Innovative Green Roof Materials for India: Synergizing Nature-Based Solutions and Sustainable Manufacturing for Climate-Responsive Cities

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Abstract. Rapid urbanization has exacerbated issues like heat islands, stormwater flooding, and increasing solid waste production, which has led to find sustainable solutions in urban infrastructure. Green roofs are the nature-based (NBS) ideal solution to mitigate urban heat island and have several ecosystem services such as thermal regulation, water management, and carbon sequestration. Nevertheless, traditional systems are based on resource-dense substrates that have strong embodied carbon and structural load. This review discusses how circular manufacturing and waste-to-resource can be implemented in the production of green roof materials with compost, biochar, and industrial by-products like fly ash, slag, and recycled construction waste. The review provides an overview of the global and India-specific studies, in which Indian studies have reported water-retention rates of between 58–68% and high biomass plant gains, whereas global studies have recorded a reduction in surface temperature by up to 10 °C and a reduction of life-cycle CO_2 emissions by approximately 35% compared to conventional systems. The policy frameworks are discussed using the Smart Cities Mission, GRIHA (The Green Rating of Integrated Habitat Assessment), IGBC (Indian Green Building Council), and the case of Bengaluru, Delhi, and Hyderabad. The article highlights the new synergy between NBS and sustainable manufacturing to implement green roofs as a way forward to resilient, resource-efficient, and climate-responsive Indian cities.

1. Introduction

Rapid urbanization in India is an important environmental and infrastructural challenge, which relates to increasing temperatures in cities, a new potential for floods, and a new waste crisis. As the cities began to expand at an unprecedented rate, the urban infrastructures urgently need new innovative and sustainable solutions [1]-[5] to enable the ecosystem

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services to adapt to climatic changes and resilient cities. Nature-based Solutions (NBS) can be regarded as a new powerful tool to address these issues by implementing natural processes to urban infrastructures [6]. Among them, green roofs can be used to successfully minimize the heat island effect, handle stormwater, and increase the sustainability of urban environments [3]-[4]. India has already given testimony on its potential. For instance, computerized simulations of cool roofs in five climatic regions have shown that the energy demand has been reduced by a substantial amount, especially in hot-dry and warm-humid regions [19]. Simultaneously, high initial costs, lack of awareness, and maintenance issues have been pointed out as the major limitations to adaptation in Indian cities [14]. These results represent the potential and the contextual factors that green roofs have in India. Green roofs are discussed in this review in the framework of urban infrastructure materials engineering, and the consideration of the significance of waste materials, circular manufacturing of substrates. Compost, biochar, and industrial byproducts reduce the need to use virgin resources, and the recycling of vast amounts of waste is in line with the principles of a circular economy [7]-[12]. With the invention of useful infrastructure components using waste, India can solve the problem of the increasing load of waste, as well as the shortage of materials at the same time. This review thus expounds on the advantages of green roofs, contrasts the circular and conventional design, sustainable manufacturing practices, insight into policy and case study in India, performance data sets, and concludes with research and policy opportunities to mainstream green roofs in Indian cities.

Fig. 1. Standard green-roof assembly with vegetation, growing media (substrate), filter/drainage layer, root barrier, waterproofing membrane, insulation, and roof frame structure.

2. Review Methodology

The paper is structured as a systematic review process to generalise evidence on green roof material, ecosystem services, and policy frameworks that are applicable to Indian urban areas. The literature search has been performed in the major databases, such as Scopus, Web of Science, and Google Scholar, which include the literature published between 2010 and 2025. Some keywords were used, such as green roofs India, nature-based solutions, circular economy construction, biochar compost substrates, urban heat island mitigation, and stormwater management.

Peer-reviewed journal articles, conference papers, and government/NGO reports that satisfied the following inclusion criteria were included: (a) green roof performance (thermal performance, stormwater retention), (b) materials innovation under compost, biochar, or industrial by-products, and (c) policy and implementation frameworks in India. International research was also incorporated, where they gave appropriate associations or techniques to compare with the Indian conditions. The criteria of exclusion were used to filter studies that lacked parameters to measure or studies that concentrated on other non-urban green infrastructure.

Information was extracted and organized into four themes in order to conduct the review: (i) ecosystem services of green roofs, (ii) circular and waste-derived substrates, (iii) India-focused case-studies and policy-regimes, and (iv) material performance and comparison-datasets of Indian and global evidence. The rest of the paper is organized in this order in order to guarantee integrity between the review structure and the Results/Discussion section.

3. Green Roofs as Nature-Based Solutions

Green roofs, as an important Nature-Based Solution, represent a multifunctional solution to provide a suite of ecosystem services that help solve critical environmental issues in urban communities. These services have a special significance for fast urbanizing countries like India.

