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Biomimetic materials and technologies for carbon neutral cities in South Africa: a literature review

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Abstract

The accelerating decline in the environment and increasing atmospheric concentration of greenhouse gases (GHGs) are closely linked to human activities. This has caused the menace of climate change with the impact globally felt. The continent of Africa, given its geographical location, is believed to be more vulnerable and will severely feel these impacts. To curtail this, mitigation and adaptation have been recognised as the most potent strategies to curtail the challenge of climate change. Increased adaptive capabilities of infrastructures and systems in South Africa is, therefore, imperative. This paper explores biomimicry, a new field that studies and emulates the forms, processes, and strategies found in natural organisms to solve human challenges. For its over 3.8 billion years of evolution, nature has effectively and efficiently tackled many of the challenges mankind is grappling with today. Hence, the objective of this study is to evaluate and present existing biomimetic materials and technologies which contribute less to the degradation of the environment. Biomimetic materials and technologies, known to possess sustainable credentials will reduce the release of GHGs and has the potential for carbon sequestration. The result will help offer sustainable alternatives to those materials and products which significantly contribute to the increase in carbon footprint.

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Keywords: biomimicry; construction industry; CO2 emission; greenhouse gas; nature

1. Introduction

The role the construction industry plays in the overall improvement of the quality of life of the society is salient and significant [1]. It is also noteworthy that globally, investing heavily in the industry is used to stabilise the economy thereby confirming the industry's leading status in the national development masterplan of many nations

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[2]. This is evident through the provision of infrastructural facilities which have in turn profited humanity as well as improved the economic development of many countries [3]. It is also proven that the sprawl in urbanisation is proximately connected to the industry due to its associated buildout [4]. The provision of cogent infrastructures such as roads, rail, bridges, waste, and waste water treatment plants, energy production and transmission plants, residential, commercial and industrial facilities [5] amongst many others are examples of buildouts linked with the construction industry.

However, in the process of urbanisation and economic development globally, the construction industry has been identified as a major player in environmental degradation and pollution. Attesting to this fact is the replacement of vegetation and forests with impermeable concrete surfaces of buildings and roads [6]. Infrastructures are known to have a long-term effect on the human environment due to their continuous emission of pollutants in large quantities [7]. Based on a study by the United States Environmental Protection Agency (USEPA), indoor pollutant levels are often higher than those outdoor, usually 2.5 and occasionally 100 times higher [5]. The study also reveals that most people spend as much as ninety percent (90%) of their time indoors [5] making them susceptible to the risks associated with the pollutants. Indoor pollutants are those emanating from backing materials, paints and other components in the building. However, a report by the United Nations Environment Programme – Sustainable Buildings & Climate Initiative (UNEP-SBCI), undertaken in collaboration with the Construction Industry Development Board (cidb) identified the construction industry to be a major contributor to CO_2 emissions in South Africa [8]. Sustainable activities, materials, and technologies should, therefore, be adopted by the construction industry in reducing its negative environmental impacts globally. The objective of this paper, therefore, is to examine biomimetic technologies and materials with low or zero environmental impact in other to achieve carbon neutral cities in South Africa.

2. Carbon emission in the construction industry

The construction industry is branded as the major emitter of atmospheric pollutants of which carbon dioxide (CO_2) is a constituent. These pollutants, CO_2 and other non- CO_2 greenhouse gasses (halocarbons, chlorofluorocarbons, and hydrochlorofluorocarbons) significantly contribute to the depletion of the ozone layer resulting in climate change. CO_2 emissions associated with building energy use in China reaches 1260 million tons in 2008 [9] while fifty percent (50%) of carbon emissions in the United Kingdom is traceable to the industry [10]. A critical examination revealed that processes, materials production and use, and other associated activities in the construction industry, are the sources through which the atmospheric concentration of carbon and other pollutants is greatly increased. South Africa, amongst other African nations, are greatly hit by the consequences of CO_2 emissions despite contributing minimally. In 2008, two-third of the global CO_2 emissions are generated by ten nations while China and the USA alone generate about forty-one percent (41%) of world CO_2 emissions [11].

Most notably is the production of cement which contribute significantly to the amount of GHG emissions through fossil fuel combustion, breakdown of raw materials involved in its production and electricity consumption [12,13]. Concrete, been the most widely used material in the construction industry [14], has cement as one of its key constituent [15] and serving as a binding component. It is, however, noteworthy that, in the production of $1m^3$ of concrete alone, several activities are involved which in turn contribute to the release of CO_2 emissions into the atmosphere. This is shown in Fig 1. below. In other to reduce the atmospheric concentration of CO_2 as a result of the production and use of concrete, Carbon Capture and Storage (CCS) emerged as a new technology designed to capture and squash CO_2 emissions into a liquid state for permanent underground storage [16]. Alternative cement with less or zero environmental impact has also been advocated as against the widely used Ordinary Portland Cement [14].

