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Biomimetic Buildings

Copying Nature for Energy Efficiency

Edited by
Negin Imani and Brenda Vale

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About the Editors

Negin Imani

Dr Negin Imani is a Post-doctoral Research Fellow in the Wellington School of Architecture. Her current research concerns biomimetic buildings for climate change adaptation and has been funded by New Zealand's National Science Challenge Science for technological innovation. As the primary investigator of this research project, she is supervising a team of researchers from different disciplines. She is exploring the possibility of designing fully automated buildings that respond to their environments like living organisms. Her current research uses her recently developed innovative, bio-inspired design tool (the ThBA) that bridges the gap between architecture and biology. She has also worked as a senior architect in architectural and engineering consulting companies in Tehran and has been working as a lecturer, teaching across Architectural Technology and Building Science courses in Otago Polytechnic and Open Polytechnic, New Zealand.

Brenda Vale

Prof Brenda Vale is a Professorial Research Fellow in the School of Architecture at Victoria University of Wellington. She has extended her life-time interest in low energy and autonomous buildings to embrace the environmental impact of those that live in them through a focus on ecological foot-printing. This interest has led to a number of recent books on reducing the impact of buildings and the built environment, and numerically establishing what type of built environment might be possible within the resources of the planet, given that humanity is currently living beyond these. Some of these books, like this one, have been written with former students.

Preface to ”Biomimetic Buildings: Copying Nature for Energy Efficiency”

The multifaceted nature of biomimicry has made it an appealing field of study and research in almost every discipline. Biomimetic design promises that the dual principles of innovation and sustainability can be achieved, noting that the majority of existing research on biomimicry has been conducted in order to investigate the potential of biological principles in delivering innovative and sustainable solutions.

The building and construction sector has proved to be the second most investigated field in this respect and has embraced the implementation of biomimetic principles at different levels. The underlying reason for such growing interest has been the proven record of reduced energy use where biomimicry principles have inspired building design and construction.

The research reported in this book contains several examples of biomimetics in practice, while also providing insights into future areas of exploration in the field. The specific target audience for this book includes architects, urban designers, building scientists, engineers, other industry professionals and researchers. The articles the book contains might also be of interest to those who wish to deepen their understanding of the concept of biomimetic building design. With the focus of this book being on energy efficiency, the articles report on theoretical concepts and practical examples that explain how biology can inspire energy saving in buildings. In addition, this collection would be of interest to students working on bio-inspired projects and those who are keen to learn more about the theoretical and practical implementation of biomimicry in building design construction.

Negin Imani and Brenda Vale
Editors

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Editorial

Biomimetic Design for Building Energy Efficiency 2021

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Nature has been the source of inspiration for the design and construction of buildings in various ways and at different levels of complexity. At a simple level, the rules of the Fibonacci series that underlie the distribution of plant petals were taken up by Le Corbusier in his Modulor, which was a system for controlling the dimensions in buildings [1], and building forms have been likened to examples from nature, such as Calatrava's World Trade Centre Transportation Hub with its rib cage structure [2]. Recent years have witnessed the contribution of biomimetic principles to develop innovative materials and structural systems, strategies for the management and operation of building services and building design strategies, such as bio-inspired space layout configurations and adaptive building envelopes. Initially, these practical implications have been inspired by biological principles found at the micro, macro or organism level.

Due to the urgent need for adaptation to and mitigation of climate change, there is the potential for finding innovative solutions to reduce building energy use by minimising operational or embodied energy or ideally both. In 2015, the construction and operations of buildings accounted for 38% of global energy-related CO_2 emissions, although this dropped to 37% in 2020 due to the restriction of activities due to COVID-19. In 2015, the energy used in making and running buildings formed 38% of global energy demand, and this decreased to 36% in 2020, again reflecting the impact of COVID-19 [3]. The same UNEP [3] source also states that to meet the Paris agreement, the building and construction sector must be virtually decarbonised by 2050. It is thus essential that any approach to bio-inspired architecture, engineering, or construction should make a positive contribution to reducing the sector's carbon footprint. Operational emissions come directly from fossil fuel combustion and indirectly from the equipment used to generate energy in the form needed by buildings, such as electricity. Electricity in buildings is mainly used for heating, cooling, ventilation, air conditioning, lighting, running electrical equipment, and supplying hot water. Embodied carbon includes the emissions occurring across the supply chain of construction materials and building products, both for making and maintenance and refurbishment.

Decarbonising buildings by making them energy-efficient has already benefitted from the strategies used by animals and plants, from the use of insulation in the building envelope in imitation of fur and feathers, to the use of heat recovery systems that mimic the counter-current circulation found in the legs of reindeer and penguins as a means of preventing excess heat loss from the extremities [4]. However, nature is vast, and it is hoped that animals and plants have strategies for saving energy that could be applied to buildings. This Special Issue, therefore, focuses on bio-inspired approaches used for reducing the energy associated with buildings and consists of three research and three review articles.

The problem in biomimicry is having a comprehensive idea of what is already known so as to reveal unexplored areas where new applications of natural systems to buildings might be revealed. As noted above, systems used to make buildings energy-efficient already imitate what occurs in nature. By establishing a new method of bibliometric analysis based on the two methods of functional analysis and scientific mapping, Varshabi, Selçuk, and Avinç analysed 148 articles and 30 review papers based on the categories of architecture, construction building technology, energy fuels, ecology, and environmental science, including inter- and multi-disciplinary work. The analysis yielded 53 works on biomimicry and building energy efficiency. A rise in the number of articles published annually was noted, with a steep rise since 2020, perhaps reflecting the urgency of decarbonising the built environment. More research effort appears to have gone into biomimicry and engineering, with buildings and construction being the second most investigated field. It is also the more developed countries that are leading this research, which is important since these countries were generally the first to industrialise and therefore have been contributing to climate change the longest. Although China is the largest national emitter of greenhouse gases but not the largest per capita emitter (the largest is Qatar, ranked 40th in terms of national emissions [5], "China's cumulative and current per capita emissions are still a fraction of the cumulative and per capita emissions of North Americans and Europeans" [6]. The authors examined the top ten most cited articles related to biomimicry and buildings, finding that most were related to the design of the building envelope. They argued this is because the envelope controls the exchange of moisture and heat between the building's interior and exterior, just as a surface or skin does in the natural world. The authors concluded that as yet, there has been little research into biomimicry and buildings, noting that: "Nature has the potential to provide unlimited examples for the production of sustainable, adaptive, adaptable, and energy-efficient buildings".

The world is becoming increasingly urbanised, with currently 56% of the population living in cities, a figure that is expected to rise to nearly 70% in 2050 [7]. Many of these people will have to inhabit buildings that already exist and that may not necessarily be designed for energy efficiency. Living in cities has given rise to urban heat islands, where the temperature inside the urban area is significantly higher than that of the surrounding countryside, a phenomenon that has been recognised for several decades [8]. This can lead to health issues and greater energy use, especially in hot climates, with the running of air conditioners [9]. The urban heat island effect has become a particular problem in Panama City with its tropical climate, where Austin, Araque, Palacios, Maure, and Mora have been researching a biomimicry approach to making building roofs more reflective to incoming radiation as a means to mitigate the urban heat island effect. Their article reports on applying observations of the Saharan ant and the zebra to roofs using a simulation approach. The hair of the Saharan ant has reflective properties. Although the stripes on the zebra have long been thought of as exhibiting camouflage properties by breaking up the outline of the animal [10], a technique used on ships in WWI [11], the authors draw on other research that suggests the stripes assist in thermoregulation to aid evaporation of sweat from the skin [12]. Comparing a base case with no application of biomimicry principles with a reflective coating applied in stripes to aid convective and evaporative cooling shows that the latter provided better cooling and reduced cooling energy use, although the authors warn that an energy cost analysis would need to be performed to ensure that such a strategy would be cost-effective.

The third research article also concerns Panama City, in this case looking for examples in nature that might help Panama City's green development. As noted above, the global increase in urbanisation must be accompanied by finding ways to lessen the environmental impact of cities, since research using the concept of the ecological footprint has shown that city footprints tend to be larger than their rural and national counterparts [13,14]. In response, Quintero, Zarzavilla, Tejedor-Flores, Mora, and Austin have developed a reference framework based on biomimicry to be used to regenerate Panama City so as to relieve its burden on the natural environment. The study began with an examination of the impacts of the city, for example, discovering that transport was the largest contributor to greenhouse gases. Other priority areas were reducing pollution, reducing heat build-up, and replacing fossil fuel energy with renewable sources such as solar. The search for biological examples focussed on reducing greenhouse gases in terms of energy, atmosphere, and mobility, and examples from nature were found that addressed these issues. As an example, mobility would be improved through better networks, and mould was given as an example from nature, since the mycorrhizal network is a wonderful example of one fungal organism that splits into countless tiny threads, which are all vital for plant life [15]. The authors identify a number of natural organisms that could form models of the regeneration of Panama City, noting that passive strategies in these models tended to align with thermoregulation and active with reducing pollution through purification. The authors also stress the need for measurable outcomes in urban regeneration, something that is vital in moving towards a more sustainable world [16]. The article concludes with a discussion of the priorities given by local experts to the solutions that emerged from the biomimicry approach to the regeneration of Panama City.

This Special Issue also contains three review articles. The first concerns the development of a method to link thermoregulation in animals and plants to the issues found in making energy-efficient buildings. Using a problem-based approach, Imani and Vale have developed a framework that links the problems found in making buildings energy efficient with examples found in nature dealing with these same thermoregulatory issues. This framework has been named ThBA (thermo-bio architectural framework), and its full development is explained elsewhere [4]. This article describes the process that preceded the development of the ThBA, which was an extensive literature review of thermoregulation in animals and plants, including how to find them, classify them, and generalise the thermoregulatory principles involved. The necessary three-step literature review is described in detail. Not all thermoregulatory strategies found in nature can be matched with problems found when making an energy-efficient building. For example, there is no parallel in building design between acclimation and acclimatisation, as buildings do not evolve over a lifetime or move from one climate to another. Weak parallels were noted, in this case, the use of portable buildings such as tents that would be made differently in different climates, but essentially a built structure for the same purpose. Thermally, the Mongolian yurt [17] behaves very differently from the black-hair tent of the Bedouin [18]. Analysis of all the literature led to the concepts of endothermy, where the heat source is within the organism, and ectothermy, where the heat source is external to the organism being linked to passive and active ways of achieving thermoregulation in buildings. This created the structure of the ThBA as a means of allowing architects to access relevant thermoregulatory strategies in nature based on the thermal challenges imposed by a building design.

The second review paper and the third based in Panama City sought to create a roadmap for moving to a circular economy for the construction sector by taking inspiration from nature. Beerman and Austin begin by looking at the existing frameworks for creating sustainable construction. They move on to look at the link between biomimicry and the concept of a circular economy. Since there is no waste in nature and the construction industry has big problems with waste, being responsible for a third of global waste [19], this was a perfect opportunity to align natural systems with man-made ones and learn from the former. As a result, Beerman and Austin's third step was the creation of a model—the Biocircular Model—that linked biomimicry strategies to stages in the sustainable construction process. The Biocircular Model was then matched to each stage in the construction of a building, and the results were assessed by local experts. This work led to a series of recommendations for sustainable construction based on the principles found in biomimicry. These principles included acknowledging the relevance of every stage of the construction process and evaluating each stage so that necessary corrections could be made; investing in technologies to ensure water and energy savings during construction and waste management; supplying the necessary training so that everyone involved in the construction process was aware of the environmental implications of construction; and maintaining collaboration between all parties. A natural inspiration for the latter would be the way that bee and ant colonies work together for the common purpose of keeping, respectively, the hive and nest going. The article emphasises that the construction system in Panama City is far from being sustainable and thus mirrors most other places in the world and that man-made systems have a long way to go to be as circular as those found in nature.

The final review paper deals with the storage of electricity and understanding what strategies natural organisms have that might prove a starting point for developments in this field. Dodón, Quintero, Austin, and Mora make the point that renewable energy systems tend to generate energy in the form of electricity and that, therefore, they need some form of storage, since both sun and wind are intermittent sources of energy, and only hydro systems have a built-in form of storage through the damming of rivers. Through a literature review, the authors looked for organisms that have the ability to generate and store electricity. They examined energy storage systems that had been used in buildings, such as pumped water storage used in conjunction with photovoltaic electricity generation in buildings in Shanghai, China, and flywheel storage used with photovoltaic systems on buildings in Germany. Since organisms store energy to survive, such as sugars in plants and fat in some animals, a biomimicry approach to energy storage seems an obvious step. Some animals, such as electric eels, also generate electricity. The authors note that photosynthesis is an effective way of turning external energy into the compounds needed by plants. The mechanisms that plants use to harvest light through the structure of leaves have proved to be an inspiration for the development of new types of photovoltaic cells. Micro-organisms have been used in biogenerators to make electricity through the breakdown of acidic-mine-draining samples, and there are plans for a large-scale version. A similar technique for using micro-organisms in the anaerobic decomposition of natural materials to produce biogas has been known for many years and has been used on a large scale [20], but the use of microorganisms to produce electricity from waste is new. The authors acknowledge that how natural organisms generate electricity and how they store energy are fields that are as yet relatively unexplored but that cost–benefit analysis would need to be performed before new advances based on biomimicry could become widely used.

This Special Issue devoted to biomimicry and the design of energy-efficient buildings highlights that much could be learned from the natural world, but that there is a long way to go before such new innovations could replace conventional technology. Given the urgency of the need to mitigate climate change and the fact that most of the buildings that will be in use in 2050, the date set for the building and construction industry to be virtually decarbonised, are already in existence, there is a need to deal with the existing built environments to make them less dependent on fossil fuels. Unless this happens, the natural world and its ecosystems, which form the focus of those interested in biomimicry, may be severely disrupted, and many of the models that nature provides could be lost as a result.

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Article

Biomimicry for Energy-Efficient Building Design: A Bibliometric Analysis

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Abstract: With the development of the biomimicry approach, new and creative ideas have been established to solve problems in architectural design. In the designs based on this process, "nature" is used as a diverse data source for the transfer of these data to various processes, functions, materials, and structures. The primary purpose of this paper is to explore the development of biomimicry as an architectural approach, with a bibliometric review of research related to biomimicry and energy efficiency. Emphasis on the importance of the need for biomimicry in modern designs is another goal of this study. In this study, articles published in the Web of Science database (2010–2021) were analyzed. VOSviewer and SankeyMATIC software were used to represent the analysis results graphically. According to the results of this study, in addition to the inadequacy of biomimicry research, the need for further research became apparent. This review can serve as a reference for future studies to transfer natural phenomena to architecture in order to solve the problem of efficient energy consumption.

Keywords: biomimicry; energy efficiency; architecture; bibliometric analysis

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1. Introduction

Climate change throughout the world has increased concerns about ecological harm. Greenhouse gas emissions from this activity inflict permanent harm. Global advances in energy efficiency have been dropping since 2015 according to IEA2020. A decrease in energy costs arrived with the COVID-19 pandemic, resulting in a reduction in energy intensity improvement in 2020, less than the revised rates for 2018 and 2019. As a consequence of the analytical studies of energy institutions, buildings account for one-third of this consumption. Buildings are also responsible for 40% of direct and indirect emissions of CO_2 [1].

The importance of construction in worldwide energy consumption has raised awareness of environmental degradation trends. This rising knowledge has sparked efforts to optimize energy efficiency while minimizing environmental impact. The use of efficient designs reduces the energy consumption of a building during its life cycle and helps solve these challenges by reducing the damage to the environment and human health.

Architects and designers have long been concerned with meeting the challenges of nature and architecture. Owing to advances in technology, nature-based design and construction techniques have led to designs based on biological approaches. These techniques, which appear with various terminologies such as bionics, bio-inspiration, biomimetics, and biomimicry, are mainly based on solving problems by inspiring/learning/developing innovative proposals based on the shape, structure, and systems of nature". It has been also argued that "designers can be inspired by nature in order to tackle building design challenges, and this has led to a connection between architecture and biomimicry" [2].

Biomimicry's goal, developing technical advancements and achieving sustainability, appears to be the best ideas of nature, and it imitates them in design processes to solve design problems. There is a rising focus on how organisms adapt to changes in the environment, with the claim that these characteristics might bring new approaches to designing technologies to improve performance [3].

New technologies can improve the energy efficiency of any kind of energy-consuming systems. Likewise, biomimicry is considered an "innovative design strategy for increasing energy-efficient designs" [4], and, thus, energy-efficient built environments. Due to the existence of diverse biological mechanisms, natural processes with low energy consumption can inspire creative solutions for optimal energy consumption. It is also a matter of debate that "bio-inspired design may present the potential for causing a paradigm change in traditional design thinking" [5]. Bio-inspired/bio-informed designs can be solution or problem oriented. In this way, these biological mechanisms are explored for novel approaches. "A problem-based approach to provide a better response to building energy reduction, means that once architects are aware of thermal challenges and want to improve thermal performance using bio-inspired design solutions, their priority is to discover appropriate biological examples" [6].