3.1. Cooling and Urban Heat Island Mitigation

Green roofs are a significant countermeasure to the Urban Heat Island effect because they replace heat-absorbing conventional roof surfaces with plant material. They help to lower surface and air temperatures by means of evapotranspiration and shading [3]. Surface temperature reductions of up to 30 °C have been reported [3], and in humid tropical cities, green roofs reduce temperatures compared with normal roofs [13]. For Indian cities such as Kolkata, Mumbai, Chennai, and New Delhi, green roofs are deemed an economical environmental mitigation strategy [14].

3.2. Stormwater Retention and Management

Green roofs play a crucial role in urban stormwater management by retaining rainwater and delaying peak flows, thereby reducing flood risk [15]. This is very important for Indian cities exposed to heavy rainfall [4]. Green roofs have the potential to absorb a large amount of precipitation, and studies have reported peak flow reductions as great as 49.17% [16]. However, their ability to absorb stormwater volumes and improve effluent quality is one of the key characteristics for reducing the negative effects of urbanization processes [17]. Green roofs have great potential for flood-prone India, and local research is therefore needed [10].

3.3. Energy Efficiency and Savings

By providing insulation and reducing heat transfer, green roofs contribute to building energy efficiency, decreasing energy consumption for cooling and heating [18]. Green roofs are a major opportunity in India, a country where cooling requirements are very high. While direct green roof information is still evolving, energy savings from a concept called "cool roofs" (with similar insulating principles) have been demonstrated to be quite significant in Indian cities. For example, the maximum energy reductions achieved from a calibrated simulation were in Mumbai (warm and humid climate), followed by Ahmedabad (hot and dry), Bangalore (temperate), and Delhi (composite).

3.4. Biodiversity Support

Green roofs are important ecological habitats in urban areas and support many plant and insect species [20]. Although they may not be fully representative of ground-level biodiversity, their structural diversity can be increased in order to improve species richness

[21]. Green roofs are part of an urban ecological fabric and contribute to biodiversity [21]. Studies indicate that green roofs can host diverse arthropod communities [22], [23], and some even show equivalent or higher species numbers compared to ground sites [20].

3.5. Relevance for Indian Cities

The green roofs have great environmental positive effects on big cities of India, which are struggling with serious environmental issues. They can play a crucial role in reducing the urban heat island (UHI) effect in Delhi and, at the same time, improving the quality of the air. As a city with a fast-depleting green cover, Bengaluru can use the green roof to improve the urban canopy, control stormwater, and fight increasing city heat. Green roofs can help Hyderabad overcome the challenges of rising temperatures and water scarcity, even in the management of water, especially at the current climate conditions, where cool roofs have already shown significant potential in saving energy [19]. Likewise, the stormwater retention and thermal comfort benefits of green roofs will benefit Mumbai, a very prone city to floods and humidity, significantly [4]. Although these opportunities are obvious, green roofs are not widely implemented in India, and the main reason is the lack of knowledge about the cost-benefit mechanisms of green roofs and the need to maintain them in the long term [14]. To realize the full potential of green roofs as a sustainable urban development tool in India, it is consequently necessary to increase the level of research in the country and raise the level of awareness of people.

4. Circular Green Roof Systems

Circular green roofing systems adopt the values of the circular economy, which aims at converting waste into resources, implementing closed-loop material circulation, and manufacturing in a sustainable way. The strategy is to reduce environmental impact, the use of materials, and increase resource efficiency during the lifecycle of the green roof.

4.1. Waste-to-Resource and Recycling Flows

Circular green roofs are all about waste as a resource in the manufacture of substrates. This removes waste in landfills and minimizes the pressure on virgin materials. There are enormous amounts of waste that can be valorized in India, such as construction and demolition waste, agricultural waste, and industrial waste [5].

In the Indian case, some of the key streams of waste that can be recycled into producing green-roof substrate are (a) construction and demolition (C&D) waste (crushed brick, concrete fines) that can be used as a lightweight aggregate; (b) municipal organic waste, municipal solid waste (i.e., after proper composting) that can be used as a source of nutrients and organic matter (c) agricultural wastes (coconut coir, rice husk, bagasse) that can be used as a bulking agent or feedstock to biochar. To incorporate such streams, a two-step process of (i) pre-treatment (e.g., shredding, sieving, thermal/chemical stabilization) and (ii) palletisation/blending with organic amendments is needed to produce uniform, plant-supportive substrates. Small-scale LCA studies and pilot projects are suggested that can be used to measure the environmental advantages and find safe levels of concentration of possibly harmful substances (e.g., heavy metals in fly ash) [9], [10], [24].

