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Natural materials (biomaterials) and biomimicry principles, as tools for envisioning the sustainable cities of the future.

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Abstract. It is widely acknowledged that the impact of human activities on the Earth's atmosphere following the first industrial revolution was so significant that it was designated as a new geological epoch with the term "Anthropocene." The search for a new design strategy that integrates the nature of urban landscapes with their architecture is critical in the Anthropocene age. Modern instances of green cities and smart cities are the direct result of the emergence of a value system with a highly aesthetic view of global ecosystems, prompting us to seek a non-anthropocentric method of reasoning and, as a result, planning. In this study, we present innovative city design that controls environmental factors and is based on urban planning of cities approached by the principles of biomimicry. The research question is whether natural materials with modern construction methods and biomimicry principles can lead to the design of cities that face the numerous challenges of climate change. Three examples of cities that have adopted the model of biomimicry design principles will be presented, in parallel with a literature review of natural materials. Conclusions will be drawn which will be followed by the formulation of proposals for the optimal planning of cities in terms of sustainability. The goal is to develop a design process targeted at the efficient design of cities in response to climate change.

1 Introduction

If every structure on Earth could manage its waste, utilize net zero energy, be built without the use of energy-intensive materials, and reuse the few materials available, then we could design sustainable buildings. How can renewable biomaterials be used to create and support green walls rather than traditional mineral building materials? How can plant walls be set up to rely on natural light rather than electricity? Scientists are challenged to address a range of issues to minimize the carbon footprint, maximize resource usage, and sequester carbon dioxide. Active building materials including microorganisms and exhibiting biological properties are now being explored. What are the advantages of adopting biomimicry and natural materials in urban planning from an environmental, ecological, and social-economic perspective for a city?

This paper's main objective is to investigate new environmentally friendly building materials and emerging carbon sequestration technologies, which recycle emissions from built-up urban infrastructure into local circular economies of raw materials and energy and whose use is suggested by new construction techniques. Ecosystem service analysis (ESA) in urban settings, according to researchers like Petersen Zari, [1] lends itself to long-term spatial planning or decision-making and permits the creation of concrete ecological benchmarks over a range of timescales. The same paper provides tables of ecological indicators and descriptions of how calculations are made to provide more information about the ESA approach. The strategic integration of ecosystem services into urban planning is likely to have significant long-term benefits for both people and other living organisms, according to preliminary findings, despite the trade-offs and conflicts that must be understood and planned for when designing the provision of ecosystem services in cities. [2].

Real-world examples of buildings that creatively or conventionally use biomaterials in architectural features or construction methods abound. In this approach, plant-based materials have proven particularly noteworthy. For instance, Hemp House [3] uses hemp concrete to build its surroundings. Fiber panels, coatings, sheets, and even bricks can be made from hempcrete, a biomaterial. Another illustration of this use is the Regional House, a facility for environmental education in Belgium. Both linen and hemp have been used in construction at different stages. For example, the sealing structure of Brass House Amsterdam [4] uses this biomaterial to ensure thermal efficiency. Some of the more common materials can also be characterized as biomaterials, even though the bio-architecture sector primarily develops unique materials. One of them is lumber, a well-known building material that is presently being investigated in fresh ways, as shown, for example, in the tall Tamedia office building [5] and the wood innovation design center [6]. This list also includes bamboo from more contemporary roofs, like the House in Masnou, Spain [8], as well as from more

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conventional roofs in Indonesia, like the Kura Kura Badminton courts [7]. It is still possible to make references to straw in this context given its widespread applications as a well-known biomaterial, including the Refuge II project [9].

It is also important to recognize the cutting-edge biomaterial technology that uses fungi to synthesize structural components. An excellent example of this is the Hy Fy experimental pavilion [10], which was built in the MoMA PS1 yard in 2014 using mycelium bricks that grew in prismatic molds from shredded corn stalk fragments in less than a week. a science-based technology that is being improved. A temporary pavilion constructed in France was added to the experimental elephant ordure bricks at the elephant theater pavilion [11]. Due to their diet of grass, their excrement is very fibrous, and when combined with other agglomerates, it forms spherical bricks with a vertical opening that may accommodate a steel tube for reinforcement that is 255 mm in diameter and 50 mm thick. While some biomaterials, like mycelium and food scraps, are combined with other materials to create usable composites, others, like wood and hemp, can be used in the construction sector in their natural state.