If scientific analysis studies are conducted conventionally, increasing the number of academic publications may result in various limitations in the research. For this purpose, structuring the analytical research with a new method is helpful when it comes to broadening the area of the investigation. Literature reviews stand out as one of these techniques and play a vital role in bringing together previous studies' results. With these types of studies, the present observation's foundation may be successfully utilized; as a result, the research phase is increased and broadened in light of the evaluations to be made regarding research in the relevant field. One of the review procedures that is widely utilized is "bibliometric analysis". Bibliometric analyses are focused on studying specific aspects of an article's content or publishing and producing different scientific communication conclusions [7].

As research progresses, terms and ideas become broader, more multidisciplinary, and more complex, and, despite this progress, questions remain unanswered. Within this framework, in this study, bibliometric research was conducted, and some aspects are discussed. Firstly, articles from Web of Science were studied in order to identify bibliometric indicators in this research, such as annual publication analysis, research area analysis, Geographical area evaluation, analysis of authorship, analysis of organizations, citation by sources, co-occurrence of keywords, and content analysis of the selected articles. Then, as given in Section 2, data visualization was performed using VOSviewer and SankeyMatic software. In the Section 3, the bibliometric findings are discussed. As an inference, biologically inspired approaches to building energy efficiency have been introduced by highlighting why and how bio-informed knowledge has been transferred.

2. Research and Methodology

The purpose of this study was to survey publications and research directions in biomimicry and architecture utilizing a scientific literature database and science survey analysis. Bibliometric analysis is an effective method for determining the growth and future possibilities of a study topic. Bibliometric methodologies have been used to investigate the growth of research topics, find relationships between logical progress and modifications to the approach, and identify expanding interdisciplinary alliances. The research methodology provides detailed quantitative and statistical scientific information regarding the processes of making decisions.

Today, detailed analyses can be conducted via numerous online databases such as Web of Science, Scopus, and Google Scholar. Additionally, different software tools such as VOSviewer, Citespace, Bibexcel, Gephi, Pajek, Publish or Perish, Ucinet, and Science of Science (Sci2) provide informative data and visualization [8]. The bibliometric data of the search results made with the relevant keywords in the WoS (Web of Science) database were analyzed and visualized with the VOSviewer and Sankey diagram mapping methods, and the relationships, trends, and collaborations between the subjects were revealed through network maps. In addition to primary databases such as WoS, Scopus, EBSCO, and

ProQuest used in bibliometric searches, networks such as Google Scholar, ResearchGate, and Academia are also available. The search results in Google Scholar, despite the variety, are not comprehensive, and the results have a different quality load, so the classification of articles for bibliometric work is the responsibility of the researcher. In Google Scholar, updating information related to articles is not accurate, so a bibliometric review of the articles may not have acceptable results. Classification studies were carried out in this study using the Web of Science, which includes indexes such as Sci, Sci, and A&HCI, where the most recent and qualified publications are published.

The bibliometric analysis in this research is based on two mechanisms of functional analysis and scientific mapping. Scientific mapping is a visual representation of the conceptual, intellectual, and social structures of research fields [7]. In this method, bibliographic data analysis is possible based on the author, document, source, institution, country, and keywords. In this research, the analysis of co-occurring words was used to map the studies, which is a method used to measure the strength of relationships between publications' keywords [9]. By analyzing co-occurring words, keywords related to the subject of the articles were obtained. Performance analysis is a method that measures the number of articles and citations published by authors and institutions in this field. In this study, mapping and performance analysis were used together in an integrative way. Bibliographic data from the Web of Science database were analyzed in VOSviewer and SankeyMATIC software. Figure 1 summarizes the study's methodology.

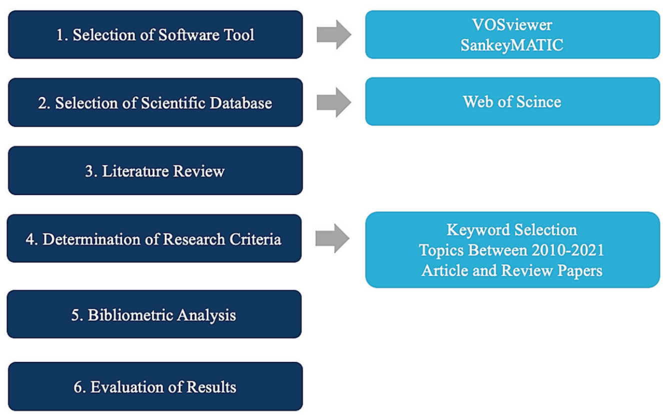

Figure 1. Methodology of the study.

Web of Science is "a website that offers subscription-based access to several databases that contain detailed citation data for a wide range of academic subjects" [10]. With the help of such an advanced tool, it is possible to track ideas and disciplines over time, with over 1.9 billion citations from 171 million records in the database. Users can also obtain all of the data for entries in a certain field of research based on a provided query phrase [10]. Visualization of similarity (VOS) mapping is a topic-based approach that allows for a comprehensive and clear representation of advancing study disciplines. It can also draw clusters and cooperation networks using vortices connected by lines [8]. The Sankey diagram (SankeyMATIC) demonstrates a wide data relation to visualize multifaceted connections. It is a type of diagram used to visualize the quantities and flows of assets in proportion to each other. The width of the lines or nodes in the diagram is used to express the size of the data. In this context, the size of the line or node also expresses the size of the flow amount [11].

Biomimicry is an approach that is widely used in material science, architecture, and engineering, etc. In this work, we integrated the network, group, and bibliometric studies of the scientific literature in the context of biomimicry and building energy efficiency by addressing some questions:

- How many peer-reviewed articles in the field of biomimicry and energy efficiency in architecture are available, and what is the overall growth?
- What are the main scientific and technological topics addressed by this data analysis?
- Which articles have received the most citations?
- What are the most active journals for this type of research?
- Which research institutes are at the forefront of this field of study?
- Which countries are engaged in promoting growth in this field?
- Who are the main authors, and who is working with whom?

Data-Gathering Method

The study used articles screened for "titles, abstracts, and keywords" in English from the WoS (Web of Science) database. "Biomimetic(s)", "biomimicry", or "bio-inspired" and "thermoregulation", "energy efficiency", or "envelope/façade" were used as keywords to analyze trends in biomimicry between 2010 and 2021.

A total of 732 items in the specified period were identified. The records were divided into eight classes: articles (569; 77%), review articles (94; 12%), proceedings papers (70; 9%), book chapters (15; 2%), and others such as early access papers, editorial materials, and meeting abstracts. A total of 251 of the items were 'open access' (34%); the remainder were available through subscription.

Articles (148) and review papers (30) under the categories of architecture, construction building technology, energy fuels, ecology, environmental science, interdisciplinary engineering, and multidisciplinary papers were selected for a detailed analysis. A total of 53 research and review articles about biomimicry and energy efficiency in architecture were obtained.

3. Results and Discussion

The data collected from the WoS database were analyzed based on the year of publication, research area, geographical area, authorships, citations, and the transition of biological phenomena to the architectural products studied.

3.1. Annual Publication Analysis

Figure 2 presents the distribution of publications by year, demonstrating that research in the relevant subject has intensified, and the number of articles has increased in the last five years. In 2021, 17 articles with the specified qualities were published, and the highest number was reached. Based on the results, more comprehensive research on biomimicry and energy efficiency is needed. On the other hand, the increasing number of articles indicates a growing interest in this field.

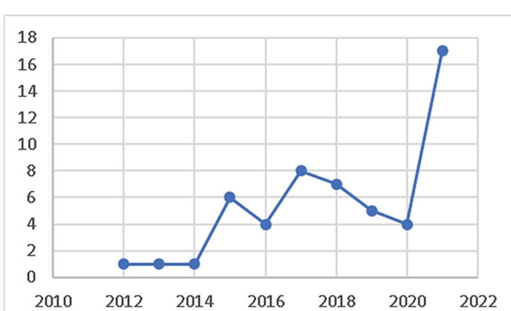

Figure 2. Annual number of publications related to biomimicry and energy efficiency.

3.2. Research Area Analysis

The pie chart in Figure 3 indicates the thematic classification of biomimicry and energy efficiency in buildings. According to the chart, "engineering" is the most researched topic (24%). Substantial studies were conducted in" building technology, energy studies, materials science, and environmental studies". Additionally, 10% of the total research area distribution consists of studies in computer science, robotics, thermodynamics, urban studies, physics, and chemistry.

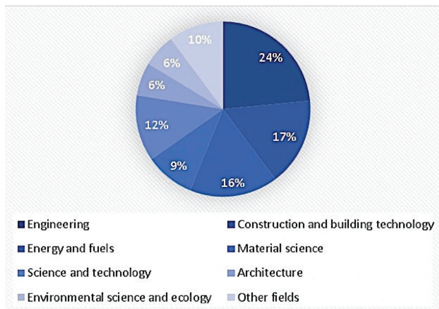

Figure 3. Subject area distribution of the related literature in biomimicry and energy efficiency.

The highest number of publications is in engineering (23), and construction and building technology (16) is in second place. Additionally, the input from the other areas has been shown clearly (Table 1).

Table 1. Publication by research area.

Research Area	Publications	Research Area	Publications
Engineering	23	Urban Studies	2
Construction and Building Technology	16	Computer Science	2
Energy and Fuels	16	Robotics	2
Science and Technology	12	Thermodynamics	2
Material Science	9	Physics	1
Architecture	6	Chemistry	1
Environmental Science and Technology	6	Instruments and Instrumentation	1

3.3. Geographical Area Evaluation

Figure 4 shows the countries with publications in the relevant field. While 20 countries contributed to the 52 articles examined, only 5 countries published 6 or more, which shows the inadequacy of such research in many countries. In terms of the number of publications on biomimicry and energy efficiency, Australia, Germany, and the United Kingdom are at the top of the list, then Italy and United States follow them. These five countries account for more than 70% of the publications in this area.

Countries in the top ranks show that economically and technologically strong countries are more active in this field. Some countries' publications appear only as single-country publications. This shows that these countries do not collaborate with other countries. Because more than half of the publications are co-authored, multiple countries may enroll for an article. The authors' collaboration networks show that growth is occurring in a multi-institutional and international way, utilizing the infrastructures accessible in the authors' organizations and countries (Figure 5). After analyzing the articles under the headings of biomimicry and energy efficiency, the results were obtained in the form of three clusters: the red cluster represents Australia, Chile, Greece, and Italy; the green cluster represents the United Kingdom, France, Spain, and Turkey; and the blue cluster represents Germany, the Netherlands, and the United States. Figure 6 shows the relation between countries and citations. The five countries with the most citations are Germany (304), the United Kingdom (205), the United States (132), Italy (120), and Australia (81), respectively.

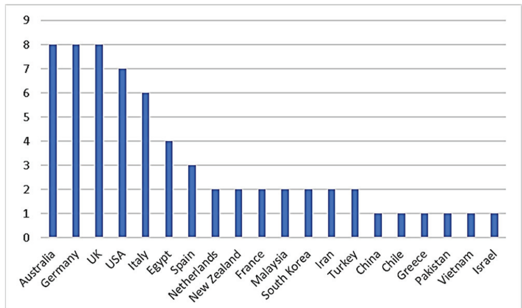

Figure 4. Countries and the number of publications.

Figure 5. Collaboration network between countries.

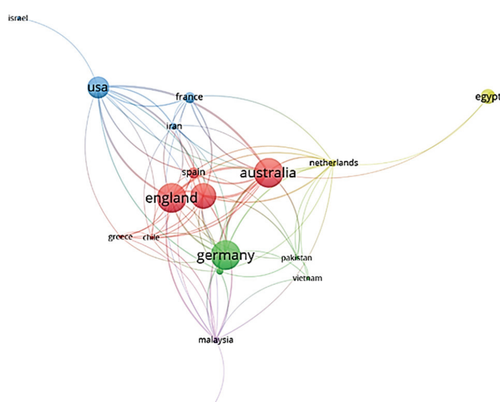

Figure 6. Network connection between citations and countries.

3.4. Analysis of Authorship

Figure 7 shows the top 10 authors with the most citations of their articles related to biomimicry and energy efficiency in buildings. According to the results obtained from the cluster network, the greatest number of citations (199), with a total link strength of 21, belongs to "Achim, Menges". In this part of the analysis, the identification of the most influential authors was considered. The top 10 authors with the most citations and their link strength are shown in Table 2, and Table 3 shows the 10 most cited articles on biomimicry and energy efficiency. Ideas and processes related to biomimicry and energy efficiency in buildings are presented in these articles. The main focus of the articles is on the energy efficiency of building envelopes according to design approaches.

Table 2. Top 10 authors with the highest number of citations.

Rank	Author	Document	Citation	Total Link Strength
1	Fiorito, Francesco	4	67	27
2	Badarnah, Lidia	4	66	9
3	Menges, Achim	3	199	21
4	Reichert, Steffen	2	134	19
5	Bridgens, Ben	2	88	13
6	Holstov, Artem	2	88	13
7	Farmer, Graham	2	88	13
8	Speck, Thomas	2	118	10
9	Poppinga, Simon	2	118	10
10	Al-Obaidi, Karam M	2	76	19

Table 3. Top 10 highly cited papers.

Rank	Title	Year	Citation
1	"Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness" [12]	2015	90
2	"Toward a new generation of smart biomimetic actuators for architecture" [13]	2018	65
3	"Hygromorphic materials for sustainable responsive architecture" [14]	2015	59
4	"A methodology for transferring principles of plant movements to elastic systems in architecture" [15]	2015	53
5	"Toward mitigating urban heat island effects: Investigating the thermal-energy impact of bio-inspired retro-reflective building envelopes in dense urban settings" [16]	2015	53
6	"Shape morphing solar shadings: A review"	2016	49
7	"How plants inspire facades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes" [17]	2017	49
8	"Material capacity: Embedded responsiveness" [18]	2012	44
9	"A methodology for the generation of biomimetic design concepts" [19]	2015	43
10	"Design optimisation of solar shading systems for tropical office buildings: Challenges and future trends" [20]	2018	40

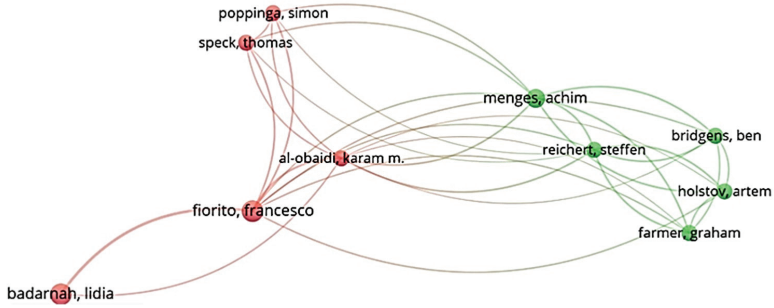

Figure 7. Most cited authors.

3.5. Analysis of Organizations

The performance of organizations with two or more publications in terms of biomimicry and energy efficiency is represented by the graph bar in Figure 8. The University of Stuttgart is the most productive research center with the most publications (6) in the related research area. The Polytechnic University of Bari in Italy, the University of South Wales in the United Kingdom, and the University of Freiburg in Germany each have three publications, while the other organizations have one or two. The list of organizations that have researched in the fields of biomimicry and energy efficiency includes a diverse range of countries. According to Figure 9, Stuttgart University, with 299 citations, has the highest number; the University of Freiburg (148) and Newcastle University (88) follow.

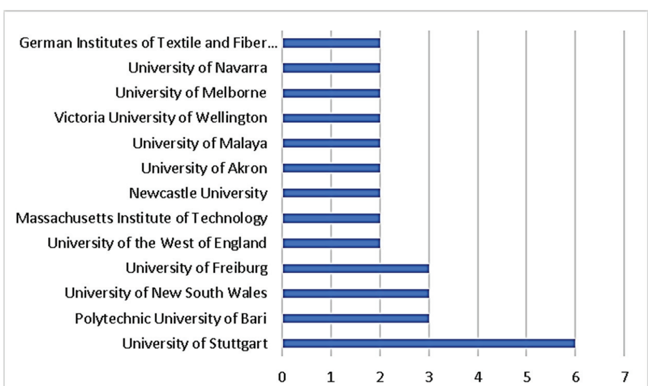

Figure 8. Organizational publications in the field of biomimicry and energy efficiency.

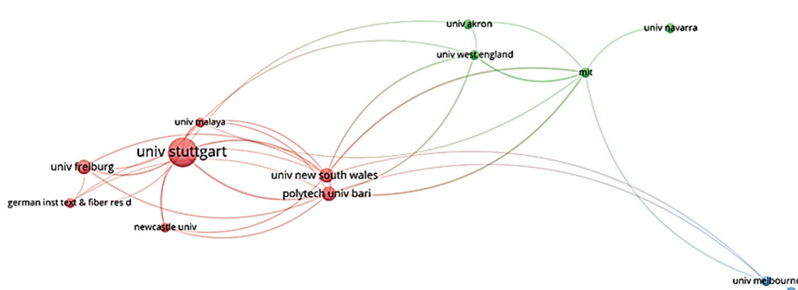

Figure 9. Visualization of organizations' citation network.