4.2. Nature-Based Materials for Substrates

Potential materials to be used as green roof substrates in the Indian context include compost, biochar, and industrial byproducts. As a by-product of organic matter, compost contains vital nutrients, improves soil composition, and retains water greatly, which promotes the development of plants in green roofs [9], [10]. Its application also complements the overall waste management goals of India in terms of valorising urban organic waste. Biomass pyrolysis results in biochar that is highly porous, facilitating better water and nutrient retention and aeration, in addition to drought resistance. In addition, biochar is a long-term source of carbon, which serves to reduce climate change through carbon capture [7]. Industrial byproducts also have significant potential to develop as a substrate with both useful properties and the reduction of waste. The residue of coal combustion after burning, fly ash, can be used to improve draining and stabilization; metallurgical slags can be used to increase structural strength and change pH; recycled construction waste in the form of crushed bricks and concrete can be used to provide lightweight aggregates with porosity to retain water. As empirical data indicates, there is no cause to believe that these materials can be successfully integrated into green roof systems without impacting performance, and construction and demolition waste studies demonstrate promising findings in both water retention and plant growth [9], [10].

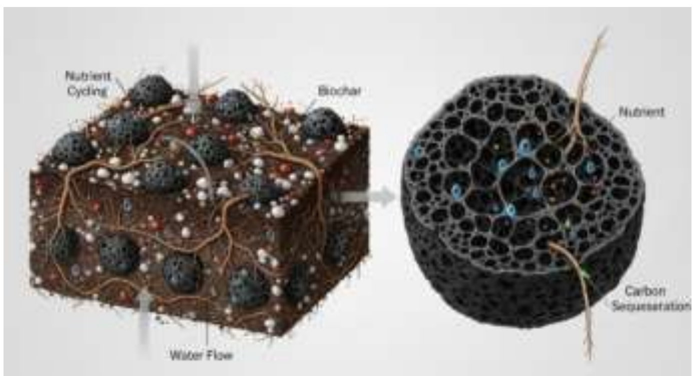

Fig. 2. Biochar in green-roof substrate and Cross-Sectional view

4.3. Sustainable Manufacturing Techniques

Such waste-to-resource prospects as composting, pyrolysis (to generate biochar), palletisation, and plastic recycling could be identified as potential waste-to-resource opportunities to develop sustainable green-roof systems in India. Urban organic waste compost yields amendments with nutrient value that enhance the fertility and water holding of the substrate [9], [10]. When the agricultural residues undergo pyrolysis, they produce biochar that improves porosity, nutrient retention, and long-term storage of carbon [7, 24]. Handling of fine industrial residues is enhanced by palletisation, which facilitates the making of uniform substrate mixes [8]. The recycled plastics can be used to make drainage mats and modular supported elements, and this will help to minimize the use of virgin plastics and enhance the performance of roof drainage capacity [33].

5. Comparative Framework: Conventional vs. Circular Systems

The following table provides a comparative overview of conventional versus circular green roof systems based on key performance indicators.

Table 1. Conventional vs. Circular Systems

Feature	Conventional Green Roof Systems	Circular Green Roof Systems	Sources
Material Input	Virgin materials (e.g., soil, perlite, peat, expanded clay)	Waste-derived materials (e.g., compost, biochar, fly ash, recycled concrete/brick)	[7],[8], [9], [10]
Life-Cycle Emissions	Higher embodied carbon from the extraction, processing, and transportation of virgin materials.	Lower embodied carbon due to waste valorisation and reduced demand for virgin materials; potential for carbon sequestration (biochar).	[24], [25]
Weight/Structural Load	It can be heavy, especially intensive systems, requiring significant structural reinforcement.	Often lighter due to porous, waste-derived materials, allowing for broader application on existing structures.	[26], [7]
Water Retention	Varies by material; may require irrigation in dry periods.	Enhanced water retention is due to the porous nature of materials like biochar and compost.	[10], [9]
Thermal Performance	Good insulation properties reduce heat transfer.	Comparable or improved thermal performance, with added benefits of reduced embodied energy.	[3], [13]
Nutrient Management	May require external fertilizers.	Nutrient-rich due to compost; improved nutrient cycling with biochar.	[10]

Fig. 3. A representative illustration of the Cross-section and experimental layout of green-roof prototypes built with recycled/reused materials.

6. India-Centric Applications

6.1. Case Studies and Local Initiatives

Green roofs are starting to be recognized as a useful measure towards environmental resiliency, as urban infrastructure in India is becoming more sustainable. On a city scale, several programs demonstrate how the concept of green roofs is being integrated into local urban design. Rooftop farming has proven to be a successful activity in Bengaluru, driven by the involvement of individual companies and local participation, and illustrating the economic feasibility and sustainability prospects [27]. Urban green space planning is also recognized as part of the wider climate adaptation measures of the city [28]. Delhi has developed all-inclusive urban greening strategies to help mitigate air pollution and the urban heat island effect and has discussed using nature-based solutions and possible pilot programs on the greening of the public transport infrastructure [6], [29], [30]. Hyderabad and Vijayawada represent examples of active and changing urban agriculture with respect to rooftop gardening, through government-sponsored support to householders to utilize their rooftops as a way to create effective green spaces, although there are obstacles to adoption [31], [32]. Conversely, due to high water risks, heavy humidity, and extreme density of the built environment, Mumbai represents an example of the potential to implement green roof initiatives, which have been the focus of numerous green infrastructure studies. Conversely, Pune is an example of the application of circular economy principles to municipal solid waste management, thus providing a model for utilizing organic waste as source materials for growth substrates [33], [34].

