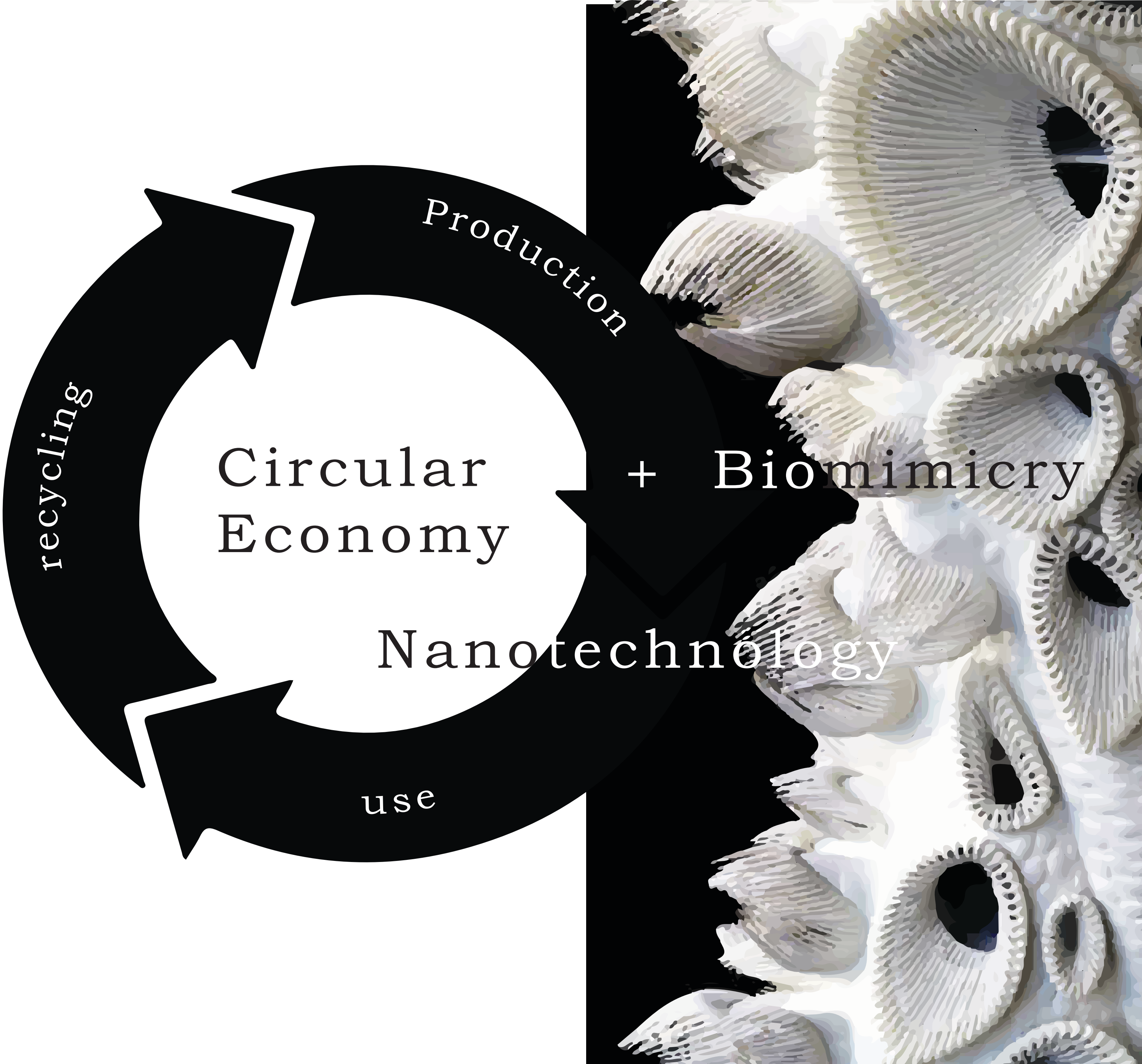

Circular Nano-Biomimicry
The Future of Manufacturing & Design

Ochuko Okor

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I *Introduction*

It is no secret that the world today is overstimulated, overpopulated and its resources are reaching its limit. As designers we are pushed to innovate, to constantly find new ways of engaging the public's attention. We have to sell the idea of making life easier, selling worth, status, and even selling space and time.The current economy functions on a linear model which facilitates an 'extract-use-waste' system. Society tends to move from one resource to another, once the former is depleted (Church et al, 2014). This has proven to be an unsustainable system as earth's natural resources are depleting and demand does not meet supply. However, today's world is filled with technological advancements, byproducts and wastes that leech on the environment and as a society, we are forced to innovate more to respond to these issues.

It appears as if the world is in damage control mode, creating impactful treaties like the Paris Agreement for the environment. According to the UN in 2019,

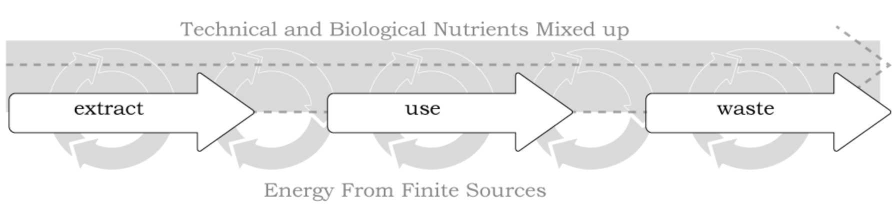
> *"we have 11 years to prevent irreversible damage from climate change".*

The idea of a closed economy introduces a no-waste system, coined as the circular economy (CE) model. CE involves the reduction of waste and carbon emissions by efficient resource and production management. Within the same framework, biomimicry is a concept that can play a key role in revealing how to create an efficient life cycle for a system which will convert waste into new inputs in other points within a life cycle.