3.6. Citation by Sources

The relationship between publications and citations is presented in the form of a network visualization in Figure 10. The size of the node is proportional to the number of publications, so the more articles, the larger the size of the node. The highest number of publications (5) and citations (176) belongs to the *Renewable and Sustainable Energy Reviews* journal, with total link strength of 24. It is followed by *Energy and Buildings*, *Buildings*, and *Sustainability*. The distribution of articles classified as biomimicry and energy efficiency in the field of architecture are mostly published in the journals listed in Table 4.

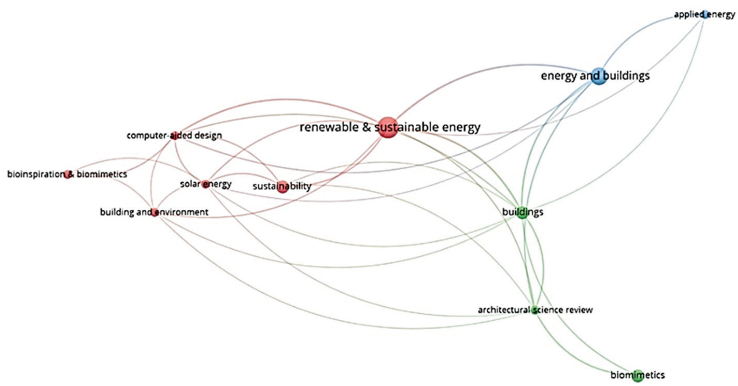

Figure 10. Visualization of publication sources' citations.

Table 4. List of journals with more than one publication in biomimicry and energy efficiency.

Rank	Journal	Documents	Citation	Total Link Strength
1	*Renewable and Sustainable Energy Reviews*	5	174	24
2	*Energy and Buildings*	4	66	18
3	*Buildings*	3	37	20
4	*Sustainability*	3	30	9
5	*Computer-Aided Design*	2	143	15
6	*Architectural Science Review*	2	52	14
7	*Solar Energy*	2	40	11
8	*Building and Environment*	2	26	7
9	*Applied Energy*	2	6	5
10	*Bioinspiration & Biomimetics*	2	17	4
11	*Biomimetics*	3	0	5

3.7. Co-Occurence of Keywords

The network diagram shows the keywords in the appropriate publications and their relationships to each other (Figure 11). The keywords analyzed were words that were repeated at least three times in the selected articles. As a result, 39 keywords were obtained in 4 groups. Relating keywords to the main content of the publications is key to revealing trends in research topics. This study found that the authors preferentially used the keywords "Biomimicry" and "Biomimetics". It was also found that the focus of the studies is on different design strategies for thermal performance through building envelopes.

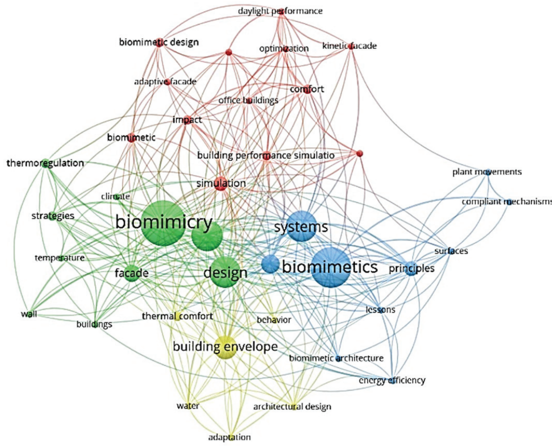

Figure 11. Co-occurrence of keywords.

3.8. Content Analysis of the Selected Articles

In nature-based research, adaptation mechanisms are explored to achieve quantitative and qualitative ideas, such as the transfer of information between scales, programs, processes, or partnerships, and, as a result, a design solution is established. Solving difficulties, such as form, materials, shape, processes, and systems, in this kind of study is confined to the biological knowledge of the designer. Support for such a study by a multidisciplinary team will significantly lessen the challenge of interdisciplinary information transmission.

A content analysis was performed in this part of the research for the articles to better comprehend and remark on biologically inspired studies that altered the energy performance of buildings in the architectural literature as a consequence of multidisciplinary investigations (Table 5).

Table 5. Content analysis of articles.

Year	Description	Reference
2012	"Biomimetic responsive material systems that do not require an external energy source or any mechanical or electronic control"	[18]
2013	"A novel type of kinetic envelope design inspired by plant movements"	[21]
2014	"Design of an adaptive responsive facade based on tracking the position of the sun inspired by shrimps' compound eyes"	[22]
2015	"An approach for generating biomimetic design ideas and water-harvesting surface designs"	[19]
2015	"Investigation of the effect of thermal energy on bio-inspired reflective building envelopes in dense urban areas"	[16]
2015	"Building systems that adapt to their environment through the usage of hygromorphic materials"	[14]
2015	"Building-shell design using smart materials that act similarly to human skin"	[23]
2015	"Responsive biomimetic building envelope with hygrometric material properties"	[12]
2015	"A novel type of kinetic envelope design inspired by plant movements for shading"	[15]
2016	"Proposing a biomimetic building envelope to reduce energy consumption, conserve materials, and increase building sustainability"	[24]
2016	"Design ideas for shape-morphing sunshades are examined, with a focus on energy-efficient smart materials and biomimetic principles"	[25]
2016	"Biomimetic design for enhancing thermal energy performance in office buildings through the use of the biomimicry approach to building energy efficiency"	[26]

Table 5. *Cont.*

Year	Description	Reference
2017	"Biomimetic building envelopes based on the adaptive approach"	[27]
2017	"Energy-efficient and environmentally responsive building envelope design"	[28]
2017	"Using biomimetic principles to develop energy-efficient buildings to reduce energy consumption "	[29]
2017	"Building envelope design to reduce energy consumption"	[30]
2017	"Building systems that adapt to their surroundings through the usage of hygromorphic materials"	[31]
2017	"Developing adaptive energy-efficient building envelope inspired by plants"	[17]
2017	"Prototype of a biomimetic passive cooling panel system"	[32]
2018	"Design of an energy-efficient building envelope for office buildings based on a solar shading system"	[20]
2018	"Design of an energy-efficient building envelope based on material design without hinges for smart and adjustable exterior shading systems"	[33]
2018	"Developing parameters for reducing energy consumption through biomimetic building envelopes"	[34]
2018	"Efficient and sensitive material design for shading elements that work without stimulus inspired by plant movements"	[13]
2018	"Design of a foldable shading system without hinges"	[35]
2018	"Design of an energy-efficient office building façade"	[36]
2018	"Design of an adaptive and energy-efficient building façade"	[37]
2019	"Biomimetic approaches to zero-energy building design"	[38]
2019	"Improving thermal performance through responsive and kinetic façade design"	[39]
2019	"Environmentally sensitive building envelope design"	[40]
2019	"Environmentally sensitive biomimetic adaptive building envelope design"	[41]
2019	"Adaptive biomimetic façade design for tall glazed structures to improve energy efficiency"	[42]
2020	"Design of a biomimetic energy-efficient building"	[43]
2020	"Biomimetic design tools for building energy efficiency by managing heat through building envelopes have been developed".	[44]
2020	"Design of a biomimetic adaptive building envelope"	[45]
2020	"Design and performance evaluation of thermo-sensitive shading prototypes"	[46]
2021	"Design of a biomimetic building envelope to improve thermal performance"	[47]
2021	"Design of biomimetic adaptable electrochromic windows to increase building energy efficiency"	[48]
2021	"Design of concrete tiles inspired by natural geometries to increase thermal performance in the building envelope"	[49]
2021	"A water-harvesting technique derived from plants"	[50]
2021	"Design of a zero-energy, nature-inspired building with high thermal comfort"	[51]
2021	"Simulation of biomimetic adaptive building envelopes that are adjusted to changing environmental circumstances"	[52]
2021	"A kinetic façade inspired by origami to increase daylight performance and energy efficiency"	[53]
2021	"Natural morphological adaptations for evaporative cooling in façade design"	[54]
2021	"Façade systems and solar panels designed on the base of automated thermal expansion, with low energy consumption and low environmental impact, without external energy sources or computerized control systems"	[55]
2021	"Surface design for evaporative exchange and temperature management"	[56]
2021	"Design of a biomimetic façade to reduce energy consumption"	[57]
2021	"Design of biomimetic building envelope systems"	[58]

When the 47 directly related articles were examined, innovative designs for the built environment, such as energy efficiency, reductions in energy consumption, water harvesting, thermoregulation, and sensitive and responsive façades and materials, were found to be produced without the help of motors, computerized devices, or external energy sources. The common feature of all these studies is that they aim to minimize the damage to nature, reduce energy consumption, and produce energy-efficient, zero-energy buildings. In this context, it is seen that biomimetic design offers many opportunities for energy-efficient buildings. The main reason why the examined studies mostly focus on the building envelope is that this has properties that require the control of various environmental factors such as ventilation, humidity, heat, light, and mechanical stress, just like shells, the skin, and surfaces in nature. Nature has the potential to provide unlimited examples for the production of sustainable, adaptive, adaptable, and energy-efficient buildings.

According to the Sankey diagram (Figure 12), more than 70% of the approaches to solving the energy problem in buildings are problem oriented. Concepts such as simulations, parametric models, kinetic mechanisms, and computational design are used to transfer the solutions found in nature to architectural designs. The data obtained by analyzing the biomimicry approach, the biological phenomena of nature, and the architectural research based on these phenomena and what topics they cover in energy efficiency are presented through data visualization. In this paper, "information analysis techniques" were used. It can be observed that the architectural studies interact with nature in the framework of a technological perspective and that architecture, biology, and technology are closely linked.

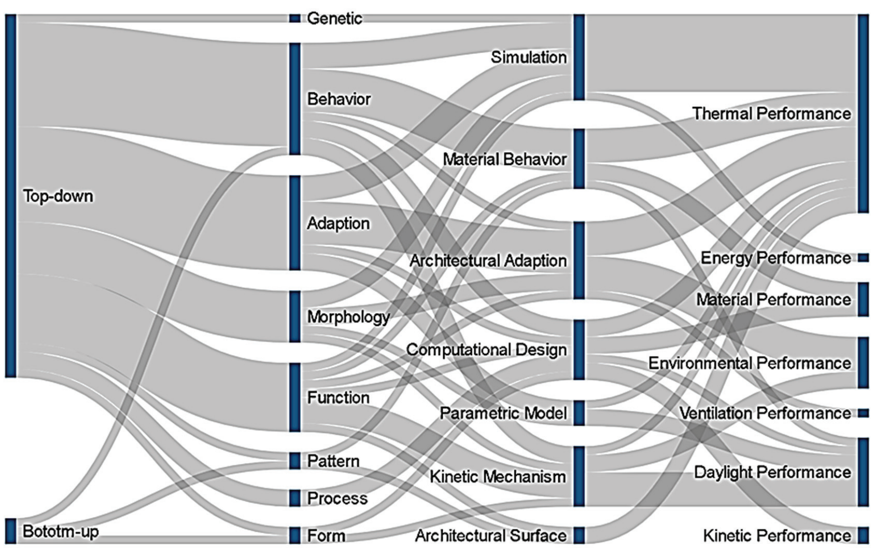

Figure 12. Sankey diagram of the biomimetic approach, biological phenomena, transition to architecture, and issues to be solved.

4. Conclusions

Biomimicry is a novel approach, and there has been very little research carried out in this area. The increased number of recently published articles demonstrates that there has been notable research in this area. Challenges in energy and climate change have led researchers to establish nature-based designs that demonstrate the importance of biomimicry in today's world. The analysis of the WoS database revealed that, in recent years, there has been notable growth in the number of publications on this topic. Germany, the United Kingdom, and Australia have the most significant influence on biomimicry research. The University of Stuttgart has the greatest number of publications and citations.

According to the detailed analysis of the papers, it was found that most of the studies focus on building envelopes to control various environmental factors through a problem-oriented approach. This review of articles on nature-inspired architectural studies has shown that architecture, biology, and technology are deeply entwined, and multidisciplinary studies are now inevitable.

According to these limited findings, it was found that further study in biomimicry is needed. However, in addition to the increasing trend of studies conducted in recent years, it was found that subject-oriented studies have also expanded. Based on this analysis of the studies, the systematic use of biomimicry can provide researchers with new solutions for energy-efficient architectural designs.

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Article

Numerical Assessment of Zebra-Stripes-Based Strategies in Buildings Energy Performance: A Case Study under Tropical Climate

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Abstract: Urban growth has increased the risk of over-heating both in the microclimate and inside buildings, affecting thermal comfort and energy efficiency. That is why this research aims to evaluate the energy performance of buildings in terms of thermal comfort (operative temperature (OP) levels, satisfied hours of natural ventilation SHNV, thermal lag), and energy efficiency (roof heat gains and surface temperatures) in an urban area in Panama City, using superficial-heat-dissipation biomimetic strategies. Two case studies, a base case and a proposed case, were evaluated using the Designbuilder software through dynamic simulation. The proposed case is based on a combined biomimetic strategy; the reflective characteristics of the Saharan ant applied as a coating on the roofs through a segmented pattern such as the Zebra's stripes (one section with coating, and another without). Results showed that the OP decreased from 8 to 10 °C for the entire urban zone throughout the year. A reduction of 3.13% corresponding to 8790 kWh per year was achieved for cooling energy consumption. A difference of 5 °C in external surface temperature was obtained, having a lower temperature in which the biomimetic strategy was applied. Besides, it was evidenced that a contrasted-reflectivity-stripes pitched roof performed better than a fully reflective roof. Thus, the functionality of Zebra stripes, together with the reflective characteristics of the Saharan ant, provide better performance for buildings' thermal regulation and energy needs for cooling.

Keywords: biomimetics; building performance simulations; indoor thermal comfort; reflective nature; zebra stripes

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1. Introduction

In the last century, there has been a high growth of urban areas where deforestation of green areas was not considered, and materials were used in buildings with high thermal retention, soil occupation, and high levels of greenhouse gas emissions. The greenhouse effect is on the other hand; urban areas consume between 60% and 80% of the energy produced, which today has generated a high environmental and energy cost for the planet [1].

Such consequences are reflected in the effect of urban heat islands (UHI) in cities that cause high rates of heat and temperature in urban areas and consequently affect people's comfort both outside and inside buildings and in the high rates of energy consumption of a part of the buildings. Latin America and the Caribbean, according to United Nations studies in 2018, had one of the highest percentages of urban population with around 81%, a trend which will not decrease [2]. Panama is no exception—there is a high uncertainty regarding energy sustainability due to the growing urbanization that has left aside parameters such as interior comfort, leading to excessive use of air conditioning systems and high levels of energy consumption [3].

Recently in the country, measures have been taken regarding regulations to be able to seek options and strategies that allow greater comfort and low energy consumption in new constructions, such as the sustainable construction manual (RES), which represents the first steps in the search for new sustainable buildings with low energy consumption [4]. Estimates by the National Secretary of Energy (SNE) project that by the year 2050, 66% of homes will have at least one air conditioning unit, which means that for that year, 55% of residential consumption will be due to the use of this equipment [5]. This is mainly due to the constant increase in temperatures, as revealed in a study focused on urban heat islands in Panama City [6]), where it was identified that the materials used in constructions and roads have a high accumulation of heat, which generates a higher temperature and an increase in the use of these devices. There is a need for ventilation and to search for other types of strategies such as bioclimatic or biomimetic [7]. In addition, a study has been carried out focused on how natural ventilation can influence a favorable climate for the indoor thermal comfort and the energy efficiency of buildings in a microclimate of Panama City via dynamic simulations coupling ENVI-met and Designbuilder software [8]. Here, it was concluded that passive use would only represent 19.41% of comfort throughout the year, which is why the use of materials in buildings that allow greater thermal insulation to improve these conditions was recommended. Moreover, the use of standard weather data based on typical meteorological conditions to perform the dynamic simulations in Designbuilder was contrasted using microclimate data instead generated via ENVI-met. An average difference of about 5.07% (with a maximum of 9.79% (940 kWh) in March and a minimum of 0.9% (121 kWh) in January) was encountered when using microclimate data instead of standard weather data for the case study, leading to the consideration of microclimate data for the study of natural ventilation proficiency and the energy efficiency of individual buildings at an urban scale.

On the other hand, the search for strategies to be more efficient in buildings has led to multiple bio-inspired strategies or concepts such as biomimetics, which refers to the search for strategies in nature and how to extract these concepts to solve a human problem [9], in applications for buildings with the purpose either of developing or improving air conditioning systems [10].

In bioinspired design specifically for buildings, it is common to adopt the first level of biomimetics that studies the organism—specifically the plants as the protagonists—and the study of their adaptive behavior—precisely their shape [11].