6.2. National Frameworks and Policies

On the national level, several policy frameworks offer an enabling environment to adopt the use of green roofs. The Indian urban renewal program, which is among the most ambitious in terms of sustainability, resource management, and smart infrastructure, is called the Smart Cities Mission and supports the implementation of green technologies into urban planning [35]-[37]. The Green Rating of Integrated Habitat Assessment (GRIHA) system encourages green building practices, which credit items like energy efficiency, stormwater control, and sustainable location planning, which green roofs directly deal with [38]-[39]. Similarly, the Indian Green Building Council (IGBC) establishes certification parameters that encourage the spirit of environmentally friendly building with a set of rules that enhance the contribution of the green roof to the achievement of higher standards of sustainability [38]. Combined, these urban-level programs and national frameworks outline the potential and institutional viability of developing green roofs as a standard urban sustainability tool in India.

6.3. Implementation Status and Material Circularity

The use of green roofs throughout India is a developing field. Recent studies reveal that the technology of green roofs is a developing field that is yet to be understood holistically and extensively in the country, despite its known benefits [14], [10]. The new reality of mass adoption of green roofs implies that data on national adoption levels and area coverage in aggregate form is a developing field of study. But there is an increasingly strong desire to use locally sourced waste products, including agricultural waste and construction and demolition waste, to grow green roof substrates. This is consistent with the concepts of the circular economy, where the use of virgin materials is minimised, and waste streams are valorised.

6.4. Policy Development and Strategic Opportunities

Improving the implementation of green roofs in India needs in-depth rather than general research. One research gap has to do with costs, reasonable maintenance protocols, and benefits, all being specific to urban and climatic settings in India. Studies focusing on the urban and climatic settings of India will help in strategic decision-making and will increase the confidence of stakeholders. Focused studies on green roofs' air purification, urban heat moderation, and stormwater management will help in decision-making and will increase the confidence of stakeholders. Comprehensive studies on the multifaceted benefits of green roofs and of urban heat moderation and stormwater management will be greatly of use to policymakers, the citizens, stakeholders, and the general public [10], [14]. The incorporation of green roofs within urban development plans and building codes will guide mass implementation while explicitly integrating green roof requirements. The construction sector would also greatly benefit from the implementation of circular economy principles that promote the use of waste and by-products as green roof growing substrates. These strategies would allow India to make green roofs a fundamental component of urban resilience and sustainable development, as a growing plant will not visually dominate the roofs of the country's urban centers.

7. Material Performance & Environmental Assessment

The effectiveness of green roof systems, including circular economy principles, can be measured using different methodologies as indicated in performance metrics and various environmental assessments. Data from studies on a global and India-specific scale demonstrate the effectiveness of these systems and their contribution to the sustainability of cities.

7.1. Water Retention

The positive effects of green roofs on retaining stormwater and planting are significant, and these are the reasons why the use of green roofs is very relevant in terms of urban sustainability in India. Regarding retention of water, experiments have proved that low-cost waste-derived substrates are effective in improving hydrological performance. As an illustration, substrates prepared using aggregates and bio-sorbents like Sargassum biomass had water retention capacities of 58.5% [9], with optimization mixes of vermiculite and coco-peat recording water holding capacities of up to 67.6% [40]. These results are in line with international evidence, including studies on a vegetated roof in Waterloo, Ontario, which retained 43.9% of overall rainfall during the study period, compared to a traditional control roof, which retained [41]. Further research also supports the capability of green roofs to decrease the volume of stormwater runoff and delay its onset, which, in turn, reduces the flood risk in crowded urban areas [42], [43].

7.2. Plant Growth and Biomass Increases

Protecting the importance of substrates in sustaining the growth and biomass increases of plants, which are essential to support vegetation and provide ecologically significant services in the long term. A study on the Indian-based plant Portulaca grandiflora has shown an impressive increase in biomass of 450.3% and a relative growth rate of 0.038 when grown on a specially developed green roof media [44]. These studies indicate hope in the utilization of engineered waste-based substrates for the retention of vigorous vegetation. Additionally, the fact that rooftop farming projects in Bengaluru have been a success is another indicator that green roofs can generate large plant biomass, which can be used to both improve urban food security and increase the urban green cover simultaneously [27].