Nanotechnology on its own is quite complex as it views and manipulates elements at the scale of an atom. In her book Nanomaterials, Leydecker (2008) mentions how material qualities can be improved through "controlled atom manipulation". The advantage of this is that one is able to influence a whole form or responses of a living organism or inanimate object to find solutions to pending problems and issues (Garg et al, 2017). When one looks at biomimicry under the lens of nanotechnology, a world of possibilities opens up. Innovations like responsive designs to atmospheric changes can be created. We are able to learn from the blueprint of nature and reapply that knowledge into our everyday lives whether in architecture, production or within the making of the environment.

But it is not until recent times that the concern of the end of life of these architectural environments has been brought to the forefront: what happens to a product or a building when it reaches its end life?

This paper aims to show how nature can act as a guide to our end of life problems, through a complex relationship with biomimicry and nanotechnology in creative processes that in particular have innovative, remediative, or preventive outcomes. It proposes a novel integrated approach involving biomimicry and nanotechnology, as critical positive influencers on the creative processes that function within the economy and the environment in general.



Linear Economy Model

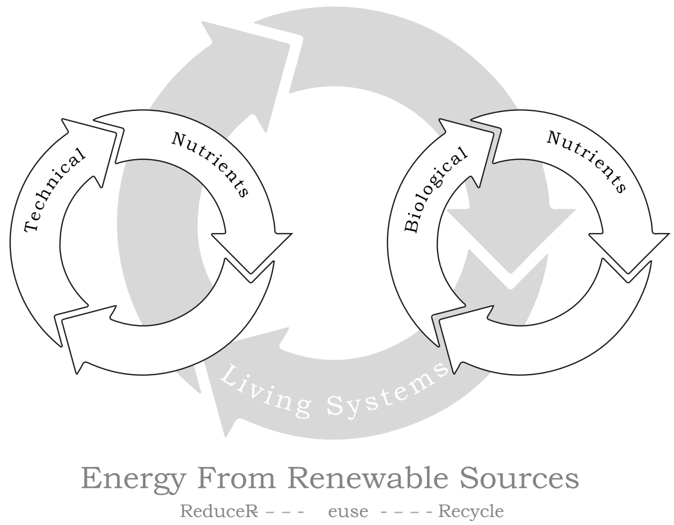
To address these gaps, the following question should be investigated:

How nano-biomimicry can be applied into design processes starting at a material level to support end-of life circularity?

More particularly, the above question would require answering the following sub-questions:

1. How can we manipulate materials to be more efficient, to use less fixtures, and to mirror and utilize a natural circular pattern found in nature?
2. Can materials be manipulated to facilitate the decomposition of toxic elements residing in our ecosystem from our complex processes?
3. Can we create environments that facilitate the augmentation of depleted natural habitats?

The previous questions arise from the integrated relationships between circular economy, biomimicry and nanotechnology and its opportunities for the building industry. This research will aim to understand how far this relationship can be taken. One challenge to address is the questions of scale: from the materials scale, to the product and building scale.



Circular Economy Model

II Background

2.1 Circular Economy (CE/ Circularity)

CE is a concept that operates on the redirecting of material flows with the hopes of operating within a framework of global sustainable development (Korhonen et al., 2017). Sustainable development here refers to satisfying the needs of a current society without compromising the capabilities of future societies to satisfy their own needs (Korhonen et al., 2017).

CE aims to achieve prolonged efficiency, in terms of eco-efficiency, product/ion efficiency and energy efficiency through the creation of circular, regenerative material flows. It challenges the 'extract-use-waste' model while advocating for simple principles like designing out waste, building resilience through diversity, relying on renewable energy sources and so on (Ellen MacArthur Foundation, 2010). Within these principles, products are expected to persist in the production cycle via processes of recycling, repair, refurbishment and remanufacturing with combustion as the last resort.

CE will benefit from the introduction of ingenious supporting technologies to drive and achieve its goals. The roots of CE can be traced to many schools of thought including that of Biomimicry, which allows for 'innovations inspired by nature' (Benyus, 2009). These schools of thought have been influenced by the concept through underlying similarities of efficiency and waste reduction.

CE is popular amongst business and policy communities (Korhonen et al., 2017 and has been recently drawn into green, industrial development conversations (Korhonen et al., year). That being said, CE has been criticized for having an unexplored scientific knowledge base, which requires the introduction of supporting technologies (Korhonen et al., 2017).