Finally, promoting net-zero carbon emissions from green construction can be advantageous for the environment, society, and economy, helping to achieve the global sustainable development goal of limiting the increase in the average global temperature to 2-1.5 degrees Celsius from pre-industrial levels [12]. The results of the research of Chen Lin et all, occurred from national policy frameworks and technology roadmaps from the United States of America, Japan, China, and the European Union, about carbon emissions, policies, models, life cycle assessment, and sustainable materials such as biochar, bioplastic, agricultural waste, animal wool, ash and self-healing concrete that can reduce the carbon footprint [12].

2 Related Work

2.1 Viscous boundaries algae-laden scaffolds for the built environment.

Fig. 1. Viscous boundaries algae-laden scaffolds. http://discovery.ucl.ac.uk/id/eprint/10146906/, access 2/4/2023

As Figure 1 shows, this thesis looks at the development of new living membranes for architecture. It investigates the design and manufacture of large-scale photosynthetic panels built of algae-laden biological materials derived from water. The study begins by identifying natural processes as fluid processes that actively integrate the temporal stabilities of development and decay. This enables us to envision building materials as fluid systems built across scales of magnitude, resulting in a transitory 'viscous' zone that provides a continuum between the object of manufactured ecosystems (architecture) and the subject of the environment (nature). The work, which is situated at the crossroads of architecture and biochemical engineering, investigates the critical role of viscosity in water-based polymeric materials to sustain biological activity. On the microscale, hydrogels have been proven to provide cell-friendly conditions while also being capable of constructing a hierarchical composite with structural and chemical stability on the macroscale [13].

The viscosity qualities of the hydrogel are critical for scale-up creation using additive manufacturing and casting processes. Morphological investigations have resulted in several large-scale scaffolds, with varied qualities ranging from homogenous 'bio-layers' to heterogenous 'biohybrids'. Each was created to improve the performance of microalgal cells and their relative photosynthetic activity in applications such as bioremediation, biosorption, and photovoltaics. This thesis approach demonstrates the possibilities of using biocompatible structures formed of viscous biomaterials in the built environment. The research seeks to apply revolutionary robotic additive manufacturing techniques to regulate, alter, and print scaffolds with the maximum level of precision [14].

2.2 Algae House (BIQ House). Hamburg debuted the world's first algae-based bio-reactive façade.

On March 23, 2013, the BIQ house was the world's first pilot project to display a bio-reactive façade at the International Building Exhibition (IBA) in Hamburg.

Fig. 2. (right)Algae House (BIQ House). https://www.architonic.com/en/project/arup-biq-house/5101636, access 3/3/2023.

Fig.3 (left) Window detail. https://www.architonic.com/en/project/arup-biq-house/5101636, access 3/3/2023.

As figures 2 and 3 depict, this passive-energy house generates biomass and heat as renewable energy resources using 200m2 of integrated photo-bioreactors. At the same time, the system incorporates additional functionalities like as dynamic shading, thermal insulation, and noise reduction, demonstrating the technology's full potential. The microalgae utilized in the facades are grown in 2,5m x 0.7 m flat panel glass bioreactors. On the southwest and southeast sides of the four-story residential structure, 129 bioreactors have been erected. The fully automated energy management center is the system's core, where solar thermal heat and algae are captured in a closed loop, stored, and used to make hot water.

Colt International spent three years researching and developing the revolutionary façade system, which is based on a bio-reactor idea developed by SSC Ltd and design work headed by the international design consultant and engineering firm, Arup. The German government's "ZukunftBau" research initiative provided funding. Jan Wurm, Arup's Europe Research Leader said that using biochemical processes in the façade of a building to create shade and energy, is an innovative concept. It has the potential to become a sustainable solution for energy production in urban settings, so seeing it tested in a real-world scenario is exciting. Thus, on April 25, 2013, the bio façade system was activated for the first time [15].