7.3. Indoor Cooling Efficiency

Green roofing is significant in reducing the urban heat island (UHI) effect, as well as improving thermal comfort in buildings by reducing heat exchange to buildings. The large green roofs in the humid tropical metropolitan areas have shown, in contrast to traditional roofs, the ability to greatly reduce surface and air temperatures [13]. Even though thorough datasets on the cooling performance of green roofs in all climatic zones of India are yet to be developed, similarities can be observed with studies conducted on cool roofs, which demonstrate similar thermal control advantages. As one example, a calibrated simulation study in India comparing five climatic regions showed that the greatest energy saving was in the warm and humid climate of Mumbai, then in Ahmedabad (hot and dry), Bengaluru (temperate), and Delhi (composite) [19]. Green roofs can benefit in the same way, acting as natural insulators to lower interior heat loads, reduce reliance on mechanical cooling systems, and consequently lead to general energy saving and better thermal comfort in the urban setting [45].

8. Environmental Assessment

8.1. Life Cycle Assessment

The life cycle assessment (LCA) provides a holistic approach to the assessment of the environmental impacts of green roofing, including the material production, installation, operation, and post-operating life cycles. The reduction of CO_2 is among the most significant consequences because green roofs show lower emissions levels than traditional roofs, and the range of reductions observed is 35 to 83 percent [46]. Green roofs also store atmospheric CO_2 by long-term plant growth and substrate utilization in addition to long-term reduction of embodied carbon [45]. This advantage is countered by the low energy benefits operationally, although the initial embodied emissions can be significant. This is also supported by the avoided emissions associated with the traditional energy consumption, and hence green roofs are considered a net-positive factor in climate mitigation [47], [24]. Waste diversion is another important LCA time outcome because the manufacture of circular substrates allows valorisation of city-level, agro-industrial, and temporary construction and demolition wastes. Green roofs are leading in terms of minimizing landfill reliance and enabling resource cycling through incorporation of these waste streams into substrate development [7], [9], [10]. Although quantitative estimates at large scales and in the Indian context are yet to be developed, experimental work consistently points to a high potential of waste re-utilization [10]. Lastly, energy saving is also an environmental and economic benefit of green roofs. Their inherent thermal insulation reduces the heat gain into the building, which decreases the mechanical cooling requirement and reduces the energy demand of the building [48], [49]. Indian research experience on cool roofs, which have similar thermal advantages, suggests that considerable energy savings under a variety of climatic conditions can be achieved through green roofs, hence the potential of such facilities in promoting meaningful sustainable urban energy management [19].

8.2. Comparative Datasets

A comparison of the data provided by Indians and global data sets shows that there are similarities along with some distinct opportunities. Though the basic performance properties, i.e. water retention and temperature control, of green roofs are universal across all regions, India-specific studies are essential to attain a high level of material choice and design to meet local climatic conditions, waste patterns, and policy requirements [10].The focus on using a variety of waste products in India to develop the substrate (e.g., Sargassum biomass [9], coco-peat or crushed brick [10], demonstrates a high degree of compatibility with the principles of the circular economy, which may have greater benefits in terms of waste diversion than more material-intensive regions. Additional full-fledged LCAs specific to manufacturing processes and material supply chains in India would furnish more accurate information on CO_2 reduction and waste diversion rates that are specific to the Indian situation.

9. Discussion

As noted in the reviewed literature, green roofs offer several ecosystem functions with great potential in addressing the urban issues faced in India. They have been demonstrated to have the potential to counteract the urban heat island effect, with studies conducted worldwide reporting up to 10° C lower in surface temperatures and an Indian simulation (using cool roofs as a proxy) showing significant energy savings in Mumbai, Ahmedabad, Bengaluru, and Delhi. Hydrologically, Indian research has shown retention abilities of water at 58-68 %, in line with international studies of 40-50 percent stormwater reduction, highlighting the need for their implementation in flood-prone cities. The feasibility of waste-derived substrates is proven by plant growth experiments, like those involving biomass growth of Portulaca grandiflora and rooftop agriculture in Bengaluru, and the worldwide biochar and compost literature supports increased porosity, nutrient cycling, and carbon capture. Circular material innovation compost, biochar, fly ash, slag, and construction waste represent a potential direction, but in India, the evidence about circular material innovation has not been studied in large-scale trials, and there is no long-term tracking or structural analysis of it. Frameworks of policy such as the Smart Cities Mission, GRIHA, and IGBC have the facilitating conditions, and local examples are available in the form of Delhi, Hyderabad, and Mumbai, although there exist obstacles which limit implementation through high initial costs, lack of awareness as well and maintenance issues. A comparative synthesis indicates that although global studies provide strong datasets of life-cycle CO_2 reductions (up to 35%) and long-term thermal performance, Indian studies are in their infancy, with more strength in the potential of valorisation of waste and less strength in life-cycle assessment and field-scale validation. In general, the benefits of green roofs in India are established, and there are a lot of research gaps that need specific pilot projects, cost-benefit analysis, and incorporation into national building codes to reach the full potential associated with green roofs as a circular and climate-responsive solution.

