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Harnessing Nature's Genius: Biomimicry As A Solution To India's Urban Environmental Challenges

Vallabha Agarwal
Student At Eklavya School, Ahmedabad, India

Abstract
The rapid urbanization in India has led to severe concerns in urban centres, including those related to water mismanagement, inefficient waste systems, escalating energy consumption, and intensified urban heat Islands (UHIs). Regardless of numerous policy interventions, including the Smart Cities Mission and AMRUT, implementation gaps have hindered meaningful progress. This paper explores how biomimicry can offer a sustainable pathway forward. Drawing from global and local examples, the paper investigates how the Namib Desert Beetle's design can inspire more efficient use of water, how termite mounds can inform passive cooling for energy-efficient buildings, how coral reef systems exemplify circular economy models for waste reduction, and how fungi can enable the design of more biodegradable packaging. If India can align urban planning with natural principles, these biomimetic strategies hold the potential to foster resilience, reduce ecological burdens, and support urban transformation.
Key Words: *Biomimicry, Urban Sustainability, India Urbanization, Water Management, Energy Efficiency, Urban Heat Island Effect, Waste Management*

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I. Introduction

India is undergoing rapid urbanization. From just 18% in 1960, the urban population has grown to over 34% as of 2023 and continues to rise (Coleman, 2018). While urbanization has the potential to increase productivity and economic growth nationwide, trends suggest that it has been unregulated and improperly managed. Several factors are attributed to this, including inadequate funding, a lack of institutional capacity, and inefficiencies in existing governance procedures. The improper management of urbanization in India is a pressing issue because it puts immense strain on basic resources and services, including water, energy, and waste management, and consequently creates socio-economic and environmental externalities.

While India has acknowledged this to some extent, as evident in the creation and launch of programs such as the Smart Cities Mission, AMRUT, Swachh Bharat, and Housing for All, delays, unmet targets, and uneven implementation persist as significant challenges. As the country's urban population is expected to grow in the coming years, it is crucial to invest in strategies that ensure the long-term sustainability of urban communities. Interestingly, to achieve this, policy designers and makers needn't look too far. Biomimicry, a field concerned with developing solutions inspired by natural models, systems, and elements, may just be the answer India is looking for. In line with this, the research question that this paper looks to answer is: **How can biomimicry-inspired strategies address the critical challenges of water management, waste disposal, energy inefficiency, and urban heat in Indian cities to promote sustainable urban development?**

This research paper argues that as Indian cities grapple with intensifying pressures due to rapid urbanization, as evidenced by reports of water scarcity, the urban heat island (UHI) effect, rising energy demands, and improper waste management, biomimicry has the potential to offer transformative solutions.

II. The Context And Challenges Of Urbanization In India

India is undergoing what many may consider a historic shift in its demographic and economic landscape, with urbanization emerging as a defining trend. It has been estimated that by 2036, approximately 600 million Indians, or around 40% of the population, will be living in urban areas (Kouamé, 2024). These cities are projected to contribute nearly 70% to the GDP, making urban areas critical engines of economic growth. However, this transformation also presents significant challenges, including those related to infrastructure, housing, governance, and environmental resilience.

While India's urbanisation rate has historically been slower than that of some other developing nations, it is now accelerating. The growth, however, has been somewhat uneven and often unregulated, especially in the peripheries of megacities like Mumbai, Hyderabad, and Delhi, where informal settlements proliferate beyond municipal boundaries. Despite flagship urban programs like the Smart Cities Mission, AMRUT, Swachh Bharat, and Housing for All – aligned with SDG 11 to make cities inclusive, safe, resilient, and sustainable – fragmented governance, weak accountability, and limited long-term planning continue to place immense strain on India's resources and systems, especially water, energy, and waste management.