2.3. Tokyo Railway

Engineers could benefit from the efficient tactics of a slime mold. An experiment implies that Physarum polycephalum, a gelatinous fungus-like mold, may lead the way to enhanced technological systems, such as more robust computer and mobile communication networks. This discovery follows the discovery by a team of Japanese and British researchers that the slime mold attached itself to scattered food sources in a configuration that was virtually identical to Tokyo's train system. Atsushi Tero of Japan's Hokkaido University, together with colleagues from other Japanese universities and the United Kingdom, spread oat flakes on a wet surface in areas corresponding to the cities surrounding Tokyo and enabled the Physarum polycephalum mold to grow outwards from the center. They observed as Figure 4 depicts, that the slime mold self-organizes, spreads, and builds a network comparable in efficiency, dependability, and cost to Tokyo's train network's real-world infrastructure. Tero states in the paper, that some organisms grow in the form of an interconnected network as part of their normal foraging strategy to discover and exploit new resources and that Physarum is a large, single-celled amoeboid organism that forages for food sources that are dispersed. It can find the shortest path through a maze or efficiently connect different arrays of food sources with low total length yet short average minimum distance between pairs of food sources, and it has a high fault tolerance to accidental disconnection [16].

The researchers recognized that encapsulating the essence of this biological system in basic rules could be valuable in informing the design of self-organizing and cost-effective networks in the real world. They captured the key mechanisms required for the slime mold to efficiently connect its food sources and put them into a mathematical model. Because the slime mold has been through numerous rounds of evolutionary selection, this formula based on its feeding behaviors could lead to more efficient and adaptive network designs for transportation and communication. Wolfgang Marwan of Otto von Guericke University in Germany wrote that the model captures the basic dynamics of network adaptability through the interaction of local rules and produces networks with properties comparable to or better than those of real-world infrastructure networks. Tero and colleagues' work is a fascinating and convincing example of how biologically inspired pure mathematical models can lead to completely new, highly efficient algorithms capable of providing technical systems with essential features of living systems for applications in computer science. They claim that their methodology can help improve efficiency and lower costs in self-organized networks without centralized control, such as remote sensor arrays, mobile ad hoc networks, and wireless mesh networks. This could pave the way for future research on biomimetic urban and road planning [17].

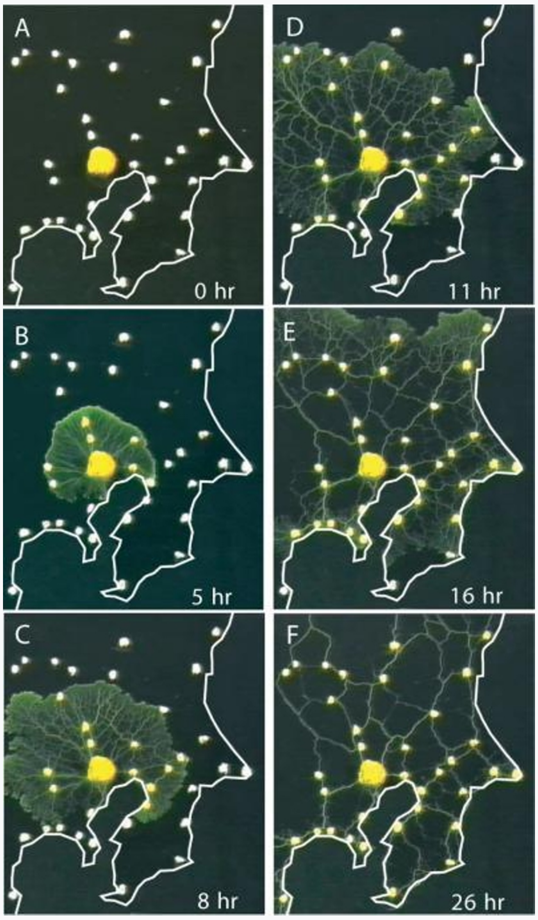

Fig. 4. This is the creation of a network in "physarum polycephalum." (a) At t = 0, a tiny plasmodium of "physarum" was placed in an experimental arena surrounded by the Pacific coast (white border) and supplemented with additional food sources in each of the region's major cities (white dots). (b–f) The plasmodium expanded with a continuous edge from the original food source and gradually colonized each of the food sources. The spreading mycelium behind the increasing margin

resolved into a network of tubes interconnecting the food sources.