For energy management in buildings, skins have been implemented in buildings due to biomimetic design abstraction. All the natural aspects that influence nature in the body are considered, and the natural skin is assimilated with the skin of the building, for example, membranes and organs as if they were the mechanical or electrical system of the building. Likewise, the reactions between light, humidity, air, sound, heat, and other factors influence real life. Under this aspect, there is a case study of the construction of the skin to reduce energy consumption [12] based on a biomimetic design matrix that adopts characteristics of different organisms in nature.

The first case is The Council House 2 [12], in Australia that emulated the bark of a tree; the north and south facades represent the bronchi of the tree, the west is the epidermis, the east and the facade that represented the nucleus was the bark which acted as a filter for light and moisture. The second case is the Water Cube aquatic center in Beijing [12], which through its skin emulates soap bubbles that can reduce surface area and energy, in which a specific geometric shape is obtained that is replicated in the edification. The results of this application include energy cost reduction by 30%, reduction of artificial lighting by 55%, and solar energy is trapped, serving as heating.

In the search for optimal conditions for the occupants, the importance of the study of thermoregulation [13] is highlighted, in which its authors emphasize the types of thermoregulation mechanisms for hot and cold climates and the models found in nature. Such as in termite mounds, the heat exchange of the prickly pear, and even humans themselves when sweating. Under this concept, an evaporative cooling system for building envelopes (Stoma Brick) was designed, based on four parts that make it up: in which the stoma brick mainly controls the entry and exit of moisture and at the same time retains it for evaporation. The design is adaptable for hot, cold, humid, and dry climates, mainly simulating a plant's stomata, conifers, and human skin.

Moreover, other strategies based on skin characteristics can be found in nature for hot climates, such as the reflective properties of the Saharan silver ant's hair [14], the head position of the Western Reef Heron [15], and the Shell in Snails and slugs [16]. Regarding the reflective strategy for heat dissipation, such as the Saharan ant [17] and the Shell in Snails [18], there are studies that focus on the application of reflective coatings on ceilings and pavements to cool down the surrounding air temperature in urban areas for urban heat island effect mitigation [19,20], a strategy called "cool roofs." A study carried out in [21], based on simulations for cities in California with a Mediterranean climate, where the albedo of all surfaces, both pavement and ceilings, was increased by 0.2, obtaining benefits of up to $-0.01\$$ per year per square meter of energy savings, and CO_2 reductions of less than 1 kg per square meter. However, this type of strategy depends a lot on the climatic zone and also has its disadvantages with respect to the application on floors or ceilings, since it can affect the visibility of people and even increase the temperature of the surfaces of some buildings of greater height to others of less height [22]. Another study applied a reflective coating using light tones combined with phase change materials (PCM) to reduce the monthly cooling energy consumption. Being in a tropical area—Singapore—a reduction of cooling energy between 5% to 12% was achieved throughout the year [23]; supporting results were later obtained in [24].

The thermoregulatory functions associated with the stripes in Zebras' skin also fall within such type of strategy. However, by mimicking the animal body via colored metal barrels, experimental evidence showed no significant difference in the core temperature of barrels covered with horse and Zebra skins with different scratch patterns. Thermographic measurements were employed. It was concluded that the stripes' coloring and patterns do not statistically significantly influence the body thermoregulation in Zebras [25]. In contrast, a study carried out in Kenya also performs thermographic experiments on live Zebras for seven hours a day. It was evidenced that there is a temperature difference of 12 to 15 degrees between contrasted stripes [26], mainly due to sweat that is accelerated by latter, which in turn, with the movement of the air, causes turbulency at the Zebra's hair, increasing cooling by evaporation.

On the other hand, studies have been carried out that involves the biomimetic design in facades specifically applied to insulators, which are simulated in TRNSYS to evaluate the energy reduction potential compared to having no strategy and thus obtaining a significant reduction in the greenhouse gas emissions in the useful life of the building, in which it applies for different types of climates, in different types of buildings [27]. It was recognized that the thermal bioarchitectural framework was valid as a bridge between architecture and biology [28] in order to find designs with efficient thermal performances. In the case of two buildings in New Zealand, in which the buildings were first simulated to recognize the main problems and divide the thermal zones, different scenarios were analyzed in which mainly passive and active techniques were used in combination. The authors concluded that imitating biological forms so far does not seem to be critical to assessing energy efficiency in buildings [29].

It is common to evaluate the potential ideas that biomimetic-based design can offer us. With a solution-based approach [30] these are generated under three main categories (biological domain, transfer, and technological domain) [31], multiple proposals for designs of more efficient buildings. In the review, as a first point, an extensive investigation of all the characteristics and biological behavior is carried out, taking aspects such as: heat control, use of organic material, respiratory control, use of water, among others. This knowledge is transferred and compared with similar processes in construction and engineering. For example, breathing control compared to ductwork, water usage compared to evaporative cooling. Finally, there is the technological domain in which they evaluate which tool or method can be implemented or improved in the design, be it at the level of the building, systems, or components. It was proposed to change load and energy consumption through passive design to retain and release heat, heat sinks emulating the toco-toucan, and develop new heat recovery systems based on aquatic species and products that reduce the range of current detectors by copying the behavior of some insects. The researchers highlighted the importance of bioinspired design and its potential in the future [32].

Finally, while there are multiple proposals focused on the interior conditions of individual buildings, few studies can be found that investigate the biomimetic approach at urban scale via experimental approaches [33–35] and even fewer via dynamic simulation [36] at this scale under tropical climates. Based on our particular interest in dynamic simulation and numerical studies, by focusing on the heat island problem mitigation, an extensive investigation of the biological analogies was carried out for a case study of the problem for the Old Town, Casco Antiguo, in Panama City [36]. Here, to evaluate and improve the thermal comfort of pedestrian (outdoor comfort) through the ENVI-met software, considerable changes were made to the roof of the buildings, emulating the physiology of Zebras and the characteristics of the Saharan ant, in addition to changes in the pavement and vegetative growth. The changes made resulted in temperature reductions of up to 4 °C in a specific area of the study and reductions in the Physiological Equivalent Temperature (PET) comfort index indicators for pedestrians. However, this study did not evaluate the impact of such biomimetic strategies in the indoor thermal comfort, envelope performance, and energy consumption.

Therefore, the objective of the present study is based on the research of reference [8], [36]. Such previous studies, performed for the same studied urban zone, concluded the following:

1. The urban heat island effect, evidenced by the external comfort, is increased by the narrowness of buildings within the urban zone under such a tropical climate [36];
2. Natural ventilation (or passive mode) appears not viable, and the extensive use of air conditioning systems (or active mode) may be required to provide acceptable indoor thermal comfort [8];
3. Other thermoregulation strategies are needed to improve external comfort [36];
4. The use of microclimatic data could significantly influence the estimation of the building energy performance [8], causing about a 10% difference lower for cooling needs than when using standard weather data.

Since [8] evaluated the passive and active modes in the base case study (with no incorporation of biomimicry) indicating that microclimate data should be used for indoor thermal comfort assessment and energy performance, but encountering that the passive mode appeared not viable, the addition of the biomimetic strategies in [36], which improved the microclimate conditions, could increase the viability of the use of natural ventilation, and the buildings' energy performance in this urban zone.

That is why the use of the same biomimetic strategies in [36] are applied to the base case study (namely, proposed case), to assess the thermal and energy performance of the urban zone. The performance is evaluated by means of indoor thermal comfort indicators, such as operating temperature, surface temperature, as well as the evaluation of the satisfied hours of natural ventilation (SHNV), using dynamic simulation through the Designbuilder software v6.1.6.011 [37] and ENVI-met. v4.4.5 [38]. The evaluation was carried out in March (driest) and October (rainiest), comparing the base case (or reference case) and the proposed case. Besides, full reflective coating is applied to the base case and compared with both other cases in terms of performance. Since the combined biomimetic strategy of [36] surpasses in performance the full reflective coating approach, a 2D transient heat transfer model is constructed to clarify this outcome contrasted with those in [25].

2. Materials and Methods

For the development of this research, the methodology implemented consists of evaluating microclimatic data within an urban zone in the Old Town of Panama City named Casco Antiguo via ENVI-met and the corresponding standard typical meteorological data. The microclimatic data were adapted via a numerical approach to assessing the energy performance of buildings within the urban zone [8]. The Designbuilder software, together with the microclimatic data, were used to assess such performance of buildings operative in passive and active modes for both the base case and the proposed case. The proposed case is based on biomimicry strategies (Figure 1).

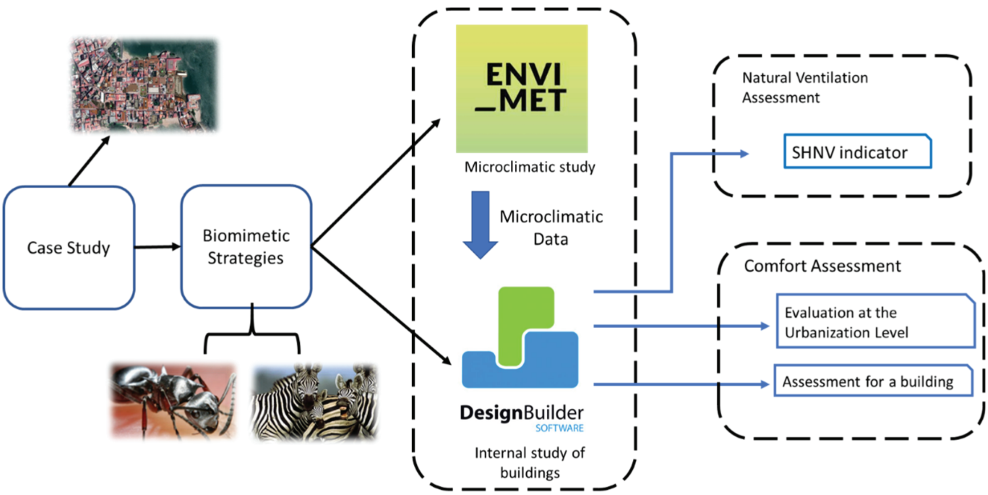


Figure 1. Proposed methodology for the development of the research. Own elaboration.

2.1. Case Study and Problem Identification

The study focuses on the Old Town of Panama City, Caso Antiguo, which is declared a World Heritage Site by UNESCO. Its colonial design is based on the laws of the Indies, in which its buildings are mainly composed of materials such as: wood, calicanto, clay blocks, concrete, tile roofs, and concrete slab roofs [1]. The area is classified as a climatic zone type 3 (LCZ3) according to Oke [39], which consists of high-density, low-level buildings (3 to 4 levels), paved ground, and few trees. To perform the numerical study, part of this urban zone was analyzed: the cutout chosen covers a dimension of 290 m (x) by 226 m (y), as can be seen in Figure 2. This urban zone was selected to analyze further previous studies conducted for the same cutout [1,8,36,40]. Table 1 summarizes the materials of the buildings in the studied zone or cutout.

Figure 3 shows the 3D model of the base case study area in Designbuilder and Table 2 presents the transmittance values for each of the buildings' envelope elements. Using the Google Earth Pro tool, the dimensions of the streets and buildings were taken from the cutout, and the Designbuilder blocks tool was used to create the buildings. Only the energy consumption and thermal comfort of gray-colored buildings are considered in the simulation results. The uninhabited buildings, churches, and historical monuments are shown in color pink, which indicates that their individual energy consumption and thermal comfort are not considered in the simulation results but their impact on other buildings performance is considered, through shading, wind blocking, and reflectiveness. In addition to the information related to the heights of the buildings, the construction materials according to the real characteristics of the pavements, surfaces, and vegetation (only trees without the consideration physiological functions, such as evapotranspiration) were placed.

(**a**) (**b**)

Figure 2. Urban zone under study: (**a**) Satellite view of the Casco Antiguo, and (**b**) cutout view of (290 m × 226 m) [36].

Table 1. Characteristics of materials employed in the 3D model [8].

Material	Texture	Conductivity (W/mK)	Specific Heat (J/kgK)	Density (kg/m^3)
Concrete block		1.04	921.10	1841.10
Clay tile		1.00	800	2000
Brick pavement		0.96	840	2000
Concrete pavement		0.96	840	2000
Cultivated clay soil		1.18	1250	1800

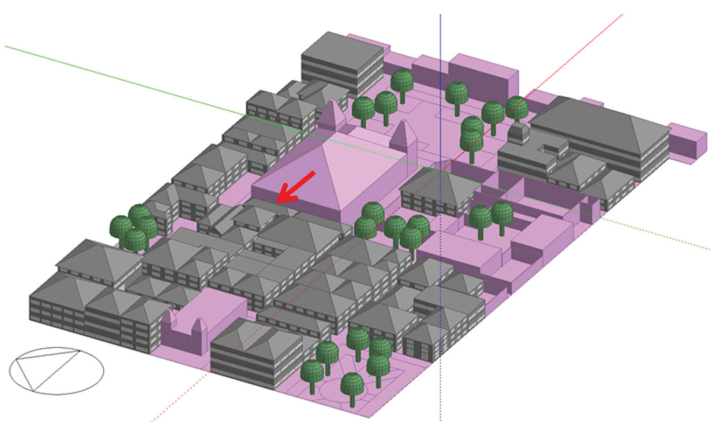


Figure 3. Base case 3D model in Designbuilder. Own elaboration.

Table 2. Characteristics of materials employed in the 3D model. Own elaboration.

Building Envelope Element	Transmittance Values (W/m^{2}K)
External walls	3.087
Internal partitions	1.639
Pitched roof (base case)	2.930
Flat roof	0.250
Pitched roof (proposed case) with reflective layer	2.828
Windows	5.778
Ground floor	0.350
Internal floor	2.929

2.2. Proposed Designs and Simulation

An evaluation of the study area previously proposed, in which applied biomimetic strategies focused on a problem-based approach, i.e., the basis of an exhaustive search for biological analogies, where the most related were extracted thanks to the biomimetic design methodology [36]. Such biological analogies were applied on the buildings' roofs to evaluate their effects on pedestrians' comfort. Now, the present study concentrates on evaluating their effects on indoor thermal comfort and energy consumption.

2.2.1. Abstraction and Emulation of the Identified Biomimicry-Based Strategies

The biomimicry problem-based approach applied to the case study led to abstract and emulated a two-pinnacle strategy based on the Zebra stripes and the Saharan ant. The Saharan ant for its highly reflective characteristics, and the zebra specifically its black and white appearance, to emulate convective currents and achieve evaporative cooling (Figure 4). Table 3 shows the summary of such pinnacles' analysis [36].

Table 3. Summary of the Pinnacles Analysis. Own elaboration.

Pinnacles Strategy	Mechanism	Fundamental Principles	Main Feature
Zebra Arrangement of animal stripes for heat regulation	Black and white streaking causes a temperature differential [30,41].	Convective currents are caused by increasing evaporation.	High convection and evaporation
Saharan ant Silver hairs with triangular structure	High reflection in the NIR range and emissivity in the NIR [17].	Reflection of thermal radiation and high emissivity to release excess heat	High reflectivity and emissivity

The emulation of such pinnacle strategies was implemented in the urban zone, as in [36] but in the Designbuilder software on the buildings' roofs. For this, an additional layer of a reflective coating was added to the based-case pitched roof construction (Table 4), following the Zebra-stripes pattern interchanging between the reflective coating and the original roof, as shown in Figure 4. A change in the pitched roof geometry was made from a multi-slopes roof to a two-slope roof for simplicity to adjust and include the stripes pattern. The reflective lines added are 1 cm thick and the width depended on the length of each building ranging from 4 to 6 m wide; no uniform stripe width and shape may be key for Zebras [42]. The buildings' roofs with flat roof constructions were kept as in the base case. The 3D model of the proposed case developed in Designbuilder is shown in Figure 5. To evaluate the base case further, the reflective coating was added to all pitched roof constructions (on gray-colored buildings) for comparison purposes to the proposed case. The value of the coating was based on the value of the reflective properties of the Saharan ant 0.97 [43], commercially a high value of reflective coating of 0.92 [44] was found and therefore that value was taken which was the closest.

Table 4. Layers in the pitched roofs based on the base case. Own elaboration.