Regarding water management, urbanization has reportedly played a significant role in depleting aquifers, disrupting recharge, and worsening flooding in various parts of the country. In Haryana, for instance, a groundwater crisis has intensified, with around half of the villages severely affected. Despite several years of conservation efforts, 47% of the 7403 villages in the state have been classified as water-stressed. Experts have noted that the deepening groundwater crisis in Haryana is a direct consequence of rapid urban expansion, ecological degradation, and unscientific urban planning land use. Dr Fawzia Tarannum, strategic advisor of GuruJal, was quoted as saying that "with 38% of the population already living in urban areas in the state and cities such as Gurgaon and Faridabad projected to reach four and three million residents respectively by 2041, the state must urgently align its infrastructure and urban planning with groundwater conservation goals" (Pati, 2025). Another significant issue is the increased risk of flooding in urban areas, largely a result of building in the path of floods. Findings from a study and an ongoing project at WRI India (Goswami and Basak, 2020) indicate that in India's 10 most populous cities, including Ahmedabad, Bengaluru, Delhi, Mumbai, and Pune, 35% of new urban development added between 2000 and 2015 has been located in high and very high recharge potential zones. Spaces, including lakes, wetlands, and forests, function as natural infrastructure that can absorb stormwater, reduce runoff volume and speed, and thereby reduce flood risk. When these areas and spaces are degraded and encroached upon, the natural flood defenses of cities deteriorate. Satellite imagery of locations within cities like Bengaluru, Chennai, and Hyderabad exhibits that between 1970 and 2020, lakes have shrunk, replaced by residential neighborhoods and playgrounds. Consequently, all these cities have seen multiple flood events in the past five years.

Moreover, as mentioned previously, many of the Indian cities are expanding rapidly but in an unregulated manner. The increase in the number of high-rise glass buildings, asphalt-heavy roads, and the destruction of natural vegetation all have intensified the urban heat island (UHI) effect. This effect is characterized by the city centre becoming significantly hotter than the surrounding rural areas. In fact, studies show that Indian cities warmed twice as fast as the national average between 2003 and 2020, with nighttime temperatures exhibiting the most pronounced difference due to heat retention in built materials (Nelson, 2025). Each 1°C rise can lead to a 4.6% spike in peak electricity demand, particularly in dense urban areas (Nayak, Vinod, and Prasad, 2023). This phenomenon leads to rising demand for artificial cooling, particularly air conditioning, which in turn puts immense pressure on urban energy systems. According to research, the energy consumption of air conditioners in India is expected to surge from approximately 190 TWh in 2023 to an estimated 600 TWh by 2038 (TCBU, 2024). This creates a vicious cycle in which cities heat up due to urban design and respond with energy-intensive cooling, resulting in both climate and infrastructure stress. Cities in India recently recording temperatures exceeding 50°C (Khan, 2024) exemplify how UHI not only compromises livability but also disproportionately affects the urban poor who lack access to cooling. Traditional mitigation strategies, including retrofitting buildings and scaling renewable energy, have been slow and fragmented in the country. Although cities, including Thiruvananthapuram, have adopted solar rooftops (New Indian Express, 2025) and net-zero building roadmaps (TNN, 2025), and buildings like the Indira Paryavaran Bhawan in Delhi have pioneered geothermal cooling (Khandelwal, Jain, and Gupta, 2020), such examples remain isolated. The underlying problem is structural. India's urban design rarely incorporates passive cooling, thermal insulation, or green infrastructure at scale. Therefore, a paradigm shift is required, one that reimagines cities not as heat traps but as self-regulating ecosystems.