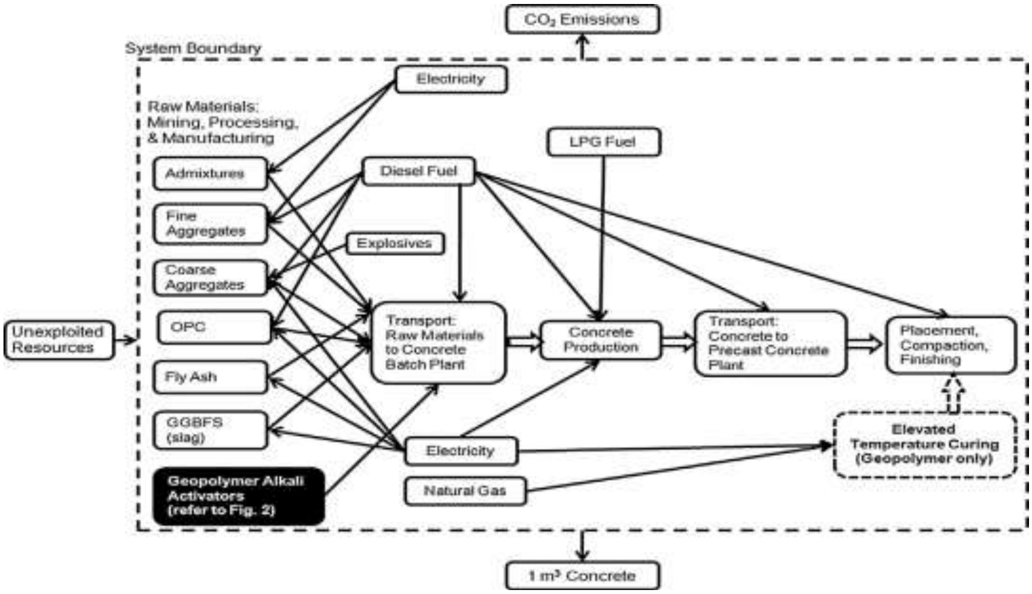

Fig. 1. CO2 emissions diagram in producing 1m^3 of concrete [14]

Various researchers have proven that the construction industry consumes a large amount of energy. The environmental impact of the energy consumed in the manufacture, transportation, and use of construction materials makes it another major factor to consider [17]. These are energy consumed during the manufacturing of building materials (embodied energy), transportation of these materials from production plants to building sites (grey energy), construction of the building/infrastructure (induced energy), operation of the building/infrastructure (operational energy) and demolition of the building/infrastructure coupled with recycling of their parts where this occurs [5]. For example, approximately thirty percent (30%) of CO_2 emissions generated in Japan are attributed to energy/electricity consumption [18]. A switch to renewable energy is now been advocated as alternatives owing to their potential in reducing the amount of emissions released into the atmosphere through the activities of the construction industry.

In other to ensure carbon neutral cities by drastically reducing CO_2 emissions, a study on three low-environmental impact houses in the city of Valladolid, Spain, reveal the importance of selecting construction materials with zero or low environmental impact [19,20]. Buildings and infrastructures are to have zero embodied energy so as to reduce the amount of carbon emitted. These are major measures proven to lessen the carbon footprint of the construction industry. Over the years, natural organisms have been an inspiring source of intelligence for the development of new products. As affirmed by Murr [21], the processes and systems of optimisation exhibited by natural organisms are superior and can be benefited from in other to meet human challenges in technologies and materials innovation. There has been various novel materials and technologies with sustainable credentials as a result of innovative ideas extracted from nature. These ranges from materials and technologies with CO_2 sequestration capabilities and those with zero environmental impact. There are lots of risks are associated with novel products and technologies [22]. However, such risks are worth taking when it is proven and glaring that, the consequences will have less or zero impact on the human environment.

3. Biomimicry approaches to technologies and products innovation

Biomimicry as the process of deriving inspiration from natural designs, processes, and systems for technological solutions to human challenges [23]. It is the science of tackling challenges by the emulation of natural strategies exhibited through structures, processes, and blueprints found in natural organisms [24]. Biomimics believes that this new field heralds an environmental-friendly perspective of exploring and learning from nature as against the traditional exploitation of nature practiced over time [25]. It is also believed that biomimicry will proffer solutions to the problems created as a result of human activities and exploitation of natural resources [26]. Due to the pressures of the construction industry on the environment and natural resources, biomimicry has shown its potential as sustainable alternatives to the consuming, polluting, and destructive technologies of the industrial era.

The application of biomimicry can be classified into three categories in a biological-inclined manner through the:

- emulation/imitation of organism’s features (form, color, structure, behaviour, motion, transparency, modularity);
- emulation/imitation of organism-community relationship (group management, survival techniques, communication, sensing, and interaction); and
- emulation/imitation of organism-environment relationship (response to climate, adaptation, waste management, source management) [27].

However, biomimetic technologies and products are borne out of either the problem-based or solution-based approaches of biomimicry. They proffer distinctive focal points and step-by-step paths under the larger umbrella of biomimicry [28], providing an avenue for the holistic application to arrive at a sustainable, effective and efficient solution.