10. Conclusion

As identified in the discussion above, there is an urgent need for sustainable and resilient urban infrastructure in India, a country where urbanization is unprecedented and urban environmental strain is exerted in the form of urban heat islands, floods, and waste management crises. This review has shown that green roofs are an effective Nature-Based Solution because they can provide a multi-functional solution to these challenges, including important ecosystem services like thermal regulation and stormwater management, biodiversity, and energy savings. Most importantly, the combination of green roofs with the principles of the circular economy and sustainable manufacturing introduces a disruptive direction of Indian urbanization. As a change of no-waste-to-resource attitude, in particular, with the innovative use of compost, biochar, industrial byproducts, etc., as the substrates in the green roofing, we may reduce the environmental impact of the conventional building process dramatically. Such symbiosis between urban resilience and sustainable processes of production not only channels large quantities of waste out of the landfill but also leads to resource efficiency and embodied carbon in the life cycle of urban infrastructure. Currently developing Smart Cities Mission of India, and green building rating systems other than GRIHA and IGBC provide a policy framework. Greater integration and intensification of policy, technological development on the material science side, and production methods are, however, required to scale such solutions. The implementation of the circular NBS within green roofs is not merely an environmental requirement, but it is also a strategic path to the development of the resilient, green, sustainable, and habitable urban centres across India.

References

1. C. Punyamurthy and R. S. Bheenaveni, "URBANIZATION IN INDIA: AN OVERVIEW OF TRENDS, CAUSES, AND CHALLENGES," *International Journal of Asian Economic Light*, 9 (2023). https://doi.org/10.36713/epra12473.
2. A. Sahasranaman and L. M. A. Bettencourt, "Urban geography and scaling of contemporary Indian cities," *Journal of The Royal Society Interface* **16**, 20180758 (2019). https://doi.org/10.1098/rsif.2018.0758.
3. X. Zhang, A. N. Soe, S. Dong, M. Chen, M. Wu, and T. Z. Htwe, "Urban Resilience through Green Roofing: A Literature Review on Dual Environmental Benefits," *E3S Web of Conferences* **536**, 01023 (2024). https://doi.org/10.1051/e3sconf/202453601023.
4. P. Patel, S. Karmakar, S. Ghosh, D. G. Aliaga, and D. Niyogi, "Impact of green roofs on heavy rainfall in tropical, coastal urban area," *Environmental Research Letters* **16**, 74051 (2021). https://doi.org/10.1088/1748-9326/ac1011.
5. K. K. Myneni and D. Rajan, "IMPACT OF CIRCULAR CONSTRUCTION ON DEMOLITION WASTE MANAGEMENT IN THE INDIAN CONSTRUCTION INDUSTRY," *International Journal of Engineering Technologies and Management Research* **8**, 12 (2021). https://doi.org/10.29121/ijetmr.v8.i1.2021.846.
6. J. S. Menon and R. Sharma, "Nature-Based Solutions for Co-mitigation of Air Pollution and Urban Heat in Indian Cities," *Frontiers in Sustainable Cities* **3** (2021). https://doi.org/10.3389/frsc.2021.705185.
7. M. A. de Almeida and R. Colombo, "Construction of green roofs via using the substrates made from humus and green coconut fiber or sugarcane bagasse," *Sustainable Chemistry and Pharmacy* **22**, 100477 (2021). https://doi.org/10.1016/j.scp.2021.100477.
8. M. Saeli, L. Senff, D. M. Tobaldi, J. Carvalheiras, M. P. Seabra, and J. A. Labrincha, "Unexplored alternative use of calcareous sludge from the paper-pulp industry in green geopolymer construction materials," *Construction and Building Materials* **246**, 118457 (2020). https://doi.org/10.1016/j.conbuildmat.2020.118457.
9. K. Vijayaraghavan and F. D. Raja, "Pilot-scale evaluation of green roofs with Sargassum biomass as an additive to improve runoff quality," *Ecological Engineering* **75**, 70 (2014). https://doi.org/10.1016/j.ecoleng.2014.11.029.
10. K. Vijayaraghavan and F. D. Raja, "Design and development of green roof substrate to improve runoff water quality: Plant growth experiments and adsorption," *Water Research* **63**, 94 (2014). https://doi.org/10.1016/j.watres.2014.06.012.
11. S. J.S and A. Thomas, "Integrated Model and Index for Circular Economy in the Built-Environment in the Indian Context," *Construction Economics and Building* **21** (2021). https://doi.org/10.5130/ajceb.v21i3.7684.
12. U. Iyer-Raniga, "Using the ReSOLVE framework for circularity in the building and construction industry in emerging markets," in *IOP Conference Series Earth and Environmental Science* (IOP Publishing, 2019), 12002. https://doi.org/10.1088/1755-1315/294/1/012002.
13. Irfandi, A. Munir, M. Muslimsyah, and K. Huda, "The Effect of Plants on Extensive Green Roofs in Urban Heat Island Mitigation Efforts in Humid Tropical Cities," in *IOP Conference Series Earth and Environmental Science* (IOP Publishing, 2021), 12043. https://doi.org/10.1088/1755-1315/881/1/012043.