Urbanization is also placing immense pressure on the country's waste management systems. There has been a rapid growth in the amount of waste being produced, with India generating around 62 million tons of solid waste annually (ITA, 2023). This is expected to rise to 260-300 million tons by 2047, an alarming increase (Kumar and Agrawal, 2020). In 2024, urban India itself was expected to generate around 150,000 tons of waste daily, overwhelming municipal infrastructure and creating overflowing landfills on city fringes (Sultana, 2024). Despite this volume, only around 75-80% of waste is collected, and a mere 22-28% is processed (PIB, 2016). Beyond the sheer volume of waste, the core of the problem lies in systematic inefficiencies, particularly the lack of source segregation and insufficient processing capacity. Cities such as Delhi have expanded their waste-to-energy capacities to handle the over 11,000 tons of waste produced daily (Sharma, 2025); yet, many such projects face delays, high emissions, and low efficiency, all of which lead to public concern over environmental safety. Meanwhile, cities like Mumbai are experimenting with ward-level decentralized composting and biogas production (Gokaldas, 2021); however, these efforts remain at the pilot level and fragmented. Improperly managing waste has far-reaching consequences, as it is a significant source of methane emissions, which contribute substantially to urban greenhouse gas emissions. It also clogs drainage systems, exacerbates flooding, and fosters conditions for disease outbreaks. Furthermore, informal waste workers, who form a significant part of the urban recycling economy, are often excluded from formal waste chains, working under hazardous conditions without recognition or support. Overall, traditional approaches, including those that rely heavily on landfill expansion and centralized incineration, are proving to be both unsustainable and socially exclusionary at present. There is therefore an urgent need to reimagine waste systems as closed-loop regenerative cycles and mimic nature's own zero-waste processes.

III. Introduction To Biomimicry And Solutions To India's Urban Challenges

Indian cities are grappling with the effects of rapid urbanization, whether it be related to water scarcity, energy inefficiency, overflowing waste systems, or rising urban temperatures. With traditional infrastructure often seeking to dominate nature rather than cooperating with it, the result is frequently brittle, resource-intensive systems. There is, therefore, an evident need for the conventional modern approaches to urban development to be rethought.

Here, biomimicry presents an optimistic alternative outlook. Biomimicry is the practice of drawing design inspiration from nature's strategies whereby, rather than being viewed as a constraint, nature is positioned as the mentor and model for sustainable design (Benyus, 2002; Klein and Seamon, 1996). Biomimicry was coined by biologist Janine Benyus, an author and biologist, in 1997. It has since grown into a multidisciplinary design and systems thinking framework with applications across engineering, architecture, and urban planning. Elaborating on the above, the core idea of such a system is that natural ecosystems operate with closed-loop cycles, generating zero waste and achieving high efficiency, all traits that are often lacking in human-designed systems. For instance, forests are capable of effectively managing water through decentralised collection and absorption systems (FAO, 2019); termite mounds in Africa maintain stable internal temperatures without the requirement for mechanical cooling (Sadiq, 2025); and coral reefs build structures with minimal energy and environmental impact.

It is therefore very likely that such natural models can inform solutions to India's urban challenges. This is even more possible when we consider the Indian context. The country has diverse ecosystems spread throughout, ranging from mangroves to deserts. These offer a wealth of biological strategies that can be adapted to local conditions. Moreover, biomimicry is well aligned with India's indigenous and vernacular architecture, which has been rooted in climate-sensitive design, the use of local materials, and passive cooling techniques for a long time. This cultural synergy makes biomimicry not only ecologically sound but also contextually appropriate.

Water Management

The Namib desert beetle is known to thrive in one of the driest environments on Earth. The reason for this is that "the beetles extract water from fog using a pattern of bumps and channels on their shells. The bumps are hydrophilic (water-loving) and the channels are hydrophobic (water-fearing), working in tandem to harvest water from the air. The hydrophilic bumps accumulate droplets of moisture from the air, then the beetle leans forward, and the hydrophobic channels allow it to drip into its mouth" (Casey, 2021). This is illustrated in Image 1.