3 Relationship between urban planning and ecosystems

Redesigning buildings in metropolitan settings to offer, integrate, or support services such as energy, water, food, air, water purification, and soil could be one approach to decrease or possibly reverse the negative environmental impacts of building the environment and reduce pressure on ecosystems. This indicates that an intelligent constructed environment would strive to contribute more than it consumes while repairing prior environmental damage. Individual smart buildings, however, may be unable to influence the larger urban built environment, the living world, or people. However, if we consider smart buildings to be those that are part of more widely interconnected urban systems that can interact with one another and with the larger urban setting, they may be better able to adapt to climate change [18]. Ecosystems in each site and climate may give a model, or set of performance criteria, for redeveloping existing cities, creating new urban regions, or reconsidering how people inhabit urban environments in the same location [19].

The nature-inspired city Lavasa, India bases the alliance between HOK, one of the largest architectural companies in the world with Biomimicry 3.8 to mimic the ecosystem of rainforests. Lavasa is a city affected by monsoon rains, where precipitation is concentrated for certain months. So, by imitating forest water management, this city was able to save water for the dry season. To help the developed area avoid mass erosion during the monsoons, the Biomimicry 3.8 team collected and translated biological intelligence from the area's ecosystems to understand how native forests handle monsoon rainfall (more than eight meters of rainfall) without significant corrosion. According to the research, the natural biological model evaporates 20-30% of the precipitation from the forest, while 60-65% infiltrates the soil and just 10-15% flows into rivers and streams as surface runoff [20].

Fig. 5. (left) The fruit of manikaka tree, RB, access 10/3/2023

Fig. 6. (right) Manilkara tree, RB, access 10/3/2023

Biologists have identified and documented more than 20 distinct creatures and design patterns in the local ecosystem that will best promote resilient and sustainable design to meet this environmental performance standard (EPS) and achieve additional goals through landscape design. They derived design techniques for water disposal, erosion reduction, and groundwater recharge from mechanisms such as leaf drop tips and root architecture of "Manilkara" Trees.

As a result, the concepts of ecological intelligence and biomimetic design resulted in a more successful design with measurable outcomes such as:

- Restoration of 70% of previously deforested land.
- 30% reduction in carbon emissions.
- 65% reduction in drinking water consumption.
- 95% reduction in waste sent to landfills.

Kalundborg, the world's first industrial ecosystem that has championed the principle of zero waste so that the by-product of one enterprise is used as a resource by the next enterprise, is another example of a project that has adopted some of the principles of ecosystem thinking. Some of these regenerative ideas are already being implemented in cities around the world. The Danish city of Kalundborg features an industrial paradigm in which any undesired material becomes a wanted resource for another enterprise. Companies have acquired and traded waste materials in a closed loop since the 1960s. A waste product from one industry becomes a raw material for another, and critical resources such as water and gas are shared among different industries [21]. According to Kenny et all, using a 'systems thinking' approach with biomimicry has the potential for significant improvement to urban infrastructure solutions, in contrast to the ad hoc approach [22].

4 Case studies of cities that adopted biomimicry principals

Three case studies in India, Brazil, and Europe will be presented, according to their ecological philosophy, based on biomimicry-inspired solutions.

4.1 The city of Lavasa in India

Fig. 7. The map of India, https://avbc.me/OF4rNEAD, access 2/4/2023

Imitating nature, its concepts, and institutions can inspire humans to create designs and procedures that tackle everyday issues. Lavasa, a city in India, shown in Figure 7, is an example of a city committed to maintaining and promoting environmental biodiversity while providing a place where man and nature cohabit happily. Lavasa is India's first hill town, built by Lavasa Corporation Limited, a subsidiary of HCC (Hindustan Construction Company Limited). Lavasa is 216 kilometers away from Mumbai. Lavasa has a variety of housing alternatives, including rental houses, apartments, and villas. Lavasa is the first fully managed and GIS-mapped city in the world.

