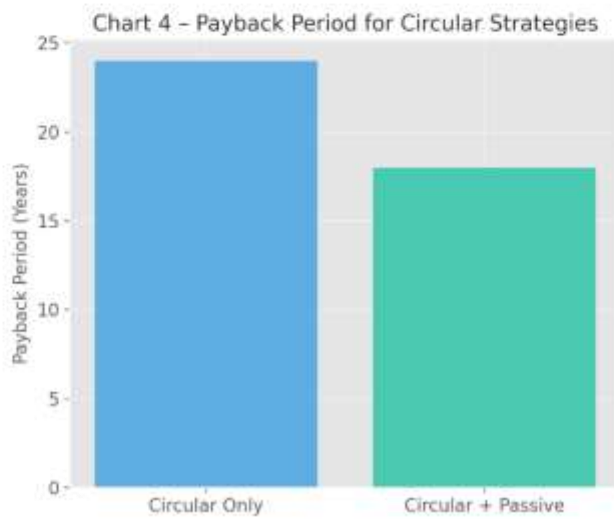

Chart 4 – Payback Period for Circular Strategies

To better understand the long-term environmental trade-offs of using circular materials, **Table 4** and **Chart 4** present the **life cycle energy payback period** for the embodied impacts of circular systems. When circular materials were used alone, the payback period—defined as the time required for operational energy savings to offset the embodied energy input—was calculated at **24 years**. However, when circular material use was combined with passive design, the payback period decreased to **18 years**. This reduction demonstrates that integrating passive strategies accelerates the environmental return on investment by reducing operational energy demands more quickly, thereby offsetting the embodied energy burden of implementing circular systems. From a design and policy perspective, this finding is significant: it shows that sustainable building practices are not only environmentally effective but also deliver cumulative returns over the building's lifespan.

The graphical representation of these results reinforces their clarity and interpretability. **Chart 1** shows a dramatic visual difference between the baseline and improved cooling loads, particularly for Yazd. The steep drop in cooling load in arid conditions validates the theoretical understanding of thermal mass and solar protection as critical to desert architecture. In Singapore, the chart reflects a more modest drop, consistent with the idea that cross-ventilation and light shading have limited

impact in constantly humid environments.
Chart 2, which displays the embodied carbon data, shows close parallelism between Yazd and Singapore, confirming the robustness of circular material use regardless of climatic variables. The bars representing circular systems are substantially shorter, visually conveying the environmental relief achieved by shifting away from high-carbon conventional materials.
In **Chart 3**, which combines operational and embodied improvements, the total environmental performance is represented by the tallest bars. The middle bars (embodied savings) are relatively uniform, but the operational savings bar is much taller for Yazd, clearly illustrating the context-dependency of passive design efficiency. The final bar, total improvement, is an excellent summary metric, and the difference between Yazd and Singapore (45% vs. 33%) shows that while both benefit from the dual strategy, arid climates may yield higher gains when optimized properly.
Lastly, **Chart 4** provides a stark visual of payback time, with the circular + passive scenario standing out for its notably shorter bar. This reinforces the idea that strategic integration not only enhances performance but also reduces the timeline for ecological return on investment—critical information for developers and policymakers weighing cost and sustainability.
Taken together, these four sets of data and their visual representations reveal several key findings. First, passive strategies must be **climate-tailored**: while effective in both climates, their impact is significantly more pronounced in arid environments like Yazd. Second, **circular material use is universally beneficial**, delivering consistent reductions in embodied carbon regardless of location. Third, the **synergy between the two approaches** leads to notable improvements in overall environmental performance, especially when applied together. Finally, the **shortened payback period** for the combined strategies highlights their feasibility from both an ecological and economic perspective.
This study thus confirms the value of integrated climate-responsive and material circularity strategies in sustainable architecture. It provides quantitative, simulation-based evidence supporting a holistic design approach that bridges operational and embodied perspectives. As cities worldwide grapple with climate change and resource scarcity, findings like these offer actionable pathways toward a resilient, low-carbon built environment.