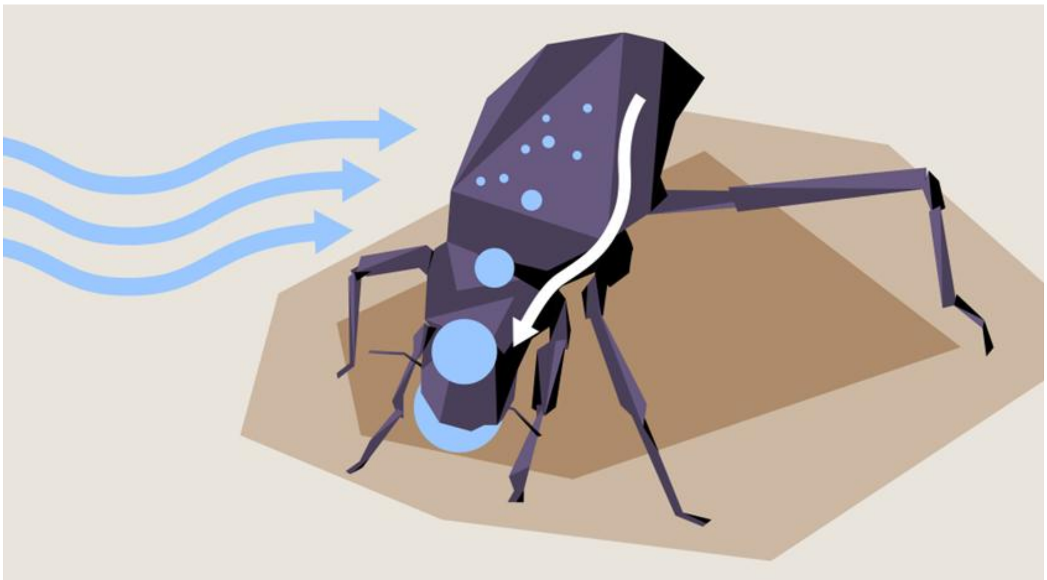

Image 1: A diagrammatic representation of water collection by the Namib desert beetle (Lambert, 2023)

With areas in India increasingly facing an urban water stress coupled with erratic monsoons, this natural strategy offers a powerful biological blueprint for addressing the urban water crisis.

Previously, researchers have been able to replicate the beatles' surface properties in engineered materials with a gradient availability where fog condenses rapidly and is efficiently channeled into storage. For instance, Yu et al. (2021) developed a special patterned fabric that mimics this mechanism, demonstrating high collection efficiency using programmable wetability zones. Similarly, biomimetic fog-harvesting surfaces created using three-dimensional microstructures have also shown excellent capability and flexibility, making them ideal for integration on urban façades, rooftops, or modular water collection units (Park and Kim, 2019).

In Indian cities where the groundwater has been overexploited and the piped supply is irregular, fog harvesting can become a decentralised, low-energy water solution. Moreover, with several parts of India, especially the coastal and hilly regions, experiencing high atmospheric humidity, these systems can be deployed for drinking water, rooftop gardens, or greywater use. Not only would it address the water issue, but it would also alleviate strain on municipal systems and foster long-term resilience to future climate variability.

Energy Efficiency

As previously explored, with India's urban areas continuing to grow denser and hotter, there is a rising dependence on air conditioning, which poses a major challenge to energy efficiency. With India's cooling energy demands expected to surge in the coming years, there is a requirement to address this crisis sustainably. Here, biomimicry, particularly inspired by termite mounds, which maintain stable internal temperatures despite extreme external heat, offers a compelling point of inspiration.

By building tall, porous mounds with intricate internal ventilation tunnels that regulate temperature and humidity naturally, termites in Africa enable a passive air-conditioning system (Wood, 2024). This principle of natural ventilation has also been successfully applied in buildings such as the Eastgate Centre in Harare, Zimbabwe, pictured in Image 2, which consumes 90% less energy for climate control compared to conventional buildings of similar size (Fehrenbacher, 2012). The building utilizes a network of chimneys and vents inspired by the geometry of termite mounds to facilitate airflow, maintain thermal comfort, and eliminate the need for artificial cooling.

Image 2: Eastgate Centre in Harare, Zimbabwe (Kaur, 2025)

Moreover, termites do not solely rely on geometry but also on material properties that regulate heat exchange. Termites construct the mounds using a blend of soil, saliva, clay, and organic matter (Sujada, Sungthong, and Lumyong, 2014). This results in porous yet dense structures with high thermal inertia. This implies that the walls absorb heat slowly during the day and release it gradually at night, helping to buffer extreme temperature fluctuations (Evangeline, 2025).