Lavasa, India's first planned hill city, as shown in Figures 8 and 9, is located three hours outside of Mumbai. It is made up of a piece of land one-fifth the size of Mumbai, with 100,000 m2 of lush foliage strewn across it. At Lavasa, integrated development will encompass five self-sustaining cities with a permanent population of 300,000 people who will be able to live, work, learn, and play in total harmony with nature. Dasve is the first, and Mugaon is the second. Every Lavasa living area boasts extraordinary facilities, panoramic landscape views, and expansive designs that bring the beauty of Lavasa's surroundings inside the home. Robust social infrastructure, 24-hour water and power supply, e-governance, and a direct City Manager all contribute to sophisticated, comfortable living conditions [23].

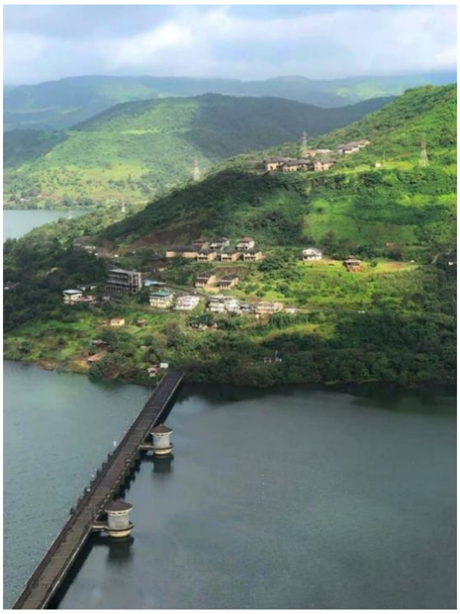

Fig.8. Panoramic view of Lavasa city. https://www.theguardian.com/cities/2015/nov/19/inside-lavasa-indian-city-built-private-corporation, access 3/4/2023

The city has a determined City Management Services team to offer the value proposition to its people and tourists through improved community living, governance delivery, and an emphasis on public safety and security, including law and order services. The Citizen Contact Centre (CCC) is the highlight. This extra value distinguishes Lavasa from other cities. Every person has access to the CCC, which serves as a one-stop shop for all types of information ranging from amenities to inquiries and billing.

Fig.9 Panoramic view of Lavasa city. https://www.theguardian.com/cities/2015/nov/19/inside-lavasa-indian-city-built-private-corporation, access on 3/4/2023

Fig. 10. Lavasa.city. https://www.theguardian.com/cities/2015/nov/19/inside-lavasa-indian-city-built-private-corporation, access on 3/4/2023

Fig. 11. Street view of Lavasa city**.** https://www.theguardian.com/cities/2015/nov/19/inside-lavasa-indian-city-built-private-corporation, access on 3/4/2023

Concerning sustainability, in the city of Lavasa, the development, and its operations have a low environmental impact, with eco-friendly technologies, pointing out the value of natural systems. As a concern for energy conservation, there is less reliance on scarce fuels, more domestic production, less driving, and more walking, (Figures 10 and 11). Finally, concerning life efficacy, these elements contribute to a high quality of life, as well as places that enrich, uplift, and inspire the human spirit [24].

4.2 Rocinha favela

The concept of "ecological succession" is integrated into the project conducted by Jan Kudlicka to regenerate the Rocinha favela (Figure 12), in Rio de Janeiro [25]. This project seeks techniques to build spaces that contribute to the social and economic development of the community because of his comprehensive grasp of the "favela ecosystem". The project intends to intervene in two stages. The first focuses on consolidating existing structures rather than demolishing the urban framework, enhancing structural safety in urban areas, and renewing façades to enhance hydrothermal quality indoors. Buildings will be arranged vertically in the second stage, classifying some community activities, such as the ground-floor commercial and service zones for hospitals, schools, marketplaces, pharmacies, etc. The rooftops will then be utilized as public space for people to stroll across, for children to play on in playgrounds, as well as for outdoor movies and cultivation areas to grow food that can subsequently be sold on the ground. The higher floors will be used for apartments. Slum regions' regeneration offers a chance for biomimicry-inspired solutions based on the system and solutions from tinkering with aspects within its system.