Material	Thickness (m)	Reflectivity (-)
Reflective Coating	0.010	0.92
Clay Tile (Roofing)	0.0250	0.3
Air Gap	0.0200	-
Roofing Felt	0.0050	0.2

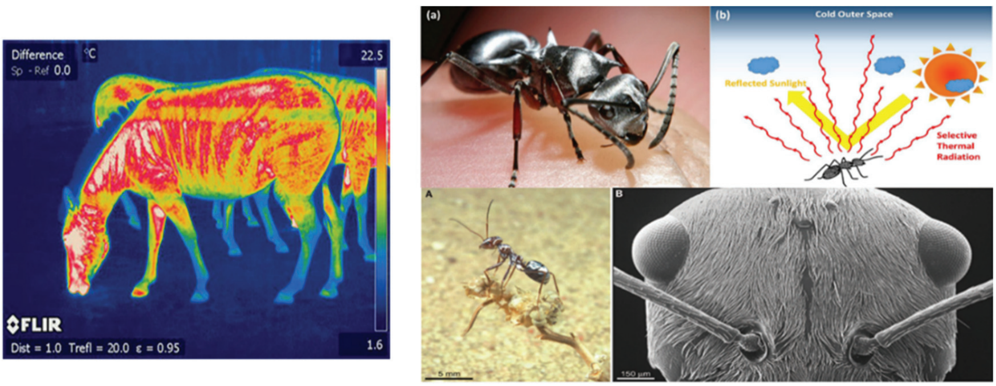
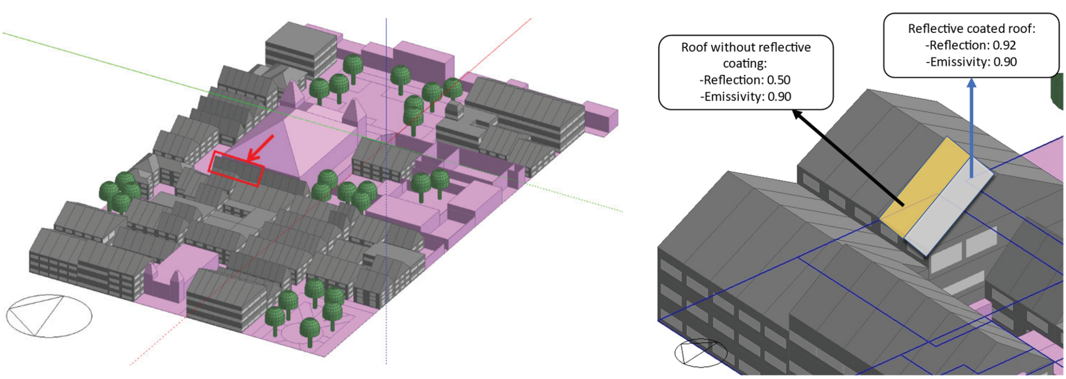


Figure 4. Convection currents due to temperature variation in the black and white lines. Infrared photo with the respective surface temperature variations (**left**). Characteristics of the Saharan ant (**right**) ([41,43]).



(**a**) (**b**)

Figure 5. Proposed case: (**a**) 3D model in Designbuilder (selected building for further analysis inside red box) and (**b**) the order of applied reflectivity and its properties. Own elaboration.

2.2.2. Simulation of the Based and Proposed Cases

The simulations for both cases were performed using microclimatic data extracted from ENVI-met for the whole year. These microclimatic data were created using a numerical approach as in [8] and results from simulations carried out in ENVI-met using standard weather data (typical meteorological data) obtained from CLIMdata Solargis © (Table 5). The resulting microclimatic data for the air temperature is presented in Figure 6.

Table 5. Standard weather data used for simulation. Own elaboration.

Month	Tmax (°C) (Hour)	Tmin (°C) (Hour)	HRmax (%) (Hour)	HRmin (%) (Hour)	Averaged Wind Speed (m/s)	Averaged Wind Direction (°)
3 January	35 (15:00)	23.9 (6:00)	94 (5:00)	44 (15:00)	0.43	126
20 February	34.6 (15:00)	22.2 (6:00)	93 (6:00)	40 (15:00)	2.77	85.77
17 March	35.6 (15:00)	24.9 (6:00)	73 (6:00)	36 (16:00)	2.3	49
11 April	35.3 (15:00)	24.8 (6:00)	82 (24:00)	44 (16:00)	1.75	87
20 May	34.8 (15:00)	24.5 (6:00)	90 (6:00)	53 (16:00)	0.87	83.3
23 June	32.8 (15:00)	23.4 (6:00)	94 (6:00)	58 (15:00)	0.45	108.25
21 July	35.5 (16:00)	24.3 (6:00)	97 (4:00)	49 (16:00)	0.3	89.3
19 August	34.7 (15:00)	24.1 (6:00)	95 (5:00)	52 (15:00)	3.9	188
1 September	32.5 (15:00)	23 (6:00)	98 (24:00)	60 (15:00)	2.1	83
20 October	32.5 (15:00)	23 (6:00)	96 (6:00)	62 (14:00)	2.33	90.67
11 November	32.9 (15:00)	23.7 (6:00)	94 (5:00)	61 (13:00)	2.55	80
16 December	34.3 (15:00)	24.6 (6:00)	94 (7:00)	50 (16:00)	4.2	34.5

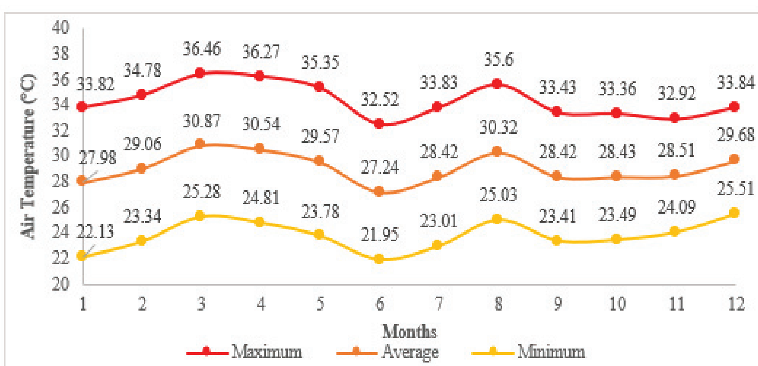


Figure 6. Resulting air temperature of the microclimate data from ENVI-met simulations [8].

The main activity in the Casco Antiguo is commercial, such as restaurants and bars, equivalent to 50% of the buildings, another 40% is dedicated to hotels and residences, and 10% are offices and public institutions. The cut-out of the old town has a different occupation profile from another area of the city [8].

The town of San Felipe has a population of approximately 3262 people and is where the Casco Antiguo is located. The population density is presented in [8] (Figure 7), which was considered equivalent to the occupation profile carried out in the simulation (Table 6).

Figure 7. Population density in the urban zone (adapted from [8]). The studied zone inside black dashed square.

Table 6. Occupied periods and energy usages in the urban zone [8].

Occupancy and Energy Usages	Schedule
Occupation Profile: 0–0.005 hab/m^2 0.0051–0.01 hab/m^2 0.0101–0.05 hab/m^2 0.0501–0.1 hab/m^2	Monday to Friday: 8:00 to 18:00 Saturday to Sundar: 13:00 to 17:00
Luminaires (24 W)	Monday to Friday: 19:00 to 22:00 Satday to Sunday: 19:00 to 5:00
Fans (70 W)	Monday to Friday: 12:00 to 16:00 Sat to Sun: 11:00 to 16:00
Computers (65 W)	Mon to Fri: 9:00 to 17:00
Refrigerator (145 W)	Sun to Sat: 0:00 to 23:59
Air conditioning unit	Mon to Fri: 9:00 to 17:00 Satday a Sunday: 10:00 a 22:00

2.3. Buildings' Performance Evaluation and Comparison

The buildings' performance was evaluated in terms of the following indicators: indoor thermal comfort, roof heat gains, and the electricity consumption for cooling. This evaluation was performed at the building level, i.e., the average values for the entire studied urban zone. The resulting values for each indicator were analyzed and compared in monthly and hourly averages, depending on the indicator. The urban zone was subjected to two operation modes: passive and active modes. The latter mode corresponds to an operation under the use of air conditioning, and the former mode corresponds to an operation under natural ventilation only. This was completed beforehand for both the base case and proposed case.

2.3.1. Passive Mode Operation

The building thermal performance during passive operation mode was assessed using the following indicators: Operative temperature, roof heat gains, and the Satisfied hours of natural ventilation (SHNV). Results are obtained only for occupied periods for monthly indicators. The SHNV is introduced here as it assesses the possibility of ensuring acceptable indoor air quality and natural thermal comfort. The latter corresponds to the percentage of the maximum number of hours when the outdoor climate is favorable for natural ventilation inside buildings, based on the thermal comfort requirements established in the ASHRAE 55 standard for naturally conditioned areas [45]. This indicator can be significantly affected by the outdoor climate, effects of building characteristics such as design, internal heat gains, and envelope energy performance. Finally, the criteria for the SHNV indicator are defined based on the average outdoor air temperature and the operative temperature, as the intersection of these two temperatures for an acceptable 80% ambient. If the thermal comfort condition does not meet the established criteria, this indicator equals zero.

2.3.2. Active Mode Operation

The building thermal performance during active operation mode was assessed by focusing on the electricity consumption for cooling purposes, only for occupied periods. The cooling temperature was set to 24 °C considering air conditioning devices with a coefficient of performance of 3.00. Natural ventilation was permitted during unoccupied periods.

2.3.3. Heat Transfer Analysis of the Zebra-Stripe Strategy

Other studies concerning the Zebra striped skin have associated this strategy with the survival way to regulate skin and body temperature. Experimental studies evidenced a significant temperature difference between white and black stripes. Thus, in order to further understand the building energy performance simulation results and for complementary purposes, 2D heat transfer transient simulations were carried out via the Energy2D software [46] based on Designbuilder results. The 2D heat transfer model setup is presented in Figure 8.

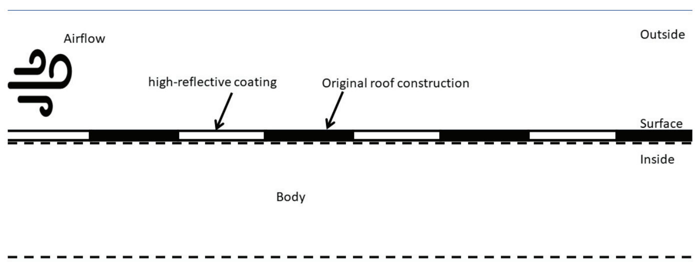


Figure 8. The 2D heat transfer transient setup to evaluate the contrasted stripes strategy. Own elaboration.

To simplify the transient heat transfer simulation and since the Energy2D software solves the heat conduction equation together with the conservation laws, the following conditions were considered:

1. The thermal boundary conditions for the outside were considered as the same as the air temperature; this was set to 0 °C (default temperature value for any surrounding in the software), except for the bottom boundary, which was set to the same temperature as the body. The mass boundaries were set as open. The thermal properties corresponded to the set-up temperature;
2. The body may represent the body of the Zebra or the roof construction material just below the coated surface. Its temperature was set to 50 °C throughout the entire simulation;
3. The outside airflow speed remained constant at 0.01 m/s (using a default ventilator). The time step was set to 10 s, and the simulation duration was limited to 30 min;
4. The stripes were also kept at a constant temperature value. The original roof layer was set to the same temperature as the body, and the high-reflective coating was set to 10 °C;
5. The values for the thermal conductivity, specific heat capacity, and density remained as the default values: 1 W/mK, 1300 J/kgK, and 25 kg/m^3;
6. Any radiation heat transfer interaction was neglected since the stripes' temperatures were set at a constant value, to consider it in advance.

This setup does not intend to replicate the exact situation considered for the energy performance simulations, but it may serve as a reference setup to evidence and understand the heat transfer problem. Finally, since a finite-difference method is used to solve the equations, all physical contact among the stripes and body are considered.

3. Results Analysis

This section presents the analysis of the results and their discussion, starting with evaluating the indoor thermal performance via operative temperature and SHNV levels. A brief analysis of the thermal lag and damping factor results is presented. This is followed by the energy efficiency evaluation in terms of roof surface temperatures and heat gains and the electricity consumption for cooling. Finally, the 2D transient heat transfer simulation results are presented.

3.1. Evaluation of the Thermal Performance via Operative Temperature and SHNV

The average operative temperature results for the entire urban zone can be seen in Figure 9. It can be clearly seen that the proposed case presented a significant reduction concerning the base case, reaching 8.51 °C of reduction for March (from 38.28 °C to 29.77 °C) after applying the Zebra-stripes strategies. The same happened in October with a 9.59 °C reduction. This reduction presented an average of approximately 8.82 °C (from 37.66 °C to 28.84 °C) throughout the year. The main reason for this reduction is associated with the application of the reflective layer, which prevents a large part of the solar radiation that falls on the building from penetrating inside it, which makes the operative temperature lower. Results also showed that when implementing the reflective coating for all pitched roofs in the base case, the monthly operative temperature values obtained are higher than in the proposed case.

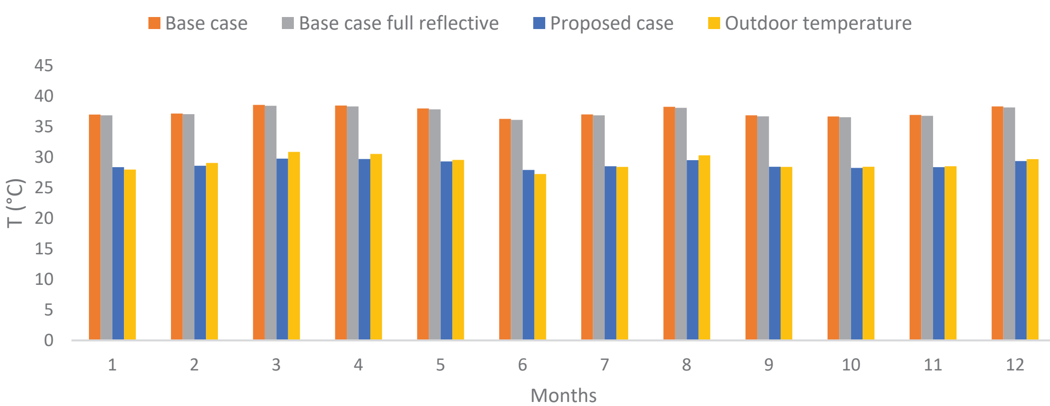


Figure 9. Monthly results of the operative temperature for the urban zone, only for occupied hours. Own elaboration.

Subsequently, an inspection throughout the urban zone allowed noticing that only a two-story building presented acceptable values for the SHNV calculation (selected building in red framed in Figure 5); the same building as the base case. Note here that Figure 9 shows the operative temperature results for the entire urban zone, while Figure 10 shows the operative temperature for the selected building. Temperature reductions can be observed for six months.

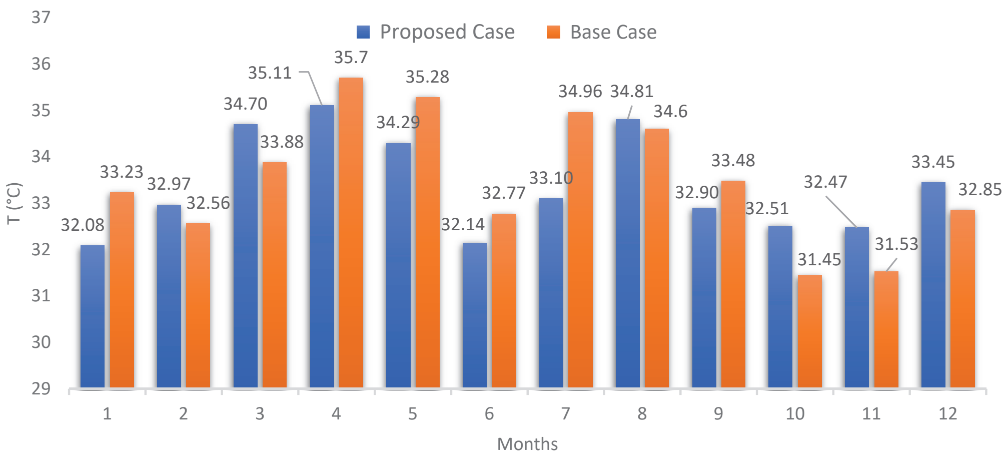


Figure 10. Monthly results of the operative temperature for the selected building, only for occupied hours. Own elaboration.

Accounting only for the selected building, the results of the operative temperature for the critical day of each month were analyzed in detail, assuming this behavior for the rest of the month: 20 February, 20 October, and 11 November. These dates were chosen because they presented acceptable values for the SHNV in the base case. Hourly temperature results indicate that the maximum temperature is no longer reached as specified by the standard weather data (Table 4); maximum values are reached at 16 h and 17 h for outdoor air temperature and operative temperature, respectively. This evidences the impact of the use of microclimatic data. However, for the proposed case with these operative temperature results and the already recorded outdoor air temperature values (Figure 6), only October presented acceptable values for the evaluation of the SHNV. The corresponding SHNV for October resulted in 37.5% (279 h of the 744 h), which conduce to a 3.18% for the entire year. For the base case, the SHNV for February, October, and November resulted in 4.17% (28 h), 16.67% (124 h), and 16.67% (120 h), respectively, conducing to 3.11% for the entire year. These results confirm the thermal unconformity recorded inside the buildings during the occupancy period of the buildings in passive mode, and such values are considered significantly low according to Causone in [47].

Moreover, two parameters that indicate the envelope's thermal performance were evaluated between the proposed case and the base case shown in the table. Such is the thermal lag, which refers to the time it takes to transfer energy in the form of heat from the exterior to the interior in hours, and the damping, which is a fraction between the difference in max and min temperatures of the interior and exterior of the building [48]. In Table 7, it can be observed that according to the thermal lag in November, the operative temperature reached its peak value (or maximum value) faster in the proposed case than in the base case. No significant changes were observed for other months. Therefore, there is a greater heat transfer penetration in the proposed case than in the base case.