Drawing inspiration from termite mounds offers a practical model for incorporating eco-friendly materials, such as compressed earth blocks, lime plaster, and porous ceramics, alongside intelligent, climate-sensitive building designs in Indian cities like Mumbai, Delhi, and Hyderabad. By building structures with natural ventilation, thick walls that store heat, and breathable surfaces, these cities can significantly reduce electricity use and maintain cool, comfortable buildings.

Urban Heat Island (UHI) Effect

Although biomimetic building designs inspired by termite mounds could significantly reduce indoor cooling demands, it is vital that the broader UHI effect, which is playing out in urban India, be addressed. UHI exacerbates the energy burden on cities by intensifying the ambient temperatures, thereby increasing reliance on air conditioning. Extensive research has been conducted into the UHI in India. For instance, in Mumbai, due to the dense concretization and lack of vegetative cover, varying temperatures have been observed between localities. "Between March 1 and March 22, 2025, suburban areas such as Vasai West and Ghatkopar experienced average temperatures of 33.5 degrees and 33.3 degrees, respectively, while Powai – one of the city's greener and less densely built areas – registered a much cooler average of 20.4 degrees. This represents a striking 13.1-degree difference within the same city" (Chittaranjan Tembhekar, 2025). Meanwhile, even Delhi presents a striking case of how rapid urbanization has contributed to UHI. Between 2000 and 2015, Delhi's built-up area expanded by 61%. This resulted in a significant loss of vegetative cover, far exceeding that of cities such as Kolkata and Ahmedabad (Goswami et al., 2022). Research suggests that the green cover in the city decreased from 17.32% in 1977 to 10.45% in 2006. While official reports cite a rebound to as much as 23.06% in 2021, environmentalists raise doubts about the actual ecological gains (Shukla, 2024). Overall, the combination of myriad factors, including the increasing population, energy use, vehicular emissions, and built infrastructure, has intensified the heat absorption and retention capacity of the urban landscape.

Biomimicry once again offers powerful strategies to mitigate UHI by mimicking natural processes for regulating heat. These include porous and reflective surfaces, ventilated canopies, and green façades modeled on forest ecosystems and leaf structures. Internationally, numerous success stories have been reported utilizing these strategies. For instance, in Singapore, the Park Royal collection Pickering Hotel by WOHA, as seen in Image 3, utilised biomimicry to combat the UHI effect. Inspired by the rice paddies of Bali and rainforest ecosystems, the building incorporates more than 15,000 m² of lush greenery across cascading balconies and sky gardens (Khandelwal, 2020). These plantings, which feature over 50 tropical species, successfully cool the structure through shade and evapotranspiration, while improving local air quality. Self-shading forms, natural ventilation, and photovoltaic-powered sky gardens further minimize reliance on artificial cooling (Visit Singapore, 2013). These interventions mirror blue-green infrastructure, blending natural ecosystems into the urban fabric for passive cooling.

Image 3: Park Royal collection Pickering Hotel by WOHA (WOHA, 2013)

In the Indian context, integrating such biomimetic strategies with traditional urban planning can, therefore, significantly reduce electricity loads, improve outdoor comfort, and help cities meet both climate resilience and public health goals. For instance, studies on the cooling intensity of trees in urban environments have shown that temperature reductions achieved can range from 0.4°C to 3.0°C (McDonald et al., 2016). This highlights the importance of initiatives such as the Mumbai Climate Action Plan (MCAP), which aims to increase vegetation and permeable surfaces to cover 30-40% of its land area by 2030. If other cities across the country could invest in and take prompt action, models like this could help mitigate the UHI effects.

Waste Management

Nature has some of the most efficient systems, exhibited by coral reefs and fungi. These can offer profound lessons for rethinking urban waste in India.