14. M. K. Mukherjee, "Eco-Environmental Factors in Green Roof Application in Indian Cities," *Journal of The Institution of Engineers (India) Series A* **95**, 137 (2014). https://doi.org/10.1007/s40030-014-0080-0.
15. T. E. Morakinyo, K. C. Dahanayake, E. Ng, and C. L. Chow, "Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study," *Energy and Buildings* **145**, 226 (2017). https://doi.org/10.1016/j.enbuild.2017.03.066.
16. A. Wadhwa and K. P. Kumar, "Selection of best stormwater management alternative based on storm control measures (SCM) efficiency indices," *Water Policy* **22**, 702 (2020). https://doi.org/10.2166/wp.2020.168.
17. N. S. Romali, N. Othman, and N. Ramli, "The application of green roof for stormwater quantity and quality improvement," *IOP Conference Series Earth and Environmental Science* **682**, 012029 (2021). https://doi.org/10.1088/1755-1315/682/1/012029.
18. T. Susca, S. R. Gaffin, and G. R. Dell'Osso, "Positive effects of vegetation: Urban heat island and green roofs," *Environmental Pollution* **159**, 2119 (2011). https://doi.org/10.1016/j.envpol.2011.03.007.
19. A. Bhatia, J. Mathur, and V. Garg, "Calibrated simulation for estimating energy savings by the use of cool roof in five Indian climatic zones," *Journal of Renewable and Sustainable Energy* **3** (2011). https://doi.org/10.1063/1.3582768.
20. S. Coulibaly, C. Aubry, F. Provent, S. Rousset-Rouvière, and S. Joimel, "The role of green roofs as urban habitats for biodiversity modulated by their design: a review," *Environmental Research Letters* **18**, 073003 (2023). https://doi.org/10.1088/1748-9326/acd801.
21. S. Knapp, S. Schmauck, and A. Zehnsdorf, "Biodiversity Impact of Green Roofs and Constructed Wetlands as Progressive Eco-Technologies in Urban Areas," *Sustainability* **11**, 5846 (2019). https://doi.org/10.3390/su11205846.
22. B. Y. Schindler, A. B. Griffith, and K. N. Jones, "Factors Influencing Arthropod Diversity on Green Roofs," *Cities and the Environment* **4**, 1 (2011). https://doi.org/10.15365/cate.4152011.
23. I. N. A. Salman and L. Blaustein, "Vegetation Cover Drives Arthropod Communities in Mediterranean/Subtropical Green Roof Habitats," *Sustainability* **10**, 4209 (2018). https://doi.org/10.3390/su10114209.
24. P. Vacek, K. Struhala, and L. Matějka, "Life-cycle study on semi intensive green roofs," *Journal of Cleaner Production* **154**, 203 (2017). https://doi.org/10.1016/j.jclepro.2017.03.188.
25. R. Kurian, K. S. Kulkarni, P. V. Ramani, C. S. Meena, A. Kumar, and R. Cozzolino, "Estimation of Carbon Footprint of Residential Building in Warm Humid Climate of India through BIM," *Energies* **14**, 4237 (2021). https://doi.org/10.3390/en14144237.
26. E. Korol and N. Shushunova, "Analysis of various types of loads from a multi-layer structure of green roof systems," in *IOP Conference Series Materials Science and Engineering* (IOP Publishing, 2021), 012089. https://doi.org/10.1088/1757-899x/1015/1/012089.
27. A. Francis, B. A., A. Afridi, P. L. M. Reddy, A. K. Tiwari, and C. N., "Urban Rooftop Farming in Bangalore: A Condensed Analysis of Sustainability and Economic Viability," International Journal of Multidisciplinary Research in Science, Engineering and Technology, vol. 8, no. 4, (2025).https://doi.org/10.15680/ijmrset.2025.0804509.
28. D. Govindarajulu, "Urban green space planning for climate adaptation in Indian cities," *Urban Climate* **10**, 35 (2014). https://doi.org/10.1016/j.uclim.2014.09.006.
29. S. M. Agarwal, "Go-Brown, Go-Green and smart initiatives implemented by the University of Delhi for environmental sustainability towards futuristic smart