2.2 Biomimicry

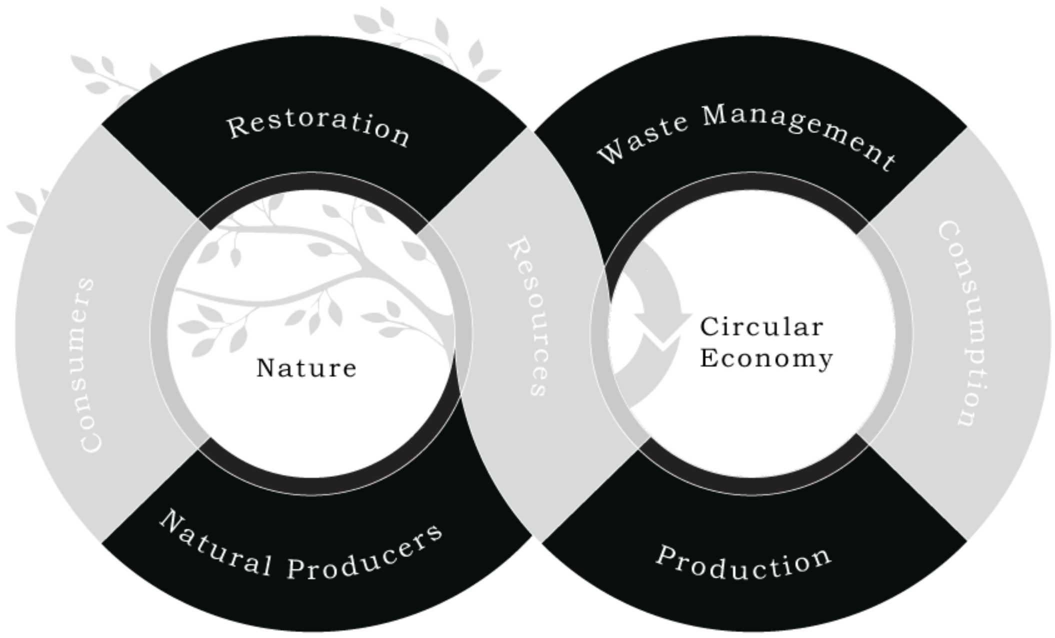
Biomimicry refers to the imitation of nature or natural processes to create solutions for complex human problems (Benyus, 2009). As a design concept, biomimicry provides the preliminary roots and influences to the CE concept, which has been refined and developed into a pertinent design tool today.

Biomimicry is a powerful tool of innovation that has been fostering groundbreaking innovations; A famous example of biomimicry and product innovation is the design of Velcro (Pawlyn, 2016) by Goerge De Mestral, a building component that mimics the interaction of animal fur and plant burr. There is an infinite knowledge that scientists, researchers, and designers can draw from biomimetic circular design, as nature has presented itself as a free resource.

According to Janine Benyus who authored Biomimicry: Innovation Inspired by Nature (2009), biomimicry relies on three main principles, that can be applied to circularity as follows:

1. Nature as a model: implies studying its characteristics, forms and processes to innovate and solve problems.
2. Nature a means of measurement: assessing how sustainable innovations our innovations are.
3. Nature as a mentor: learning from nature.

All principles are very well applicable within the framework of the circular economy. CE draws from Nature's cyclical life cycle where waste is food. In various processes within a natural cycle, it is observed how byproducts become resources for other processes within the cycle. Biomimicry can be an efficient driver in achieving zero-waste systems. This idea carries over to the circular economy. Between the relationship of CE and biomimicry, the pace and quality of innovation in the design industry can be improved through the introduction of other technologies. An example of this is nanotechnology.



Principles of CE and Its Relation To Nature

2.3 Nanotechnology

'Nano' means something very small or minute; also refers to a billionth in a metric measurement system. Nanotechnology is the "control or restructuring of matter at the atomic and molecular levels in the size and range of about 1 to 100nm" (Bhushan, 2017). The ability to manipulate physical and chemical properties of materials opens doors to novel performances, structures and, eventually, forms.

Nanotechnology in design refers to a range of systems, such as biological systems, that with the use of nanomanufacturing and nanomaterials as well as integration of nanostructures, can be designed into larger systems (Bhushan, 2017).

A unique characteristic of nanotechnology in design is its ability to replicate natural systems (Paheco-Torgal & Jalali, 2011). It makes revolutionary contributions with environmental and industrial fields with the introduction of smart materials and often referred to as design of the future (Paheco-Torgal & Jalali, 2011). The technology allows for inanimate objects to exhibit self-regulatory characteristics including self-cleaning, self-healing and self-assembly.

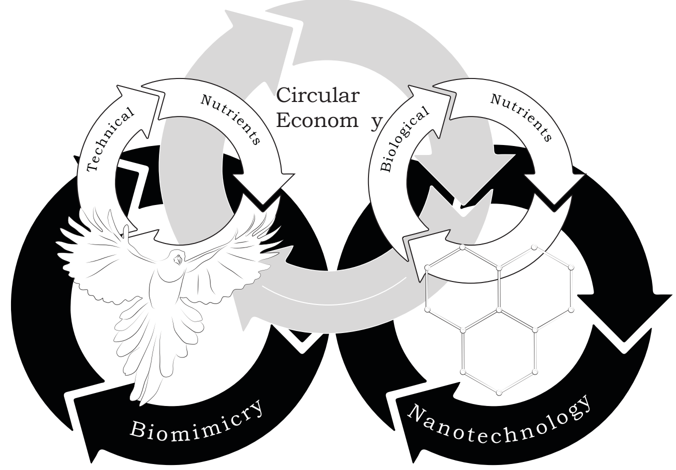
Although nanotechnology contributes to the acceleration of innovation design technology, concerns have been raised about nanotechnology's toxicity risk and non-efficient cost (Lavicoli, 2014).