Fig. 12. Rocinha favela, Rio de Janeiro, Brasil. rb.gy/zu79e, access 8/8/2023

4.3 Kalundborg

An industrial ecosystem has emerged in the Danish city of Kalundborg [26]. Public and commercial businesses have been buying and selling waste products from industrial production in a closed cycle since the 1960s. Key resources like gas, steam, cooling water, and gypsum are shared among many sectors, which benefits both the economy and the environment. A residual product of one business becomes the raw material of another. Fish farms, greenhouses, homes, and many other operations use extra heat to produce byproducts that are then sold to neighboring businesses or used by other industries. The goal is to significantly reduce environmental effects while also reducing resource use. The Kalundborg model is being exported to many industrial areas across the world, because of several educational institutions that have created curricula and classes about it [27].

Fig.13. Kalundborg, Denmark [27].

5 Discussion and conclusions

The design of society's major infrastructure systems is generally based on anthropogenic learning and seldom encapsulates learning from nature. Problems created by such behaviors have previously not been thought to present a serious threat to humanity [28]. Many built environment professionals are now reconsidering the impact of such systems on the environment and their vulnerability to issues such as climate change.

This paper presents an approach to delivering sustainable urban infrastructure that addresses 21st-century needs by emulating natural form, function, and process - biomimicry – in infrastructure design. The case of Lavasa is a paradigm where man and nature co-exist harmoniously while ensuring economic and environmental sustainability. We hope that the world's first model city based on the principles of Biomimicry, will consist of a successful experiment for many future cities around the world.

Additionally, concerning biomaterials, they provide opportunities to improve the ability to build in a fully circular and sustainable manner. This is because they are biodegradable, and store CO_2 over their lifetime, lowering the carbon footprint of buildings and products. Furthermore, some studies demonstrate that the use of biomaterials in civil construction has significant benefits not only for the sustainability agenda but also for user well-being. Fungal mycelium products have high insulating properties and are resistant to fire and water. They grow quickly and can form highly durable connections with neighboring mycelium products, making them very useful materials in construction. There are already companies operating in this field, such as "Ecovative Design" or "MycoWorks," that develop degradable materials to replace products based on polyester or petroleum because the manufacturing of biomaterials reduces CO_2 emissions in any event. In the case of fungi, agricultural waste is recycled into the substrates where the mycelium grows, a procedure that is part of the circular economy.

This paper reveals the need for sustainable solutions, by the current inquiry into biomimicry-informed design and highlights potential applications from literature that demonstrate precedence for nature to inspire the design of urban infrastructure. Using biomimicry in our cities can drastically reduce our harmful footprint on the environment. Systems such as renewable energy, waste management, and recycling must all be implemented if we are to save our species from global extinction. We believe that biological systems will once again be a very important part of creating infrastructure, cities, and buildings. Active building materials will come to work in addition to conventional materials, and in some cases, they can even replace them. To use them in construction, sustainable ways of mass production should be found at a reduced cost, but also to optimize their physical characteristics on a case-by-case basis. In this approach to biomaterials, regardless of material and process, one issue is clear: the current built environment requires more than solid and static materials. It requires materials that can autonomously remodel, regenerate, grow, and adapt in response to their environment.

Additionally, this research indicates that the benefits of a city about environmental, ecological, and social aspects using the principles of biomimicry, can consist of a good paradigm for designing the cities of the future. The vision for the 21st century is to build cities that function like forests and buildings that act and react like trees.

6 Limitations

A substantial barrier to sustainable building implementation in the construction sector has been highlighted as the cost. Additionally, there is a dearth of trustworthy data and little awareness about sustainable buildings, which makes it difficult to finance projects and raises the cost. In some nations, there is also a dearth of government policy backing and a dearth of planned building norms for green-rated projects that have been formalized legislation, which reduces the appeal of green structures. Furthermore, compared to conventional construction technologies, green building solutions are more expensive and take longer to install. The future use of life cycle analysis in sustainable construction should be improved to produce strong measures and policies and to boost knowledge of green building for universal access to fully advance the construction industry's system-wide transition to carbon neutrality.

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