universities: Observational study," *Heliyon* **9** (2023). https://doi.org/10.1016/j.heliyon.2023.e13909.
30. S. Paul and H. Nagendra, "Vegetation change and fragmentation in the mega city of Delhi: Mapping 25 years of change," *Applied Geography* **58**, 153 (2015). https://doi.org/10.1016/j.apgeog.2015.02.001.
31. B. Savitha, T. M. P. Kumar, and G. Ravi, "Own Grown Food Concept - Perception of Urbanites of Twin Cities of Telangana State," *International Journal of Environment and Climate Change*, 135 (2021). https://doi.org/10.9734/ijecc/2021/v11i430401.
32. H. Rallapalli, S. Sreepada, and J. Gorle, "Challenges in Adopting Productive Landscaping Approaches in Indian Cities," in *IOP Conference Series Earth and Environmental Science* (IOP Publishing, 2019), 12094. https://doi.org/10.1088/1755-1315/294/1/012094.
33. J. Fiksel, P. Sanjay, and K. Raman, "Steps toward a resilient circular economy in India," *Clean Technologies and Environmental Policy* **23**, 203 (2020). https://doi.org/10.1007/s10098-020-01982-0.
34. V. Shah, S. Suhane, and D. Gajjar, "Green Infrastructure Entities- A Study of Indian and International Cities," *Research Square (Research Square)* (2021). https://doi.org/10.21203/rs.3.rs-1104643/v1.
35. M. F. Jawaid and A. R. Khan, "The Smart City Mission in India And Prospects of Improvement in The Urban Environment," *IOP Conference Series Materials Science and Engineering* **955**, 012001 (2020). https://doi.org/10.1088/1757-899x/955/1/012001.
36. N. Aishwarya, A. Chellasamy, and S. Bhaghat, "Smart City- Far and Near Dream in Indian Context," *International Journal of Computer Applications* **174**, 25 (2021). https://doi.org/10.5120/ijca2021921006.
37. F. Vespasiano, T. Gujrati, B. Abbasi, and F. Bisegna, "Integrated Smart City Solutions: A Multi-Axis Approach for Sustainable Development in Varanasi," *Sustainability* **17**, 3152 (2025). https://doi.org/10.3390/su17073152.
38. C. R. S. Varma and S. Palaniappan, "Comparision of green building rating schemes used in North America, Europe and Asia," *Habitat International* **89**, 101989 (2019). https://doi.org/10.1016/j.habitatint.2019.05.008.
39. G. Gangwar, P. Kaur, and I. P. Singh, "Principles of Design for Sustainable Group Housing Projects in India," *Civil Engineering and Architecture* **8**, 1234 (2020). https://doi.org/10.13189/cea.2020.080608.
40. K. Vijayaraghavan and A. Badavane, "Preparation of growth substrate to improve runoff quality from green roofs: physico-chemical characterization, sorption and plant-support experiments," *Urban Water Journal* **14**, 804 (2016). https://doi.org/10.1080/1573062x.2016.1264429.
41. K. V. Linden and M. Stone, "Treatment Performance of an Extensive Vegetated Roof in Waterloo, Ontario," *Water Quality Research Journal* **44**, 26 (2009). https://doi.org/10.2166/wqrj.2009.004.
42. E. Burszta-Adamiak, "Analysis of Stormwater Retention on Green Roofs / Badania Retencji Wód Opadowych Na Dachach Zielonych," *Archives of Environmental Protection* **38**, 3 (2012). https://doi.org/10.2478/v10265-012-0035-3.
43. P.-A. Versini, F. Stanić, A. Gires, D. Schertzer, and I. Tchiguirinskaia, "Measurements of the water balance components of a large green roof in the greater Paris area," *Earth system science data* **12**, 1025 (2020). https://doi.org/10.5194/essd-12-1025-2020.
44. K. Vijayaraghavan, J. Arockiaraj, and S. Kamala-Kannan, "Portulaca grandiflora as green roof vegetation: Plant growth and phytoremediation experiments," *International Journal of Phytoremediation* **19**, 537 (2016). https://doi.org/10.1080/15226514.2016.1267699.

45. S. Pandey, D. A. Hindoliya, and R. mod, "Experimental investigation on green roofs over buildings," *International Journal of Low-Carbon Technologies* **8**, 37 (2012). https://doi.org/10.1093/ijlct/ctr044.
46. M. G. Rasul and L. K. R. Arutla, "Environmental impact assessment of green roofs using life cycle assessment," *Energy Reports* **6**, 503 (2019). https://doi.org/10.1016/j.egyr.2019.09.015.
47. J. Schade, J. Mukkavaara, B. Brunklaus, and M. von Scherling, "Greenhouse gas emissions and sustainability of green roofs and stormwater systems at a district level – comparisons with a life cycle perspective," *E3S Web of Conferences* **349**, 4003 (2022). https://doi.org/10.1051/e3sconf/202234904003.
48. C. Clark, P. Adriaens, and F. B. Talbot, "Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits," *Environmental Science & Technology* **42**, 2155 (2008). https://doi.org/10.1021/es0706652.
49. N. Chang, B. Rivera, and M. P. Wanielista, "Optimal design for water conservation and energy savings using green roofs in a green building under mixed uncertainties," *Journal of Cleaner Production* **19**, 1180 (2011). https://doi.org/10.1016/j.jclepro.2011.02.008.