III *Research*

Biomimicry, Nanotechnology & Circular Economy

"There is little quantitative evidence to suggest that the act of mimicking an organism in design is in itself a means to achieve greater sustainability"
-Maibritt Zari, Regenerative Urban Design and Ecosystem Biomimicry

It is true that there is little quantitative evidence that equates biomimicry to a means of achieving greater sustainability, but biomimicry has the potential to proffer pathways to address global challenges, tangible advancement in material sciences and energy systems (Zari, 2018) and support other ideologies put forward by the CE. Nanotechnology is capable of replicating natural systems and behaviors, particularly on an atom scale, thus, making it a tool of biomimicry capable of engineering sustainable advancements put forward by the ideology of the CE. Nanotechnology is also able to manipulate systems to create more efficient renewable energy sources, create possibilities for regenerative design, which has the potential to design out waste and finally, enhance material resiliency.



Circular Nano-Biomimicry

Research Thesis Diagram

Within the field of construction and design, nanotechnology operating through the lens of biomimicry is already prominent in different levels of architecture (Hemeida, 2010). For instance, nanostructured cementitious materials have been created, i.e the use of nanoparticles to strengthen and enhance the durability of cementitious composites (Leone, 2012). Nanocomposites is a broad term that involves the embedding nanoparticles into conventional materials. One limitation for nanocomposites is the uncertainties in its complexities. Regardless of this, the presence of these explorations of nano-biomimicry in architecture are opportunities to examine closely that can assist in achieving a CE:

Material: nano-biomimicry continues to produce new materials and structures with highly specialized properties and responsive designs. Nano-biomimicry allows for the addition of nanoparticles into conventional materials to enhance their properties and functions. Nanoreinforced materials tend to outperform other alternatives. Carbon nanotubes are very durable elements that have numerous uses and are added to common materials to make them stronger and lighter, for instance baseball bats (De Volder. et al 2013). There are also materials like reinforced concrete where the properties of concrete are enhanced through the addition of cellulose nanocrystals to concrete to reduce its footprint, by requiring less to do more.

In 2014, a Caltech professor of materials, science and mechanics, Julia Greer, designed fractal trusses at a nanoscale that can be used in the future as structural engineering materials (Miniature Truss Work, 2014). This required design on a nanoscale using lithography to create the truss design patterns and form.

Function: closely tied to material properties is a nanomaterials performance and functionality. Nano-biomimicry has been used to create materials and structures with characteristics that respond to and solve complex problems encountered daily. This has attributed nano-biomimicry materials with a lot of self-regulatory and responsive features. These include, but not limited to self-cleaning, self-healing, self-assembly, air-filtering, and solar transformations. Present within the architecture and design field today, materials with self-cleaning, water resistant abilities, exhibit the 'lotus effect'.

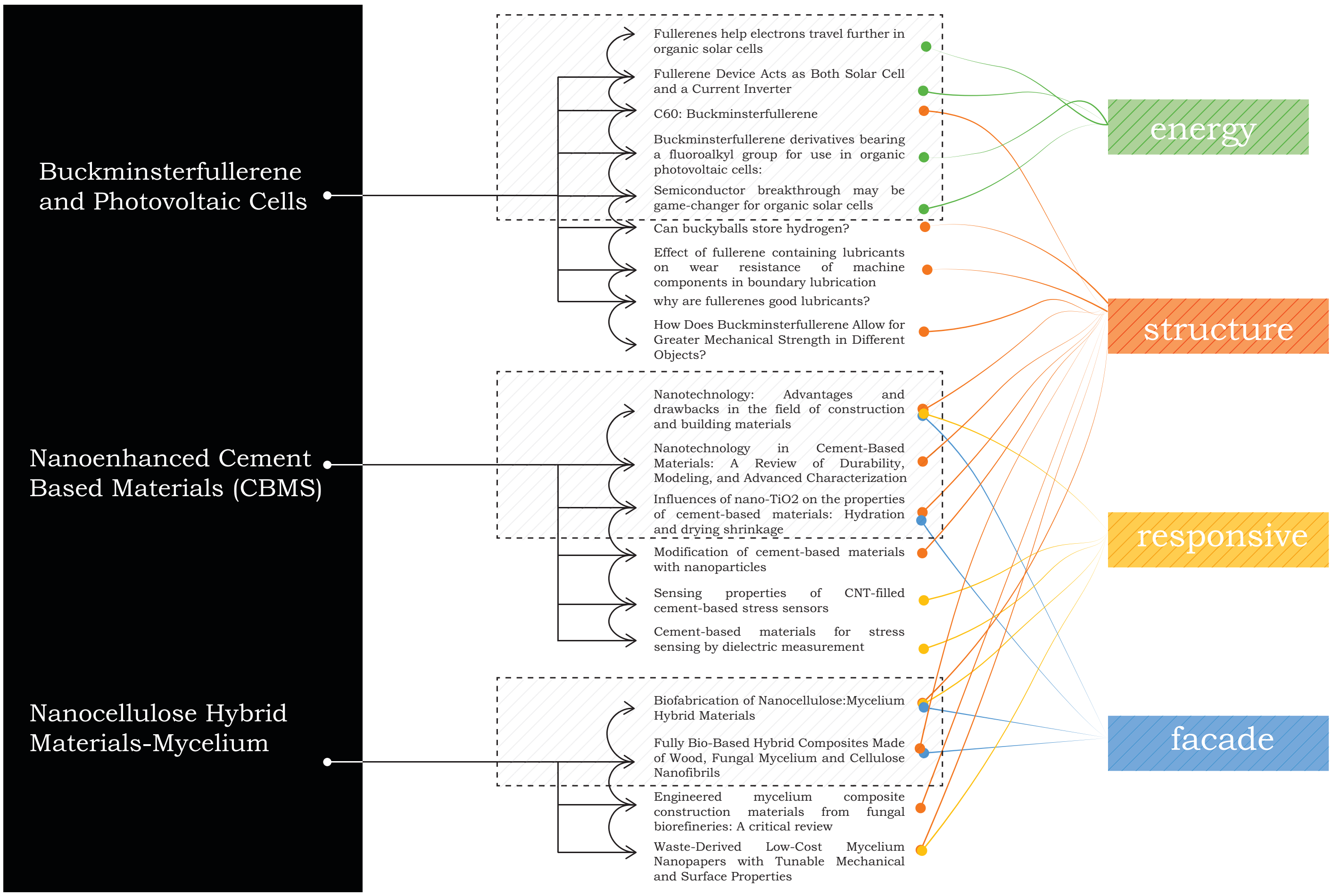
The lotus effect refers to the use of superhydrophobicity as a form of self-cleaning, where water molecules fall off the surface of the leaves taking with it undesirable particles (Marmur,2004). Using this lotus effect, engineers and designers have been able to create self-cleaning windows, facades and so on. The availability of these materials and structures allows designers creative freedom to design life-changing spaces and structures.