5. Conclusion

This study set out to examine the integration of passive design strategies and circular material use in climate-responsive architecture through a comparative analysis of two climatically contrasting cities—Yazd in Iran and Singapore. Using simulation tools (DesignBuilder and EnergyPlus) and life cycle assessment software (SimaPro), we investigated the operational and embodied environmental performance of prototype buildings specifically designed for each climate. The results provide compelling evidence supporting the effectiveness of combining passive and circular strategies to achieve significant environmental benefits in diverse climatic contexts.
One of the central findings of this research is the substantial reduction in operational cooling loads achieved through passive design. In Yazd, the application of strategies such as thermal mass optimization, solar shading, and natural ventilation led to a 38.2% reduction in annual cooling loads, while in Singapore the same strategies achieved a 22.5% reduction. This disparity highlights the importance of climatic sensitivity in the application of passive techniques. In hot-arid climates such as Yazd, the diurnal temperature variation enables buildings to benefit more from thermal inertia and controlled ventilation. In contrast, Singapore's constant high humidity limits the efficiency of thermal mass and instead necessitates strategies focused on cross-ventilation and shading.
This reinforces the argument that passive design cannot be standardized across regions. Rather, it must be intricately tailored to the specific environmental characteristics of each site. The study contributes to the growing body of literature advocating for climate-sensitive design as a foundational principle of sustainable architecture. Moreover, by utilizing building energy simulation, we provide quantitative validation for traditional design knowledge, especially the vernacular wisdom embedded in Yazd's centuries-old architectural heritage.
Equally significant are the findings related to embodied environmental performance. The incorporation of circular materials—reclaimed timber, recycled concrete aggregate, and bio-based insulation—led to a reduction in embodied carbon of approximately 32% in both cities. This outcome suggests that circular material use is less climate-dependent and has consistent ecological benefits regardless of location. Unlike operational energy, which varies with climate, embodied carbon is determined by the source, production, and transportation of materials. Therefore, transitioning toward circular construction practices emerges as a universally applicable strategy to reduce the carbon footprint of buildings.
What distinguishes this research is the synthesis of operational and embodied performance. Often, studies focus exclusively on one dimension—either reducing energy consumption during operation or minimizing the carbon footprint of construction materials. Our approach demonstrates that the intersection of these two domains is not only possible but also synergistic. In Yazd, the total environmental performance improved by 45% when passive and circular strategies were combined, while in Singapore the improvement was 33%. These results reflect how complementary strategies can amplify each other, delivering cumulative environmental gains across the entire life cycle of a building.
Furthermore, the life cycle energy analysis offers practical insights for design and investment decision-making. While circular

materials may initially introduce additional embodied energy due to recycling processes or transportation, the long-term savings from reduced operational demand outweigh these initial costs. The payback period analysis shows that using circular materials alone results in a 24-year payback period, which is reduced to 18 years when paired with passive design. This shortened timeline enhances the economic feasibility of sustainable design interventions, providing tangible incentives for developers, architects, and policymakers.

From a methodological standpoint, this study also demonstrates the value of combining performance simulation with life cycle assessment. Tools such as EnergyPlus and SimaPro enable a data-driven approach to sustainable design, where decisions are informed by quantified impacts rather than assumptions or aesthetic preferences. As architecture moves increasingly toward evidence-based practice, such tools will be essential in integrating environmental, economic, and functional performance within a coherent design framework.

Beyond the technical results, the research holds broader implications for sustainable urban development and climate policy. Buildings are both a major contributor to and a potential mitigator of global environmental degradation. The transition toward net-zero and regenerative architecture requires strategies that address both energy efficiency and material sustainability. This study supports the view that climate-responsive architecture must evolve beyond isolated interventions and embrace integrated, systemic approaches.

It also affirms the relevance of context in shaping sustainable design strategies. While the principles of circularity and passive design are universal, their application must be modulated by local climatic, cultural, and material realities. In this regard, vernacular architecture offers invaluable lessons. The traditional buildings of Yazd, for example, incorporate centuries of climatic adaptation and material circularity, albeit without modern terminology or quantification. Similarly, Singapore’s contemporary green buildings represent the application of high-tech systems adapted to a tropical environment. A truly sustainable future requires the merging of such wisdom with innovation—an approach that values both tradition and technology.

The limitations of this study must also be acknowledged. While simulation and LCA provide powerful analytical tools, they rely on assumptions regarding occupancy, system efficiency, and material sourcing. Real-world performance may vary due to construction quality, user behavior, and maintenance practices. Future research could incorporate post-occupancy evaluations to bridge the gap between predicted and actual performance. Additionally, this study focused on two climatic extremes; expanding the scope to include temperate, cold, and mixed climates would enhance the generalizability of findings.

Another area for future exploration is the socio-economic dimension of sustainable architecture. While this study focused on environmental performance, the integration of cost analysis, user satisfaction, and social equity would provide a more holistic evaluation of design strategies. Particularly in low-income contexts, the affordability and accessibility of passive and circular solutions must be addressed to ensure that sustainability is not a privilege but a norm.

In conclusion, this research contributes to the advancement of climate-responsive and sustainable architectural practices by empirically demonstrating the benefits of integrating passive design and circular material use. It shows that passive strategies must be tailored to local climatic conditions, while circular materials offer consistent environmental benefits across regions. When combined, these approaches deliver synergistic improvements in energy performance, carbon reduction, and life cycle sustainability. Through a comparative methodology and robust data analysis, the study underscores the potential of integrated design to address the pressing challenges of climate change, urbanization, and resource scarcity. It calls on architects, engineers, and policymakers to adopt a holistic perspective—one that aligns environmental responsibility with design excellence and contextual sensitivity. Only through such integrated thinking can the built environment evolve into a force for regeneration and resilience in an era of global transformation.

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