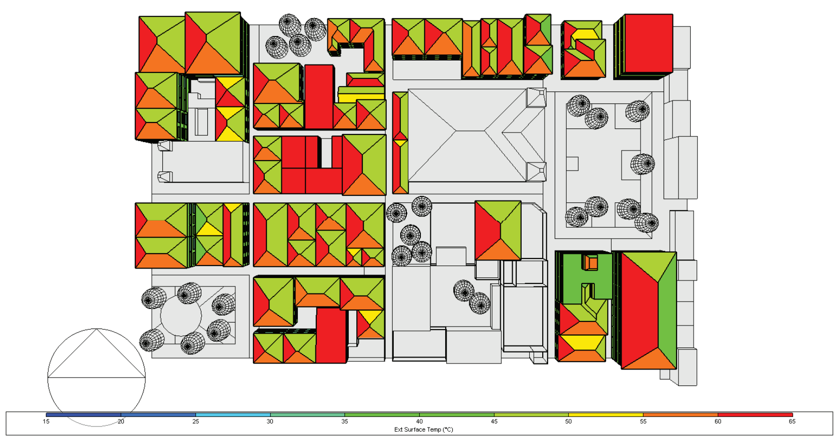
3.2. External Surface Temperature for the Proposed Case

The external surface temperature results for 17 March and 20 October, at 15 h, are presented in Figures 11 and 12, for the base case and proposed case, respectively. As it is 3:00 p.m., it can be seen that the temperature is higher on the west side of the roofs, in March the vast majority of the roofs oscillated 55–60 °C and the east side 45–50 °C, by October the west side of the roof oscillates between 60–65 °C and the east side between 45–50 °C—therefore for the base case in October a higher temperature is obtained.

Table 7. Comparison of the thermal lag and damping factor, for both cases. Own elaboration.

	Date	Thermal Lag (h)	Damping Factor (-)
Base case	20 February	1	1.0046
	20 October	1	0.9562
	11 November	4	0.8648
Proposed case	20 February	1	0.9799
	20 October	1	0.9805
	11 November	3	0.8745

(**a**)



(**b**)

Figure 11. External surface temperature for the base case: (**a**) 17 March and (**b**) 20 October at 15 h. Own elaboration.

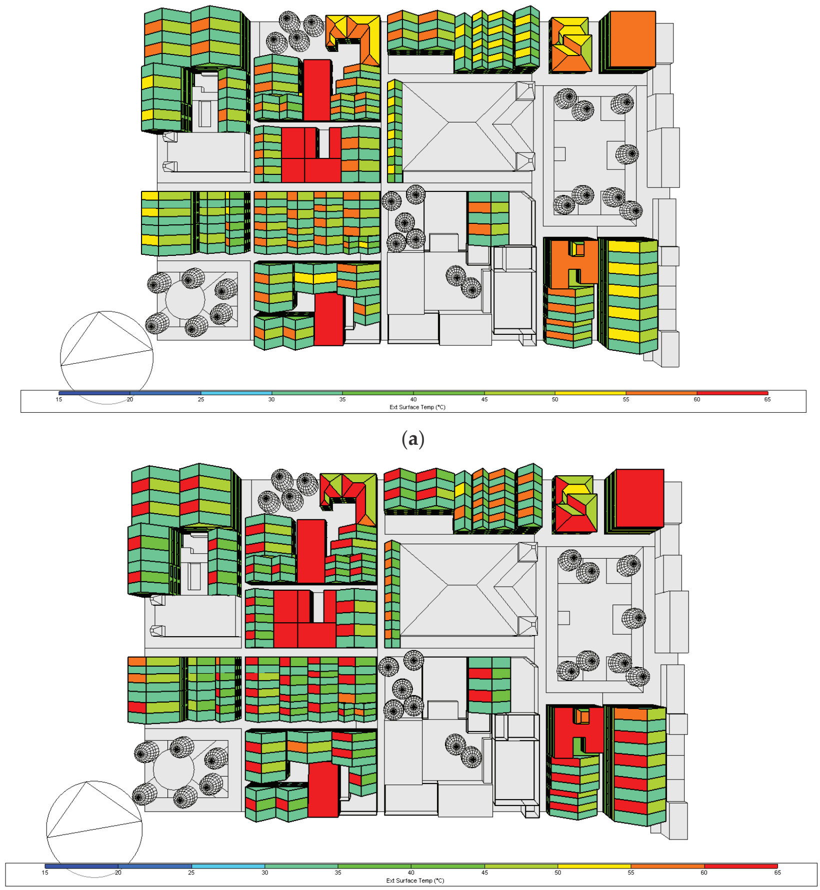


Figure 12. External surface temperature for the proposed case: (**a**) 17th March and (**b**) 20th October at 15 h. Own elaboration.

As expected, significant differences between the reflective coating and the original roof construction surface temperature can be observed. Similarly, low surface temperature values were obtained when implementing the reflective coating for all pitched roofs in the base case. Regarding the monthly average surface temperature values, for March, the difference between the roof of the same building using the Zebra-stripes biomimetic strategy (ZSBS) oscillates in a range of 27.5 °C and 30 °C in the reflective segment and in the non-reflective segment between 32.5 °C and 35 °C, that is, a difference of 5 °C between both segments. For flat buildings in which the ZSBS were not applied, the temperature difference of these buildings concerning those with strategies is about 5 °C.

For October, the difference between the roof of the same building having the ZSBS oscillates in a range of 25–27.5 °C in the reflective segment and in the non-reflective segment between 32.5 °C and 35 °C, corresponding to a difference of 7.5 °C between both segments. In buildings not having the ZSBS, the temperature difference concerning those that have the ZSBS is 3.75 °C. For March, considering the complete area of the model, the proposed case decreased 7.5 °C with respect to the base case. The same happened for October.

3.3. Comparison of Roof-Ceiling Heat Gains and Cooling Electricity Consumption

Figure 13 shows the monthly averages for the roof-ceiling heat gains for the urban zone during the occupied hours for the base and proposed cases. Besides, the base case when implementing the reflective coating on all pitched roof constructions is shown. As expected, the lowest heat gains are encountered for the base case with fully reflective coating on all pitched roofs. The proposed case presented slight reductions concerning the base case.

Figure 13. Comparison of monthly roof-ceiling heat gains for the urban zone, during occupied hours. Own elaboration.

On the other hand, the electricity consumption for cooling needs can be observed in Figure 14. Slight differences are encountered between the base and proposed cases, with an average difference of 3.13%. The latter corresponds to an annual reduction of 8790 kWh, which is significant when considering electricity costs, but this should be addressed further contrasted with the retrofit costs to implement the proposed case at a real scale. The active operation mode was not simulated when implementing the reflective coating on all pitched roofs for the base case.

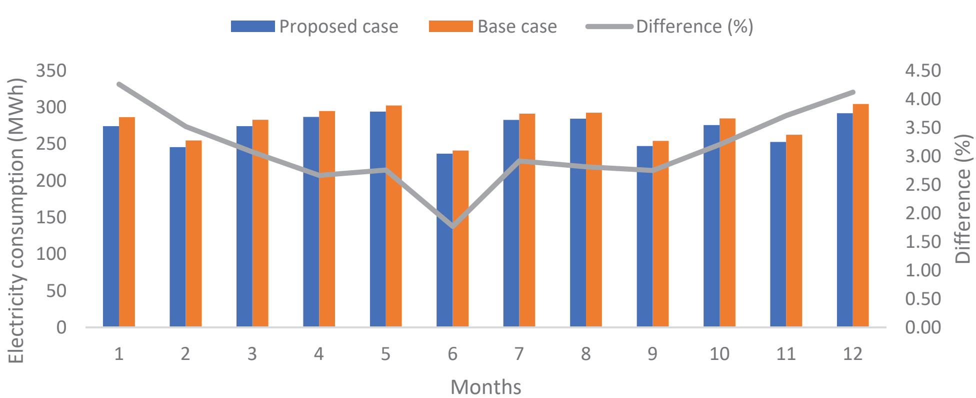


Figure 14. Comparison of monthly electricity consumption for cooling (only for occupied hours). Own elaboration.

3.4. Heat Transfer Analysis of the Zebra-Stripes Strategy

Considering that the proposed case has presented significant results with respect to the base case and base case with fully reflective pitched roof construction. The 2D transient heat transfer simulation results when implementing the ZSBS are presented in Figure 15 (case A). Gray color flashes indicate the temperature range where the highest temperature zones (50 °C) correspond to the clearer zones (in white) and the lowest temperature zones (0 °C) to the darkest. The blue lines represent the heat flux lines. These results were compared with the case where the reflective coating covered the entire surface (case B) in terms of a temperature measurement at the center of the "body". At the end of the simulation time, this temperature measurement reported a lower value for case A than case B, with a difference of 3.8 °C. The graph in Figure 15 shows that in the one with total reflectivity (case B, orange line), the temperature decreases more slowly than the one with the biomimetic strategy (case A, blue line). In more detail, case A shows distortions of the heat flow lines around the contrasting segments, which indicates that the temperature differential in the segments increases heat dissipation, explaining its speed compared to case B.

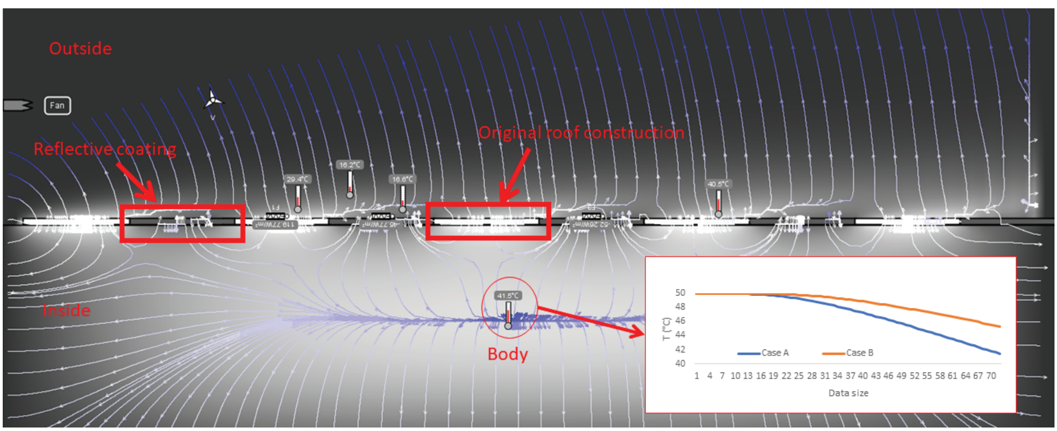


Figure 15. Transient simulation results for the 2D heat transfer model with and without segments reflective coating. Case A: Zebra-stripes strategy and Case B: reflective coating covered the entire surface. Own elaboration.

4. Discussion

A proposed model was made based on the emulation of the characteristics of the Saharan ant employing a high reflectivity coating applied to the buildings' roofs and the contrasted stripes of the Zebra by applying the reflective coating in a segmented distribution. All this is using the Designbuilder software in which the microclimatic data were taken for the dynamic simulation carried out in the ENVI-met software. From the simulation results obtained, the following could be highlighted:

- In the proposed case, the indoor operative temperature of the entire urban zone under study was reduced by about 8–10 °C on average for the year, compared to the base case, due to the application of the reflective coating on the roof, preventing heat gain in inside;
- Regarding the external surface temperature of a building with biomimetic strategies for March, the reflective and non-reflective segments presented a temperature difference of about 5 °C, and it was also found that the building with strategies is 5 °C colder than a building without the strategies. In October, the temperature difference between

the reflective and non-reflective segments was 7.5 °C, while buildings with strategies have 3.75 °C less (colder) without applied strategies;
- The interior temperature for damping for November in the proposed case reached its peak value faster than the base case due to a reduction in the hours of the thermal lag indicator;
- Significant reduction in the electricity consumption for cooling was achieved by the proposed case, with respect to the base case, with an average of 3.13% (about 8.8 MWh);
- The simplified setup for 2D transient heat transfer simulations evidenced enhanced heat transfer dissipation for the proposed case compared to a fully reflective coating on the surface.

Although the operative temperatures reached lower values than the base case, results from the SHNV indicator confirm the thermal unconformity recorded inside the buildings during the occupancy periods in passive mode, which is considered significantly low just as in [47].

Moreover, the proposed case performed better than the base case and the base case when implementing the reflective coating over all roof constructions in terms of indoor operative temperature values and electricity consumption for cooling. The average reduction in electricity consumption for cooling of 5.07% (about 505 kWh) when using microclimate data as in [8], compared to the average reduction of 3.13% (8.8 MWh), here in the proposed case, might not represent high enough energy savings to undergo the microclimate data generation process from standard weather data or in situ data collection for simulation purposes only, as suggested in [8,49]. However, the use of microclimate data could strengthen the evaluation-verification process of new urban designs [49] before implementation at a real scale by giving more precise values for energy needs forecast.

Furthermore, the difference in the roofs with the applied Zebra-stripes biomimetic strategy is comparable as it occurs with the Zebra, which through its black and white coloration, obtains a temperature differential that causes convective currents that accelerate heat dissipation [26]. The effectiveness of this biomimetic strategy is also observed at the surface temperature at the roof west slopes of both cases for both months (Figures 11 and 12). For instance, above the park on the left (surrounding with trees), the buildings' roofs west slope without the reflective coating (color yellow in Figure 12a) appeared 5 °C lower than the same slopes in Figure 11a (in orange). The same can be spotted on the buildings' roofs above the cathedral and those on the righthand side (below the park).

To corroborate, the 2D transient heat transfer simulations helped realize that the heat flow perturbance at the surface of the body (heat flow lines in Figure 15) caused by the stripes allows a faster temperature drop than the surface with homogenous heat flow. However, the impact of this strategy could be enhanced by combining different patterns since the latter may be as fundamental as the stripes' pattern distribution and shape [25]. It is worth highlighting, based on the study [25] that denies the fact that Zebra stripes do not have a significant effect on the decrease in body temperature, our study is based on biomimetics, which does not take the behavior of the analogy directly. Rather, it is adapted to the applications and needs of the design, for example, the reflective coating that also promotes heat dissipation. Finally, using a commercial coating with a reflectivity value of 0.92 [44] on roofs limits the Saharan ant reflectivity value of 0.96, which brings an opportunity for future coating developments. Although significant energy saving for cooling was attained with the combined biomimetic strategy used here, a cost-effective analysis of retrofitting the roofs' construction contrasted with energy saving costs, needs to be performed, as in as in [21], before implementation.

5. Conclusions

The main objective of this research was to evaluate the indoor thermal comfort and energy efficiency of buildings in an urban area in the Casco Antiguo of Panama City through biomimetic strategies from a previously carried out study. Among the findings this investigation provided, the following can be retained: The functionality of Zebra stripes, together with the reflective characteristics of the Saharan ant, provide better performance for buildings' thermal regulation and energy needs for cooling. Further investigation through experimental studies might support the effectiveness of this combined biomimetic strategy, but a cost-effective analysis of retrofitting the roofs' construction contrasted with costs energy saving needs to be performed before implementation.

It is important to highlight that biomimetics has been applied throughout history by nature without generating negative impacts on the environment. That is why it must be learned from, and we must seek alternatives to solve the challenges currently faced by society through the application of different approaches so that they may be solved sustainably.

A recommendation for future work would be to conduct more in-depth studies verifying the effectiveness of the strategies applied in this study, such as convective currents that influence heat dissipation through experimental tests. The evaluation of the application of biomimetic strategies in walls added to the strategies of this study.

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Sustainability Assessment of the Anthropogenic System in Panama City: Application of Biomimetic Strategies towards Regenerative Cities

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Abstract: To understand the sustainability problem for Panama's metropolitan area, its urban metabolism was investigated. A way to evaluate its current state was obtained by estimating a sustainable indicator based on the Green City Index. With the abstraction of the identified problems, the biomimetic strategy "problem-based approach" was carried out, where different pinnacles of nature were selected as a reference for the design of regenerative solutions. These were inspired by the understanding of the living world and how to include ecosystems in urban designs. Therefore, a framework was proposed for positive generation and natural solutions in cities to take advantage of the regenerative potential in Panama City. Using ecosystem services, a set of indicators were developed to measure regeneration over the years at the city scale. The results indicate that from the 11 selected pinnacles, 17 solutions inspired in nature were proposed to regenerate cities. Consequently, a SWOT analysis was realized along with a questionnaire by experts from different fields. The findings obtained show that the feasible solutions were: arborization, green facades, solar roofs, e-mobility, green corridors, bicycle lanes, sidewalks, and biofilters. This research represents a step towards creating and developing regenerative cities, thus improving the quality of life of living beings and ecosystems present in society.

Keywords: biomimicry; regenerative design; urban metabolism; green city; sustainability

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1. Introduction

The considerable increase in the consumption of fossil fuels and the overexploitation of resources are some of the various points that prove how the causes of climate change are anthropogenic. The most polluting human activities include agriculture, energy transformation, industry, such as manufacturing, transportation, and commercial activities. Cities and urbanizations are among the leading causes for this, considering that they consume 40% of the final energy and are related to 70% of global greenhouse gas emissions [1].