That being said, nano-enhancements and composites can play a role in creating means of achieving sustainability. In order to bolster the argument of nano-biomimicry supporting ideologies of CE, I have chosen to examine case studies that provide opportunities for the integration of nano-biomimicry with circularity. The goal is to investigate how these materials are currently being introduced into the building sector and how they create grounds to achieve sustainable performances within the environment. Following this investigation, a proposal of possible new strategies to support circular concepts will be introduced.

Research Statement:

Nano-biomimicry has the potential to create paths to address global challenges, tangible advancements in material sciences, energy systems and support other ideologies put forward by the Circular Economy school of thought.

Research Methods: *Case Studies*



3.1a. Energy Generating Systems: Buckminstefullerene and Photovoltaic cells

A fullerene is a non-planar closed carbon compound that has multiple scientific applications and has led to the discovery of more fullerenes and many fullerene-based materials. The Buckminsterfullerene C60 is a type of fullerene that is made up of 60 carbon atoms. It was named after Buckminster Fuller due to its similarities of its geodesic structure and that of Buckminster Fuller's geodesic dome (Locke, 1996). The spheroidal molecule also known as BuckyBalls is known to have many capabilities, including storing hydrogen and also photovoltaic applications.

There is a race to find a green approach in the production of organic devices [ref] and innovation with the BuckyBalls could be one of them. Engineers at University of Michigan have recently made a breakthrough with the BuckyBalls that can influence the production of organic photovoltaic cells. Due to its optical absorption properties, the engineers have found that the BuckyBalls are able to create energy wells within organic materials, allowing electrons to travel farther than originally thought. They have discovered the possibility of manipulating organic materials conductive properties, thus allowing for the shrinkage of conductive electrodes to an invisible grid (University of Michigan, 2018). This gives rise to transparent solar cells that can be laminated onto windows and facades.

Although the discovery is recent and theoretical, the idea of transparent photovoltaic cells can play a huge role in creating a unique source of renewable energy, and an excellent opportunity of CE innovation. For instance, a hypothetical situation would be a city without power grids. Each building in this city would be the source of its own power, being wrapped in a transparent photovoltaic facade that channels its gained energy into the building network.

The mechanics of this system will need to be flushed out extensively, but it starts to bring rise to questions like: how can this harvested energy be stored, reused or transferred to other dependent buildings or smaller units? Thus, buildings become like plants, absorbing the sunlight to work. This further starts to influence the way an architect designs buildings; the architect will be forced to rethink wall and floor compositions and so on.

Also, this collected solar energy can be converted into heat and stored within the nanoenhanced surface. Is it possible to create a responsive surface that stores heat and, for instance, defrosts ice and snow as a result of change in temperature. This looks at the possible thermal responsive surface treatment to asphalt or concrete, taking the concept of hydrophobicity found in the lotus to another level.

