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Topic of Research: **Performance Evaluation of Vertical Greenery Systems for Energy Efficient Architecture: A Case of Delhi**

Findings

Rapid urbanization and climate change have intensified thermal stress in cities, with buildings consuming over 27% of global energy and contributing significantly to the greenhouse gas emissions. Vertical greenery systems (VGS) have emerged as promising nature-based solutions for improving building performance; however, their implementation remains limited, particularly in composite climates such as Delhi, due to insufficient empirical evidence on their multidimensional performance and economic viability.

This research evaluated the environmental, social, and economic performance of two VGS typologies, green facades and living walls, in the composite climate of Delhi using a comprehensive mixed-methods approach. Field experiments monitored hygrothermal conditions in naturally ventilated residential buildings over one complete annual cycle, comparing VGS-equipped facades with bare controls. Building energy simulations, calibrated against field data, quantified the annual energy savings across different orientations and building types. Social impacts were assessed through stakeholder perception surveys and eye tracking experiments measuring visual attention and perceived restorativeness. Economic feasibility was evaluated through a cost-benefit analysis incorporating installation costs, operational expenses, energy savings, and monetized co-benefits.

Field measurements demonstrated significant thermal moderation by the VGS, with living walls achieving superior performance compared to green facades. Surface temperature reductions reached 23°C during peak summer conditions, translating to indoor air temperature reductions of up to 4.1°C. Living walls maintained better humidity control and provided year-round thermal benefits, whereas green facades showed seasonal performance limitations during the winter and monsoon periods. Calibrated energy simulations revealed substantial reductions in electricity consumption: up to 41% for living walls and 29% for green facades when applied to all building orientations, with west-facing installations delivering optimal performance.

Social acceptance was consistently high across all stakeholder groups, with aesthetic improvement and temperature reduction identified as the primary benefits. Eye tracking data

confirmed that VGS significantly enhanced visual attention, visual appeal, and perceived restorativeness. However, maintenance costs and technical complexity remain the primary implementation barriers.

Economic analyses have revealed mixed viability outcomes. Under favourable conditions, living walls achieved positive net present values (NPV ₹18,000–45,000 per installation) with benefit-cost ratios exceeding 1.2, whereas green facades demonstrated marginal viability (NPV ₹2,000–8,000). Monte Carlo simulations indicated 60-70% probability of economic viability for living walls compared to 45-55% for green facades. Energy savings constituted the dominant benefit category, although payback periods of 12-18 years suggest the need for policy support.

Three integrated frameworks were developed from these findings: a Performance Evaluation Framework enabling systematic VGS assessment, a Design Optimization Framework providing typology-specific guidance, and a Policy Framework outlining regulatory and incentive mechanisms. These evidence-based tools address the current gap between VGS potential and its practical implementation.

This research provides the first comprehensive evaluation of VGS performance in composite climates, demonstrating their measurable benefits while identifying implementation constraints. The findings support the targeted integration of VGS in sustainable building strategies, with living walls showing significant promise for high-performance applications. The developed frameworks offer practical pathways for scaling VGS adoption, thereby contributing to climate-responsive urban development in rapidly growing cities.

Keywords: vertical greenery systems, composite climate, hygrothermal performance, socio-economic sustainability, nature-based solutions