Currently, the urban footprint in Panama City is 23 times larger than it was in 1905, where 65.08% of all Panamanians live in urban areas [2]. The urban footprint in the metropolitan area is growing faster compared to the population residing outside these areas.

During the First World Climate Conference, scientists from different parts of the world agreed that climate change trends were alarming. Since then, similar alarms have been raised through the Rio Summit, the Kyoto Protocol, and the Paris Agreement in 2015. Among the globally agreed goals, there are the Sustainable Development Goals; of which this paper will address: Water and Sanitation (SDG 6), Affordable and Clean Energy

(SDG 7), Sustainable Cities and Communities (SDG 11), Climate Action (SDG 13), and Life of Terrestrial Ecosystems (SDG 15).

In addition, it is stated that, with the efforts made so far, the global warming of 2 °C will be exceeded during the 21st century, above the objectives of the Paris Agreement, which established limiting the average temperature increase to 1.5 °C. Although, according to the latest United Nations report, over the next 20 years, the global temperature is expected to reach or exceed the 1.5 °C mark unless rapid and deep actions against climate change are made. It is possible to maintain these figures if nations are told to keep their emissions reduction commitments, which should be in the range of 25 $GtCO_2e$ and 41 $GtCO_2e$ by 2030 [3]. If these values are exceeded, by the year 2040, there could be a rise in sea level, affecting coastal cities, such as Panama. For instance, a sector that needs real action in its operating and embedded emissions is the energy sector. According to Panama's National Energy Secretariat, about 70% of the national consumption is concentrated in the capital city, and the National Energy Plan 2015–2050 also states that by 2050, per capita consumption will increase by 90% [4].

In the search for new sustainability strategies in cities that attack these problems, designers have adopted biological research knowledge. In recent years, biomimicry has become relevant in engineering and architecture, giving way to intelligent, self-sufficient, and distinctive buildings in form, structure, and operation. Author Janine M. Benyus gave biomimicry's first definition in 1997. She defined it as the art of imitating or drawing inspiration from the forms and processes of nature to solve human problems [5].

In architecture, many buildings have already adopted this approach by addressing formal biomimetic design methods in their envelopes and integrating functional solutions, such as the Eastgate Building in Harare (Zimbabwe), the Taichung Metropolitan Opera House, and the Council House 2 (CH2) in Melbourne, Australia.

There are three main levels in biomimicry: organism, behavior, and ecosystem. The organism level refers to a specific organism, such as a plant or animal, where part of it, or the whole organism can be mimicked. The second level refers to the imitation of behavior, where an aspect of behavior is translated into a broader human design context. Finally, the third level is the imitation of entire ecosystems and their principles for working successfully, along with their actual functions. Within each of the levels, there are five possible dimensions; following theses aspects, the design can be biomimetic in how the organism looks (form), what it is made of (material), how it is made or produced (construction), how it works (process), or what it is capable of doing (function) [6].

On the other hand, many of the biomimetic case studies examined by Pedersen Zari in [7], suggested that ecosystem biomimicry may be the most effective way to respond to climate change and biodiversity loss. Yet, right now, ecosystem biomimicry remains the least explored aspect of this branch. A well-known example of ecosystem biomimicry can be seen in the industrial region of Kalundborg (Denmark), where a model of industrial ecology was used. This industrial park is an enduring collaboration between public and private organizations where participants exchange waste materials, residual energy, heat, and water for mutual benefit [8].

Currently, there are two main approaches used in biomimicry, from the perspective of the design problem:

1. The first approach attempts to identify a human design need or problem and then proceeds to look at nature and investigate how certain organisms and ecosystems resolve conflicts; this is known as a top-down or problem-based approach.
2. The second starts with identifying a particular characteristic, behavior, or function belonging to an organism and ecosystem and then investigates different ways of imitating it and adapting it to new designs and products; this is the bottom-up or solution-based approach [9].

In a survey for the strategies that have been taken in different groups of biomimicry practitioners, five of the most recognized groups were discussed: Biomimicry 3.8, Ask Nature, the Biomimicry Institute, Biomimicry Switzerland, and Biomimicry San Diego, concluding that the majority of the groups specialized in the problem-based approach for biomimetic designs [10].

Besides, there are many projects in the current European Union research framework program for nature-based solutions (NBS), known as HORIZON 2020. Many of them strive to explore how NBS works in different urban contexts with respect to the political, social, cultural, institutional, environmental, and economic context [11].

Moreover, the concept of regeneration is emerging extensively in recent investigations by biomimicry practitioners. Pawlyn and Pedersen Zari explained that regenerative systems examine several relevant contemporary examples, which deal with biomimetic technologies and architectures that help the urban built environment adapt to climate change and be favorable factors for the ecological health of the ecosystems. The regenerative design restores the ability of ecosystems to function optimally through the design and development of the built environment [6,12].

One of the concepts most closely linked to regenerative design, which seeks to approach its real application, is ecosystem services. These services are the benefits that humans obtain, directly or indirectly, from ecosystems that support human physical, psychological and economic well-being [6]. The services that humans obtain from the ecosystem are usually divided into provisioning services, such as food and medicine; regulatory services, such as pollination and climate regulation; supporting services, such as soil formation and solar energy fixation, and cultural services, such as artistic inspiration and entertainment. Based on these, strategies have been developed to apply these services in the urban environment [13,14] so that humans themselves contribute to their wellbeing and to the ecosystems with which they coexist. These services apply to the urban developments and can be described as follows:

- Nutrient Cycle: This can be added to cities through food and material imports and lost through exports. It attacks the inability to recover and reuse materials through processes, such as dumping and sewage being discharged to oceans or other regions.
- Habitat Provision: Allows shelter and protection of organisms, providing access to nutritional needs. Such needs are relevant for both permanent and transient populations of organisms and are extremely important for maintaining biodiversity.
- Climate regulation: Regulates processes related to the chemical composition of the atmosphere, the greenhouse effect, the ozone layer, precipitation, air quality and temperature moderation and weather patterns. On a global scale, it encompasses the capacity of ecosystems to emit and absorb carbon and other compounds. In contrast, on a local scale, it considers vegetation to reduce temperatures in urban environments and remove pollutants from the air.
- Purification: Encompasses systems that keep air, water, and soil pure. Urban vegetation is an effective way to remove certain air pollutants, but it is not the only way. Some building materials and filtration systems, for example, can do a similar job and may be more suitable for integration into some types of construction, particularly in medium or high-density areas. Examples are porous metal-organic frame materials, titanium dioxide materials, air ionizers, particulate absorption filters, and other materials.
- Water supply: Includes the regulation of hydrological flows, as well as storage, purification, and water retention. As water is used for consumption for human and animal needs, it is used in large quantities for crop irrigation or other agricultural purposes and industrial processes. Some aspects directly related to the water supply service are water retention, volume management, the timing of runoff, flood control, and drinking water quality.
- Energy provision: The use of biomass and renewable energy is essential as an ecosystem service. Knowledge of energy use will serve as feedback, as an analysis of human behavior and the degradation it causes in ecosystems. However, attempting to replace lost ecosystem services artificially will increase energy, thus leading to further degradation of ecosystems [6].

Examples of ecosystem services analysis (ESA) applied to design include the Lavasa Hill project in Maharashtra, India, and the Lloyd Crossing project proposed for Portland, Oregon. Lavasa was redesigned using the Ecological Performance Standards framework designed by the Biomimicry 3.8 organization and identified six ecosystem services essential to the ecological functioning of the site that was relevant to the development of the urban project in the area. These are water uptake, solar gain; carbon sequestration; water filtration; evapotranspiration, and nitrogen and phosphorus cycling [13].

Considering all the above, the general objective of this study is to conceptualize a reference framework for the proposal of a design methodology based on biomimicry with a vision towards restoration-regeneration at the city scale. This would be done by consulting nature's models to solve several aspects that must be covered in cities with wrongdoings. The solutions will mainly focus on clean energies, energy efficiency, air purification, urbanism, and sustainable mobility with nature's strategies and guides. Through this approach, possible opportunities in applying renewal and regeneration in cities are evaluated, using a qualitative and quantitative study through sustainable indicators.

2. Materials and Methods

The design of this research was based on the use of a biomimicry problem-based approach to conceptualize and propose a reference framework towards a regeneration model at the city scale. This starts by assessing the current potential for sustainability to identify the main problems within the different systems that make up cities. Figure 1 describes the proposed structure to implement this methodology and the stages that make up this work.

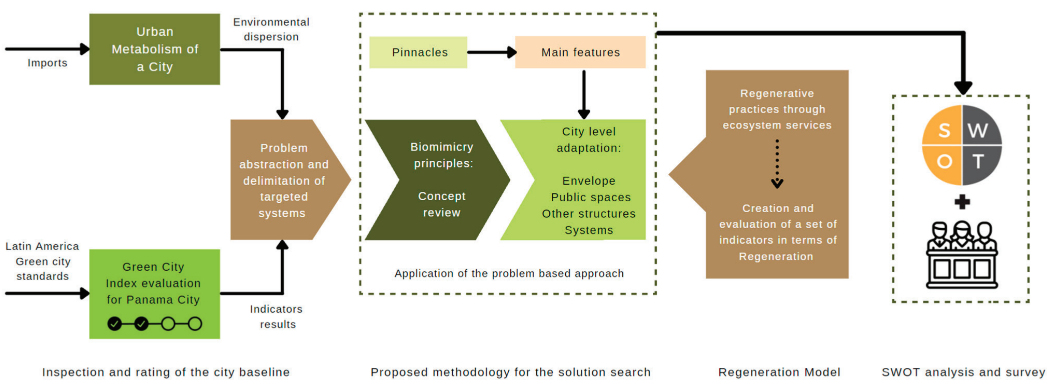


Figure 1. The schematization of the structure proposed for this paper. Own elaboration.

2.1. Baseline: Urban Metabolism of the City

The metropolitan area of Panama is governed by a tropical climate, specifically under two main climatic regions: the Central Region (or R4) and the Eastern Pacific Region (or R5). Both have similar precipitation levels, with rainfall decreasing considerably from December to April (dry season) [14]. As a result, Panama's average outdoor air temperature remains in the range of 23 and 27 °C for the coastal areas and the countryside.

For the temperature of the city itself, the analysis carried out in [15] showed that the area adjacent to Calidonia and Santa Ana had the highest temperatures, ranging from 28 °C to 30.5 °C; while the area with the lowest temperatures was the segment between Clayton and Metropolitan Park with 25.83 °C. This happens since the latter is mostly low-density housing with very dense vegetation. On the other hand, there is a high concentration of economic activity and population in Panama City and the Panama Canal core. Therefore, these territories can be described as "Metropolitan Areas of the Pacific and Atlantic" where approximately 80% of the country's Gross Domestic Product (GDP) is generated [2].

When it comes to the operation of cities, it can be said that a city works similarly to a superorganism that runs through mechanisms and interactions both internally and with the ecosystem. A similar concept is known as urban metabolism (UM), this can be described as the process in which a city obtains its resources from the local environment or by exchanges, then the city consumes these inputs to produce economic outputs in the form of products and services, and then it releases the residues into the environment [16]. There are different types of UM, however, this paper will be focused on the metabolism that occurs in cities through their carbon footprint.

Due to the urban footprint mostly distributed in the Pacific Metropolitan Area, it was necessary to obtain a delimitation of which systems maintained a larger carbon footprint within its limits or boundaries. Therefore, for this baseline case, the Green House Gas (GHG) emissions figures for each sector were collected.

In the results of the GHG emissions inventory according to the year 2013, the latest updated, each inhabitant of the city's urban area emitted around 4.90 tCO_2e. When discussing total emissions, it is denoted that the sector that contributes with the highest emissions is the transport sector, accounting for 46%; this means that the transport system should be taken as a priority. This is followed by stationary sources (residential, services, institutional and industry), which account for 37% of total emissions. The next sector is waste management, with 7%, and the industrial processes and product use (IPPU) sector with 6% of the total. Finally, the energy, agriculture, livestock, and fisheries (AFOLU) sector is a net absorber of CO_2, with 960,270 tCO_2e in 2013 [17].

2.2. Sustainability Assessment and Problem Definition

There are different ways to evaluate the performance of a city. For instance, among the different urban sustainability indicators, we can mention the Wellbeing Index, which has not been widely used during the last decade due to the appearance of several new sustainability indicators. Besides, the City Development Index (CDI) is considered as a way of measuring urban development and the accessibility to urban facilities. In this regard, between 1993 and 1998, the United Nations Human Settlements Program calculated this index for 232 cities in 113 countries. In conjunction, when evaluating the dimensions measured by the specific index, it is noteworthy that three of them, Ecological Footprint, Environmental Performance Index, and Green City Index, are responsible for covering the environmental and social dimensions. In contrast, the Human Development Index covers the social and economic dimensions [18].

Here, for the case of Panama City, the Green City Index (GCI) is selected, because it has been used since more recent years (2009) and is applicable at the urban scale. Such is the research project conducted by The Economist Intelligence Unit (EIU), sponsored by Siemens, consisting of a series of estimates that began in 2009 and covered more than 120 cities in Europe, Latin America, Asia, North America, and Africa [reference].

Moreover, the GCI has a specific weighting for each indicator; this weighting should be multiplied by the results of the final value for the quantitative data and the qualitative section. Table 1 shows the result obtained from this estimation, where each indicator was compared with a standard value from the guide presented by the Latin American Green City Index [19]. This standard has an optimum minimum and maximum value for a city that is on average sustainable. Data for calculations were obtained from scientific publications, statistics, regulations, and plans or studies generated by the Panamanian government. See Appendix A for the detailed table.

Table 1. Summary of the evaluation for the Green City Index indicators (Ranges based on [19]).

No.	Category	Far below Average (0–20%)	Below Average (20–40%)	Average (40–60%)	Above Average (60–80%)	Well above Average (80–100%)
1	Energy and CO_2			51.14%		
2	Land Use and Buildings			47.95%		
3	Transportation		39.00%			
4	Waste				69.08%	
5	Water				71.11%	
6	Sanitation				64.65%	
7	Air Quality	16.67%				
8	Environmental Governance				88.00%	
	Total Result			55.95%		

● Inadequate/poor, high risk, behind schedule. ● Reasonable, moderate risk, partially behind schedule ● Good, low risk, on schedule.

According to the weighting for all indicators in the GCI, the city is within the average sustainable performance in the total result, with 55.95%. However, in the case of the individual indicators, there is an alarming risk in terms of air quality, with 16.67%. For the transportation indicator, there is below-average management, with 39%. On the other hand, the sections on land use, with 47.95%, and energy and CO_2, with 51.14%, despite being within the average, are at moderate risk and they could be improved to achieve the programmed agenda of goals. Due to this distribution, the priority sectors for action must include air quality and transportation. Additionally, the Energy and CO_2 sectors and Land Use and Buildings are rated as average with the same need for intervention. These were considered in the analysis due to their contributions to GHG emissions, inorganic waste, and pollution, which are significantly high.

Some of the indicators used for this index showed a score of 0.00 because of a lack of reliable data sources, as in the sulfur dioxide level indicator. In some cases, values exceeded the internationally established standards (20 $\mu g/m^3$ maximum) [19], for example, in the levels of nitrogen dioxide in Panama (36 $\mu g/m^3$) and suspended particulate matter (49 $\mu g/m^3$).

Other indicators also exceeded the standard, such as length of the collective transportation network (0.03 km/km^2, which is much lower than the minimum of 0.30 km/km^2), electricity consumption per capita (2226 kWh/inhab/yr, which is higher than the maximum of 815 kWh/inhab/yr) and water consumption per capita (274 L/inhab/day vs. the maximum of 126.90 lt/inhab/day).

The GCI score for the Pacific Metropolitan Area of Panama (1.5 million inhabitants) was favorable, however, it ranks poorly in transport and air quality compared to other cities in the index with similar populations, such as Quito (2.1 million), Curitiba (1.8 million), Montevideo (2 million) and Porto Alegre (1.4 million). Table 2 presents the comparison of GCI results in these cities.

A biomimetic analysis of the problem-based approach is sought, where the problems encountered through the index were classified into elements, and those of priority were chosen. In Figure 2, a scheme of the most significant issues among the city sectors is presented to highlight their role in the GHG emissions contribution.

Table 2. Comparison of Panama City and other Latin American cities from the Green City Index final evaluation. Adapted from [19].