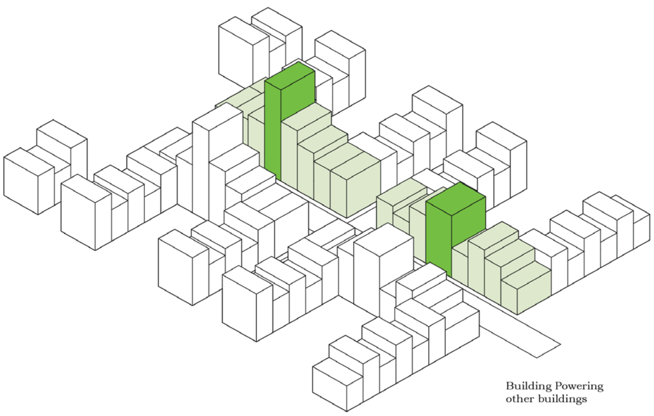


Diagram Showing One Building Powering Surrounding Buildings

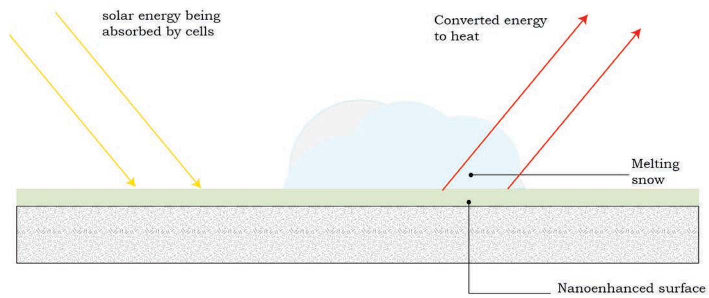


Diagram Showing Treated Asphalt Collecting and Emitting Heat During Winter

3.1b. Material Deconstruction Systems: Nanoenhanced Cement Based Materials (CBMS)

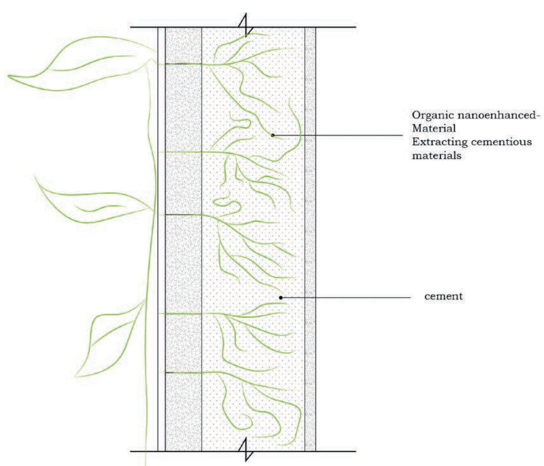
As one of the most commonly used building materials in construction, concrete is responsible for 70% of construction and demolition waste materials(U.S. EPA, 2016). Therefore it is important to conceive sustainable ways to manage the flow of concrete materials within its product life cycle. One of the reasons why concrete can quickly become waste is as a result of corrosion issues. This is due to concrete's high permeability, allowing for water and other elements to seep into its pores causing carbonation and chloride ion attacks (Paheco-Torgal & Jalali, 2011). The durability of concrete is challenged. It will benefit from technological manipulations at a nano and micro scale to enhance its strength and sustainability.

This issue is already being tackled head on within the construction industry, by the development of nanoenhanced cementitious products. Scientists have achieved greater strengths in cementitious products by using nanoparticles to reinforce them, thereby creating nanocomposites. Scientists have successfully increased the compression strength of cementitious materials through the use of nanosilica particle (Paheco-Torgal & Jalali, 2011). The addition of nanosilica particles have led to a denser microstructure of concrete and reduced water absorption in concrete. The nanocomposite cementitious product will therefore be more durable and have an extended life span within its product life-cycle, cutting down the amount of concrete that contributes to construction and demolition waste.

Nanoenhanced concrete is also able to display photocatalytic properties through the photocatalysis of semiconductor materials within the products. Photocatalysis is a process that takes place once light interacts with the surface of a semiconductor (Paheco-Torgal & Jalali, 2011). The photocatalysis of titanium dioxide creates the lotus effect or superhydrophobic surfaces by reducing the contact angle between water molecules and a surface (Paheco-Torgal & Jalali, 2011). A nanoenhanced concrete with titanium dioxide, therefore, is able to equip the concrete with responsive self-cleaning abilities. This reduces the energy disposed

An example of Self-Cleaning Concrete being executed can be seen in "Dives in Misericordia", Rome.

From above, nanoenhanced composites prove to be advantageous, but it also has room for improvement and should be approached with caution. Strengthening and increasing the durability of concrete does not unburden the concrete waste at the end of its product life-cycle. Investigations with nanotechnology can be pushed further to activate a process of sustainable degradation within the concrete atoms. Though there are still many uncertainties in working with nanotechnology, there can be explorations into the possible breakdown and extraction of useful elements within concrete through nanotechnology. The introduction of an organic nanoenhanced material to extract cementitious waste materials from existing cement waste products can be explored. This material could be a lab grown plant with nano properties for extraction. It could also be enhanced with parasitic properties that release nano cells into the cement that causes and initiates a breakdown of atoms that fuse the concrete together. The useful extracted materials can be replastercized to remake building materials. Although before these can be pursued, the cost of production of these nanocomposites and nanoenhancements need to be offset. The cost of production of nanoenhanced concrete has delayed mass production of the cementitious composites (Paheco-Torgal & Jalali, 2011).



Oranic Material Growing Into Concrete to Extract Useful Materials

3.1c. Structural Material Systems: Nanocellulose Hybrid Materials-Mycelium

Nanocellulose materials are materials in the industry that have potential to be bio based barriers. Nano cellulose "refers to the cellulose with nanoscale dimension" (Trache & Thakur, 2020). These could be crystals, or fibrils. It is a very viable material that displays many features and can be applied into the making of many composites. It is eco friendly and displays high biocompatibility, thermal expansion and many more (Trache & Thakur, 2020). Although very promising, the use of nano cellulose is cautioned as the material on its own is brittle and moisture sensitive. However the addition of materials like plasticizers to improve these properties. Nanocellulose has developed many uses in the industry through insertion, manipulation and composition with other materials.