3.1. Problem-based approach

The problem-based approach is also known as design looking to biology approach [29], problem-driven biologically inspired approach [30], top-down approach [27,31], problem-to-solution approach [32,33], and challenge to biology approach [34]. This approach entails identifying a problem and thereafter understanding and conceptualizing the strategies that organisms or ecosystems optimize to resolve similar challenge [35]. This approach is effectively adopted by innovators, engineers, and designers [23] with various sustainable technological breakthroughs accomplished.

3.2. Solution-based approach

On the other hand, solution-based approach is also known as biology influencing design approach [29], solution-driven biologically inspired approach [30], bottom-top approach [27,31], solution-to-problem [32,33], and biology to design [34]. In this approach, a specific attribute, function or behaviour in an organism or natural ecosystem is spotted and thereafter translated into a design solution [29]. Here, the biological knowledge prompts the design innovation. The success of this approach is, however, dependent on the knowledge of relevant biological systems or organisms which can only be made possible by a collaborative design process [27] to involve biologists, designers, and innovators.

4. Biomimetic innovations in construction materials and technologies

Natural organisms exhibit a vast array of efficient multifunctional materials which can be applied to products innovation and development [36]. These notable attributes found in nature are what made biomimicry the answer to the issues of environmental degradation and pollution. Biomimicry has become a widely known field, inspiring novel innovations in engineering and material science [37]. Despite the challenges of ingenious and atomistic application, it is noteworthy that the application of biomimicry has propelled technologies and products innovation which are patented and commercialized with many others in the development phase. Below are few carefully selected biomimetic materials and technologies (under development or commercialised) with excellent and distinctive sustainable attributes for achieving a carbon neutral environment.

4.1. Biomimetic carbon capture, storage, and utilisation

Innovative breakthroughs in the production and use of cement should be those with capabilities to sequester CO_2 emissions [16], a feat which biomimicry has achieved. Drawing insight from the strategies and processes in natural organisms, especially bio-mineralisation and their ability to use CO_2 as a resource, concrete and cement materials with less environmental impacts have been developed. This has now challenged companies to engage in technically and economically sustainable carbon capture and utilization in their manufacturing process and products innovation.

Blue Planet is one of the companies offering carbon capture and mineralisation services amongst many others with the inspiration drawn from the natural organism's ability to perform the same function. Based on the company's literature, lightweight coarse and fine aggregates are made from sequestered CO_2. This is done by employing the bio-mineralisation process in natural organisms (i.e. building solid reefs out of calcium carbonate by hard corals) to produce Blue Planet bagged concrete [38]. 50-80% of CO_2 emitted from power plant flue gasses are concentrated using patented technology to make the concrete aggregates [39]. This carbon neutral concrete provides a sustainable alternative to the construction material known to possess the highest CO_2 footprint.

Another company, TecEco Pty. Ltd of Australia, developed 'Eco-Cement', which is an environmentally sustainable and recyclable cement, incorporating reactive magnesia (also known as magnesium oxide or MgO) and water to form magnesium hydroxide during the cement mixing process [40]. "The porous microscopic architecture of the setting cement allows CO_2 to permeate through the material and react with the magnesium hydroxide to form magnesium carbonate, a mineral that confers extra strength and rigidity. In forming magnesium carbonate, the CO_2 is effectively trapped as a solid mineral within the concrete. Since magnesia is produced by baking magnesium carbonate ore (a CO_2 releasing process), the cement is essentially carbon neutral, disregarding processes like baking and transportation" [41]. Since alkaline quicklime contributes to the atmospheric volume of CO_2 in the production of Portland cement, Eco-cement offers an alternative with the potential to capture atmospheric CO_2.

Carbon capture and utilisation technologies are also developed by a US-based chemical company, Novomer, by observing exhibited carbon cycle in photosynthetic organisms [42]. Based on the company's literature, "Novomer is commercializing a proprietary catalyst system that transforms waste carbon dioxide (CO_2) into high performance, low-cost polymers for a variety of applications. These polymers contain up to 50% CO_2 by mass, sequestering this harmful greenhouse gas permanently from the environment" [43]. In the production of these products, the use of waste CO_2 which is an inexpensive starting material ensures their cost-competitiveness [44].

5. Conclusions

Nature has discovered and adopted high-performance strategies due to its over 3.8billion years of evolution. A holistic appraisal of human activities reveals a close or same routine as observed in nature. It is, therefore, imperative for man to learn and emulate the sustainable process, strategies, and materials operational in the natural world i.e. harnessing freely available energy, resilience amongst many others. This is a decisive step with the potential of CO_2 mitigation and adaptation, hence, reducing the carbon footprint. However, biomimicry heralds an era where these effective and efficient methods are learnt and emulated from nature's rich knowledge base to proffer sustainable solutions to human challenges. For the innovation and development of materials and technologies with sustainable attributes, biomimicry provides a comprehensive guide to achieving durability, efficiency, compatibility, and multi-functionality. Biomimetic materials and technologies offer carbon capture, storage, and sequestration capabilities with a huge potential to achieving carbon neutral cities in South Africa. Biomimicry also encourages the collaboration of biologists, engineers, designers and other stakeholders, with many novel eco-friendly ideas and strategies bound to be birthed. Furthermore, construction industry stakeholders and professionals are to adopt sustainable construction practices and consideration of the natural ecosystem as a means

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