Coral holobionts, which are defined as complex communities of corals, bacteria, and fungi, exhibit a perfectly circular economy wherein no resource is wasted (Димитров, 2025; Martynoga, 2025). Elaborating on this, each organism's by-product becomes a critical input for another: carbon, phosphorus, and nitrogen are all continuously cycled within the system to build thriving ecosystems from seemingly barren ocean floors. These natural synergies enable the creation of value without any waste. As has already been explored, Indian cities generate thousands of tons of waste daily, and this is often unsegregated and poorly managed. If the country built systems inspired by the coral reef's resource-sharing model, then municipal systems could enable waste symbiosis between sectors. For example, biodegradable food waste may become a nutrient stream for urban farming or biofuel production, mimicking the coral's metabolic loops.

Simultaneously, another aspect of waste generation that needs to be critically acknowledged is the sheer amount of non-biodegradable materials, particularly plastic, used in e-commerce and food delivery packaging in the country. As reiterated in a report by Mishra (2024), "major drivers of this problem are the booming e-commerce and food delivery sectors. Industry reports say that in 2023, India's e-commerce market accounted for 1.2 MT of plastic waste, much of it single-use. The e-commerce plastic packaging market size was $23.34 billion in 2023. The food delivery sector is another big contributor, generating approximately 3,50,000 tonnes of single-use plastic waste annually." Fungi-based material innovation can be a helpful intervention in this case. Mycelium, the root-like structure of fungi, can be cultivated into packaging that is both strong and lightweight, as well as fully compostable (Pohan, Kusumawati, and Radhitanti, 2023). Companies such as Ecovative and MycoWorks have already begun creating packaging from fungal composites that degrade naturally without emitting toxins. These materials successfully replicate the resilience of mycelial networks while using artificial byproducts as feedstock.

India can adopt a dual biomimetic approach, scaling mycelium packaging into tier-1 and tier-2 cities, particularly for the food delivery and e-commerce sectors, while investing in localized waste-to-resource ecosystems inspired by coral reefs. Such strategies can support India's Swachh Bharat and Smart Cities missions, which in the long run will reduce landfill load, create green jobs, and enable the cities to switch from linear to regenerative models of urban metabolism.

IV. Conclusion

With India grappling with the mounting challenges of rapid urbanization, ranging from water scarcity and poor waste management to rising energy demands and intensifying urban heat, biomimicry can emerge as a robust framework for rethinking city design. While humans look far and wide for solutions, nature, which surrounds us, offers blueprints for resilience, efficiency, and circularity.

This research paper explored how the design of the Namib Desert beetle, with its unique ability to harvest moisture from the air, can inspire water management systems in Indian cities, whereby fog can be captured and converted into usable water. Termite mounds, which are known to regulate temperature through passive ventilation, can also inform sustainable architecture, significantly reducing reliance on energy-intensive cooling. This idea has already been realized and successfully implemented in Zimbabwe's Eastgate centre and is potentially scalable across Indian metros. Furthermore, to combat the UHI effect, which has been extensively documented in India, nature-based solutions in the form of green façades and vegetative envelopes – akin to those used in Singapore's Park Royal on Pickering – may be crucial. These can significantly lower ambient temperatures and enhance urban comfort. Beyond this, India also struggles to manage waste effectively. As a result, drawing inspiration from coral reef ecosystems could inform a vision of circularity in which nothing is wasted, and every byproduct supports the larger system. India also uses a large amount of plastic packaging, mainly in its e-commerce and food delivery sectors. In this case, a call for innovation and materials is necessary, wherein fungal mycelium-based packaging can provide a promising biodegradable alternative.

All in all, these strategies not only reduce environmental burdens but also promote economic and social benefits. In order to realize this vision, Indian cities need to integrate biomimetic thinking into their policy infrastructure and innovation. Instead of viewing nature as separate from urban development, nature must be embraced as a mentor and model – a thought that aligns quite deeply with traditional Indian philosophy.

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