Current applications of Nano Cellulose materials within the industry include biomedical products, wood adhesives, nanocomposites and so on. Dried axisymmetric particles found in nanocellulose can form tightly packed film that can block oxygen and grease (Abitbol et al., 2020). These mechanical properties make nanocellulose good for composite reinforcement or the creation of hybrids. An upcoming nanocellulose hybrid material is the hybrid of nanocellulose and mycelium. Both nanocellulose and mycelium are from natural materials like trees, plants and algae. They are both promising in attaining sustainable alternatives. The production and processing of the mycelium-nanocellulose composite are similar to papermaking (Attias et al., 2020). Each element has its own strengths within the composite, the nanocellulose brings mechanical strength to the films, while the mycelium "screens typical cellulose–water interactions, giving fibrous slurries that dewater faster and films that exhibit significantly improved wet resistance in comparison to pure NC films" (Attias et al., 2020).

The nanocellulose-mycelium can be used as a structural biobased material due to its properties. The cell wall of the mycelium is like an interwoven chitin mesh and polysaccharides, which gives it the capability to provide protection and withstand hydraulic pressures (Attias et al., 2020). It is also able to maintain internal humidity and provide wet resistance. These processes allow this unique composite material to be utilized in different versatile forms like films, aerosols and many more. Nanocellulose-mycelium composites have many potentials that can be taken to a large scale production and projects. A concern to consider will be the time factor involved in production of these nanocellulose-mycelium composites.

Can Nanocellulose Hybrid Materials like Mycelium biocomposites be used in retrofitting and renovation?

Honing on these properties of nanocellulose-mycelium composites, the industry can think of ways of integrating these processes into retrofitting and structural renovations. Is it possible to create a controlled environment on site, taking the processing of the composites and integrating it into the element, for instance a wood/timber piece, forming a grown patch from the element it needs to fix. Understandably this process may not work for non organic materials, like metals. Although, processes like coating can still be brought on site.

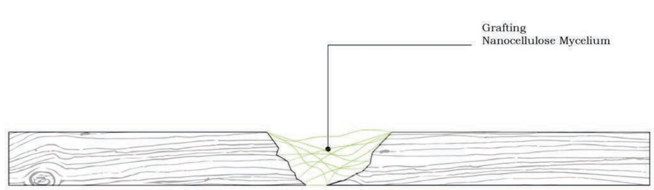
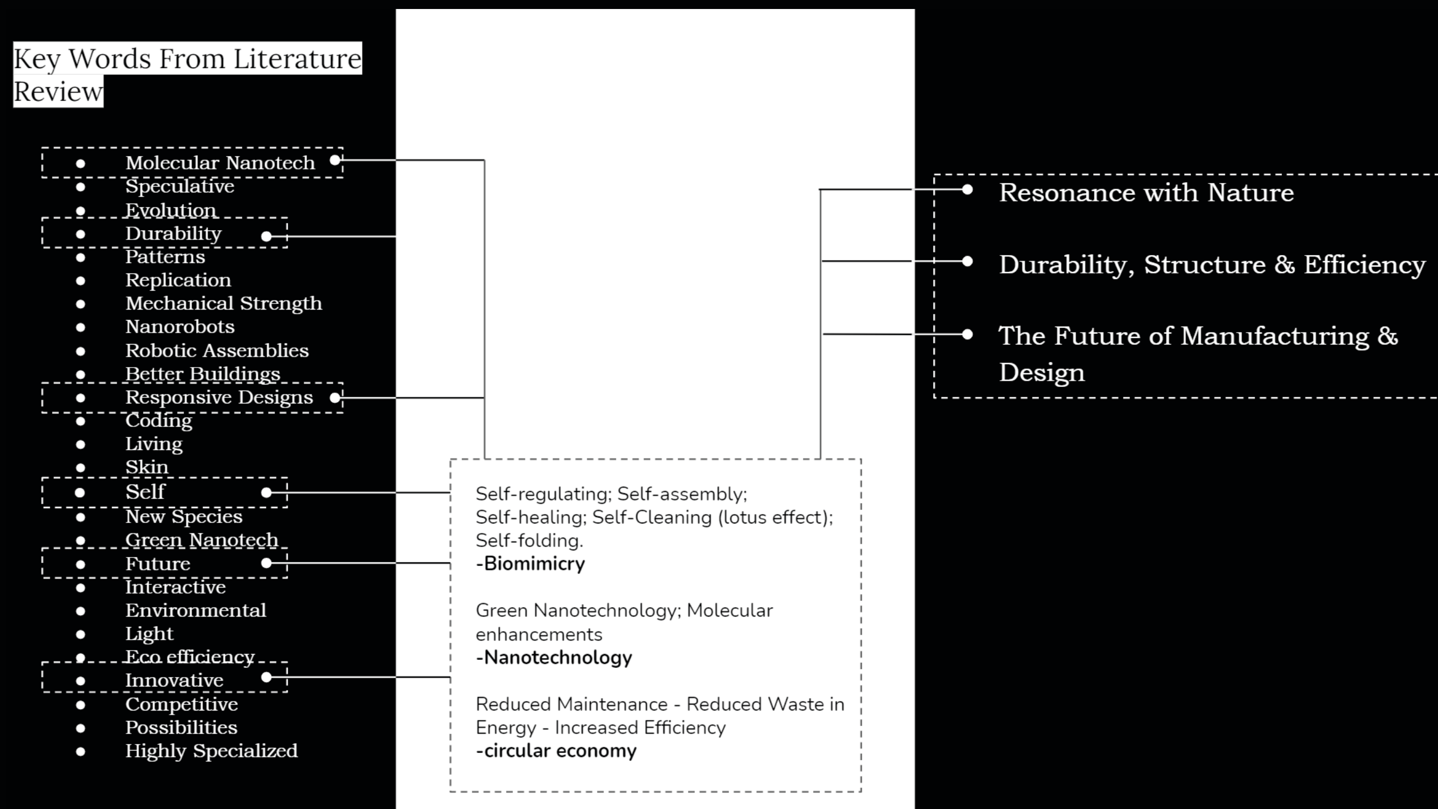


Diagram of Possible Grafting pf Structures With Nanoenhamced Mycelium

Research Methods: *Thematic Categorizations*



Following the emerging scientific possibilities outlined in the literature review, plausible links can be drawn between nanotechnology, biomimicry and circularity. It can be inferred that they can be tools of innovation for each other that need to be further explored. The following themes were identified as common schools of thought that provide opportunities for innovation within circularity, as well as general gaps within the discourse.

3.2a. Resonance With Nature

Nano-biomimicry has been able to inform engineers and designers who delve into material sciences and construction related fields to create products and structures that respond to natural phenomena in the same way natural systems do.

Adaptive structures. Adaptivity in structures has been introduced to optimize structural configurations in response to changes in the environment. Adaptive structures can be interpreted as living structures. This can be seen, for instance, in structural response to weight, light, and temperature. Example about weight (nanotruss), example about light, Temperature regulating materials are made with the integration of phase changing materials like salt hydrates.

Opportunities for circularity present themselves within the efficiencies of nano-biomimicry. Green nanotechnology is a concept that tries to foster a green economy through the exploitation of nanomaterials to create environmentally and economically sustainable products and processes (Lavicoli, 2014). This provides impactful developments within economic sectors. One of which is improving the renewable energy sector by the reduction of impacts on raw materials. There has been a rise of companies that harvest sun and wind energy with the use of nanotechnology (Hemeida, 2010).

3.2b. Durability and Structure

Although a lot is still unknown about nanotechnology, engineers have been able to manipulate and design in nanoscale to create novel structures that can be used to facilitate and support complex operations. This is a popularly acknowledged and salient feature of nanomaterials and nanocomposites. They have worked their way into discussions in the construction industry due to their improved mechanical durability and lightness. Other characteristic enhancements made possible through the integration or use of nanoparticles in materials include antimicrobial, anti-fogging and even fire-retardants (Lavicoli, 2014).

Opportunities for circularity here lie within reduced requirements of energy and strain on materials. With a material able to withstand more loads and environmental strains, less of it will be required to do more, which will mean less natural materials have to be extracted for production. Being able to exhibit proficiency in structure and while maintaining lightness through the use of less material is typical of natural systems. Nano-biomimicry techniques can foster circularity in this way.

A major concern about this concept is the end-life treatment of nanomaterials and nanocomposites. Due to their artificial means of development, will nanomaterials and nanocomposites pose difficulties and even risks in returning back to the production cycle or the environment? The ability for biodegradable processes to take place within nanocomposites and nanoparticles need to be explored and simplified to allow for replication.

3.2c. The Future of Manufacturing and Design

Nanotechnology and biomimicry have both been described as the future of design due to their contributions in innovation. That being said, a lot is yet to be explored and learnt from both fields, which means that there is room for more opportunities in innovation. At the rate of technological advancements, nano-biomimicry will be able to contribute to the increase of the pace of new efficient processes and products. This will be achievable through encouraging designers and engineers to take creative sustainable risks while exploring the ins and outs of nano-biomimicry.

Opportunity for circularity lies in the ability of nano-biomimicry to foster smart designs, whether it be in construction or in other industries. It will lessen the need for fasteners and bonds used in manufacturing and allow for thinner compact designs. The self-healing capabilities will lessen the need of physical maintenance as the structure is able to monitor itself in most cases and possibly create alerts when something is out of the ordinary. This reduces a waste in human energy or labour as they are able to focus their energy on other things.

Nonetheless, exposure to nanotechnology and nanoparticles can be risky to the labour force. Advice for cautious implementation of nanomaterials and composites in living and occupational spaces (Lavicoli, 2014) until the extent of toxicity of nanomaterials is made known. With the introduction of these new methods of production, labourers from various industries will have to be retrained and reeducated on how it works. How will the interaction between old and new materials affect production?

IV *Conclusion*

On examination of these few topics, it is evident that nano-biomimicry has a strong potential to aid circularity in versatile ways. Combining the technology of nanotechnology with the understanding and implementation of biomimicry, everyday products and materials can be designed to be smart and more efficient: using less materials to perform more functions. Nano-biomimicry can also tackle the existing waste problems by adopting parasitic characteristics to break down these waste products within the ecosystem or extraction characteristics to extract useful materials. Nano-biomimicry also opens doors for innovation in new material properties, functions and materials in general, that can be responsive to time and environmental changes.

However, the industry must remain aware of the challenges that nano-biomimicry carries. The cost of production and implementation has to be moderated in order to encourage adoption of these new technologies. More research has to be done to get a better understanding of both fields as there is a wealth of undiscovered information residing in each field that can reveal positives and negatives. In the end, these new products developed can be combined to create a smart sustainable environment that supports the circularity.

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