Category	Far below Average (0–20%)	Below Average (20–40%)	Average (40–60%)	Above Average (60–80%)	Well above Average (80–100%)
Energy and CO_2		Porto Alegre, Montevideo	Panamá, Quito	Curitiba	
Land Use and Buildings	Montevideo	Quito	Porto Alegre, Curitiba, Panamá		
Transportation		Panamá, Porto Alegre	Montevideo	Curitiba, Quito	
Waste		Montevideo		Porto Alegre, Quito, Panamá	Curitiba
Water		Montevideo	Porto Alegre, Quito	Curitiba, Panamá	
Sanitation		Montevideo, Quito	Porto Alegre	Curitiba, Panamá	
Air Quality	Panamá	Montevideo	Porto Alegre	Quito	Curitiba
Environmental Governance		Porto Alegre	Quito	Panamá, Montevideo, Curitiba	
Total Results		Montevideo	Quito, Panamá		Curitiba
Panamá (yellow)	Quito (blue)	Curitiba (green)	Montevideo (orange)	Porto Alegre (red)	

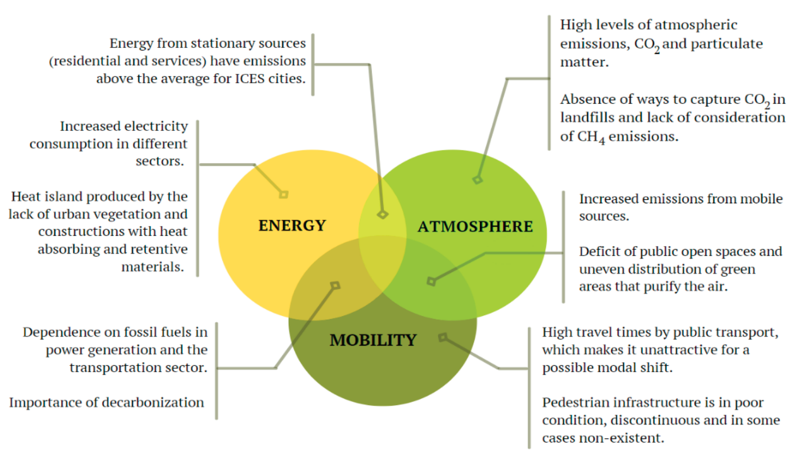


Figure 2. Categorization of the identified problems as a priority. Own elaboration.

According to these problems, some of the challenges defined to start searching in nature include the following:

- Reducing the energy loss for air conditioning of spaces and increasing cooling efficiency by dissipating excess heat. This leads to identifying "heat regulation" as a challenge.
- Finding better ways to "produce energy" without generating emissions, focusing on organisms in nature that take advantage of solar radiation.
- Determine how nature performs its atmospheric decontamination; how it traps particles or reduces carbon in the air. Thus, this challenge will focus on purification and filtration.

- Exploring alternatives to the motorized mobility for reducing its emissions, focusing on the strategies of nature's organisms to "transport" themselves while foraging and communicating with each other.

2.3. Biomimicry Abstraction: Search for Biological Analogies

Since the most affected sectors were identified (Table 1) as the ones related to the GHG emissions, along with the challenges involved, the search for biological analogies is now performed to accomplish successful biomimicry abstraction. For this, the main problem of reducing such GHG emissions was examined from the point of view of three main elements: energy, mobility, and atmosphere. These will be the themes to be followed during the search for biomimetic solutions. For each topic, a study of the most essential processes that nature performs on its own is presented.

A method of exploration based on the one presented by [20] known as "BioGen" was included in this paper. Developing a biomimetic design solution, required executing multiple stages, such as the following:

1. To elaborate and analyze the pinnacle's strategies and principles.
2. Analyzing, classifying, and abstracting those strategies.
3. To combine the different strategies options and seek to integrate them to make a preliminary design concept.
4. To evaluate and verify solutions in that design.

The pinnacle search required classifying the different strategies used by living organisms. This was possible by a comprehensive biological literature review. Some of the sources used were Ask Nature, Biomimicry 3.8, and expert knowledge from different sectors.

Figure 3 presents the exploration model intended to be covered. The three elements or approaches (energy, atmosphere, and mobility) were segregated into four levels of exploration. These levels are the function level (the challenges to be explored, what they need to do), mechanism level (how they handle the identified function), factor level (they affect the distinguished processes or are ways of performing that mechanism), and finally, the pinnacle level, representing the example of nature that complies with the previous levels for that function.

For selecting essential pinnacles, first, the main forms of energy production were considered, by selecting those pinnacles that perform processes using the sun and water, which could be replicated in cities, taking plants and *Fenestraria aurantiaca* as examples.

In thermal regulation, pinnacles that could reduce the environment's temperature, either by evaporation or convection, were extracted, e.g., how the elephant's skin works with evaporative cooling and the termite mound's natural ventilation. Finally, analogies were sought in nature that minimizes solar irradiation, with a particular focus on shading; hence, the role of trees and the orientation of the flower *Strelitzia*, were considered.

In filtering, attention was paid to examples from nature with surfaces where particles adhere, as does the *Saintpaulia*. This was taken as a priority rather than other features mentioned in the model, such as the aspect "shape".

Purification was more linked to the sequestration of CO_2, VOCs, and other harmful substances, where the biological analogy of microalgae was selected to add to the design's features. In addition, the use of trees as natural air purifiers was considered because of the amount of pollutants they absorb, while also providing shade for the heat regulation function.

Finally, strategies focused on route optimization were chosen in the transportation challenges, such as ant colonies and the *Physarum polycephalum* mold. Table 3 shows the strategies carried out by each selected pinnacle for this model.

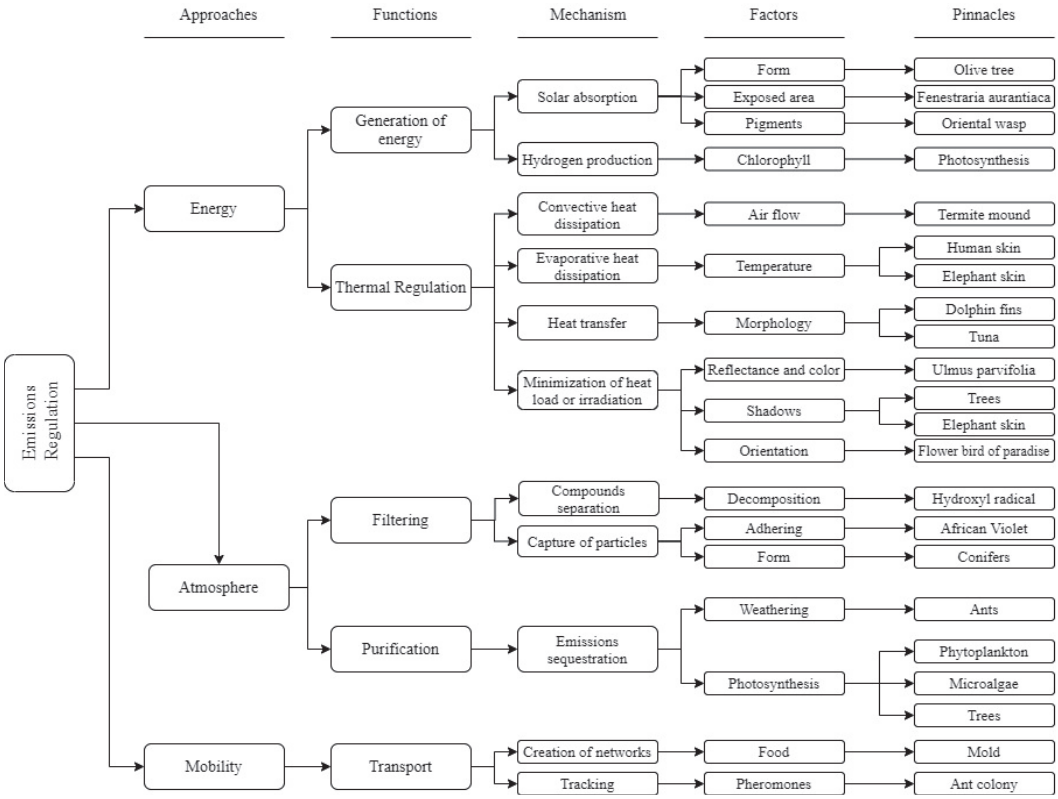


Figure 3. Exploration model for energy, atmosphere, and mobility approaches. Own elaboration.

To reduce the search and complexity of the different pinnacles, an imaginary pinnacle is evaluated for each category analyzed. The "X" symbols will denote the corresponding characteristic for each pinnacle according to the category analyzed. Then, the imaginary pinnacle will acquire the most dominant characteristic in every category, which is repeated in two or more pinnacles. If there are no coincidences, all features will be inherited by the imaginary pinnacle.

The analysis matrix of the pinnacles selected for the energy approach is presented in Figure 4. The relevant characteristics for power generation and heat regulation are highlighted in the yellow and red box, respectively, representing the imaginary pinnacle for each challenge to be analyzed.

Table 3. Strategies carried out by the selected pinnacles. Own elaboration.

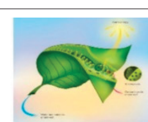
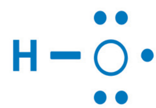
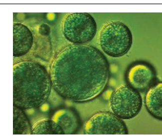
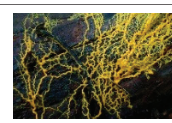
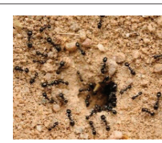
Fenestraria aurantiaca	It can collect, filter and distribute light to photosynthetically active cells on the side of its body walls.		[21]
Photosyn-thesis	Plants use the chlorophyll pigment to absorb solar energy and donate electrons in the photosynthetic process, and to replace these electrons; they split the water molecule into hydrogen protons.		[22]

Table 3. *Cont.*

Termite mound	In their mounds, they implement the variation of wall thickness, the orientation of protruding structures and the application of an efficient design with air ducts that are close to the surface.		[23]
Elephant skin	The network of wrinkles on the surface of an elephant's skin improves its thermoregulation by retaining water in the crevices along the skin.		[24]
Trees and plants	Block sunlight and increase the surrounding humidity, resulting in a decrease in temperature, depending on characteristics, such as density, the thickness of foliage, leaf texture and clarity of color. Modulate the microclimate and sequester toxic compounds.		[25]
Strelitzia	It can contain elastic energy when an external force is applied to it, obtaining a reversible and repetitive mechanism, which can cover the sun from various angles.		[26]
Hydroxyl radical	Controls the exposure time of certain organic compounds. It decomposes into water and oxygen and leaves no residual oxidants after biochemical reactions. Eliminates 99.9% of pathogenic microorganisms, destroys pollutant gases and reduces suspended particulate matter and COVs.		[27]
Saintpaulia	This plant has leaves that contain trichomes (tiny hairs) on their surface, thus trapping particles that can adhere to the leaf surface.		[28]
Microalgae	It can capture light and use its energy to absorb CO_2 and other inorganic nutrients into its biomass. As a result of photosynthesis, they produce oxygen. In addition, they possess the ability to produce sugars for their structure and plant oils.		[29]
Physarum polyce-phalum	It can self-organize, spread out and form extensive and very efficient networks to find food sources. Moreover, it covers the shortest possible distances, making the best use of resources.		[30]
Ants colony	When they find a food source, they return to their nest, leaving behind a small amount of pheromone along the way. When other ants find this compound, they follow the trail. If they find food, they will reinforce the trail with more pheromones until they return to the colony. Therefore, there will be positive feedback that leads all ants to follow a single path.		[31]

		Process					Flow		Adaptation			Scale				Environmental context					Morphological features					Other features				
Challenge	**Pinnacle**	Convection enhancement	Evaporation enhancement	Irradiation minimization	Radiation absorption	Hydrogen production	Active	Passive	Morphological	Physiological	Behavior	Nano	Micro	Meso	Macro	Arid	Tropical	Moderate	Continental	Polar	Conduits	Pigments	Porosity	Texture	Elasticity	Reflective	Reduce exposure area	Shadows	Water usage	One-way flow
Energy generation	**Fenestraria aurantiaca**				X		X			X				X		X						X		X			X		X	
	Plant photosynthesis					X	X			X			X			X	X	X	X			X							X	
	Imaginary pinnacle				X	X	X			X			X	X		X	X					X							X	
Heat regulation	**Termite mound**	X						X	X					X		X	X				X		X							X
	Elephant skin		X				X	X	X					X		X								X			X	X		
	Trees			X				X	X					X	X	X	X	X	X			X		X		X		X	X	
	Bird of Paradise plant			X				X	X					X			X	X							X				X	
	Imaginary pinnacle			X				X	X					X		X	X	X						X				X	X	

Figure 4. Pinnacle analysis matrix for the energy approach. Own elaboration.

The analysis matrix for the atmosphere approach and the selected pinnacles are presented in Figure 5. Features relevant to filtration and purification are highlighted in the purple and blue box, respectively, representing the imaginary pinnacle of each challenge.

		Process			Flow		Adaptation			Scale				Environmental Context					Morphological features				Other features				
Challenge	**Pinnacle**	Emissions sequestration	Chemical compound separatio	particle capture	Active	Passive	Morphological	Physiological	Behavior	Nano	Micro	Meso	Macro	Arid	Tropical	Moderate	Continental	Polar	Branches	Pigments	Adherent surface	Oxidant	Reactive	Decompose VOCs	Decomposing CO2	Produce O2	Shadows
Filter	**Hydroxyl radical**		X		X	X			X	X				X	X	X	X	X				X	X	X	X		
	Saintpaulia			X		X	X					X			X	X			X	X	X				X	X	
	Imaginary pinnacle		X	X		X	X		X	X		X			X	X			X	X	X				X		
Purify	**Microalgae**	X			X			X				X			X	X	X			X				X	X	X	
	Trees	X		X	X			X				X	X	X	X	X	X		X	X				X	X	X	X
	Imaginary pinnacle	X			X			X				X		X	X	X	X			X				X	X	X	

Figure 5. Pinnacle analysis matrix for the atmosphere approach. Own elaboration.

Finally, Figure 6 shows the analysis matrix with the pinnacles selected for the mobility approach. The relevant function for this challenge was transport, in grey. In this analysis, the chosen pinnacles had behavioral adaptations, and both required constant feedback, allowing them to find optimal routes in their search for food.

2.4. Characteristics of the Pinnacles

According to the three design-pathway matrices, they indicated several dominant properties within the different categories relevant to the design concept, these are:

Passive flow predominated in heat regulation and filtration; however, active flow persisted in purification, generation, and transport.

The influence of morphological adaptation was observed in all heat regulation and particle capture processes, while physiological adaptation was more prevalent in energy generation and purification. Finally, for both mobility functions, behavior predominated.

Challenge	Pinnacle	**Process**		**Flow**		**Adaptation**			**Scale**				**Environmental Context**				**Morphological features**			**Other features**				
		Creation of networks	Track	Active	Passive	Morphological	Physiological	Behavior	Nano	Micro	Meso	Macro	Arid	Tropical	Moderate	Continental	Branches / Routes	Efficient arrangement	Connections	Pheromone release	Feedback	Food search	Fast growth	Route optimization
Transport	**Physarum polycephalum**	X		X		X		X			X			X	X	X	X	X	X		X	X	X	X
	Ants colony		X	X				X			X		X	X	X	X	X	X		X	X	X		X
	Imaginary pinnacle	X	X	X				X			X			X	X	X	X	X			X	X		X

Figure 6. Pinnacle analysis matrix for the mobility approach. Own elaboration.

The mesoscale is considered relevant in all the functions presented. However, the environmental context was precise: tropical for each function, and arid, or moderate only in certain processes. Therefore, pinnacles that share the same climate as Panama were considered more relevant.

The morphological characteristics most present in the pinnacles were pigments for energy generation, filtration, and purification, texture, heat regulation, and ramifications in transport. Other characteristics to be considered in the bio-inspired solutions are:

- Solar utilization for energy generation.
- Reduction of the exposed surface and use of shading for heat regulation.
- Reflectance to minimize irradiation.
- Improving adhesion for filtration.
- Compound decomposition and sequestration of CO_2, VOCs and O_2 production.
- Feedback and pathways in the design for mobility.

2.5. Solutions Based on Nature

In accordance with the most dominant characteristics of the biomimetic abstraction, it is proposed that certain strategies influenced by nature get adopted in Panama City, taking into consideration ideas from the biomimetic model, such as:

- Shading: use of trees, roofs, and louvers.
- Pigments: trees, microalgae, and plants on green roofs and/or walls.
- CO_2 reduction: filters, vegetation, green hydrogen.
- Solar utilization: photovoltaic panels and solar sheets.
- Routes or branches: sidewalks and green corridors.
- Morphology: applied to buildings, louvers, and sidewalks.
- Passive behavior: found in buildings, roofs, bus stops, and sidewalks.
- Dynamic behavior: found in green roofs, green corridors, microalgae filters, emissions sequestration, non-motorized mobility, and electric mobility.

The dominant characteristics presented from the selected pinnacles will be part of a proposal for regenerative solutions in Panama City. Table 4 presents a description of these proposals and their successful applications.

Table 4. Summary of proposed solutions for the implementation of cities. Own elaboration.

Solution	Description	Application in Other Parts of the World	Ref.
Solar roofs	It consists of photovoltaic solar energy as a primary or secondary source for buildings. The aim is to adapt the roofs of residential, commercial, and industrial buildings to house solar panels or collectors in 20–30% of the available space.	In countries like Vietnam, rooftop solar is booming. Despite the COVID-19 pandemic, Vietnam saw rooftop solar installations increase from having 378 MW in 2019 to 9583 GW, or a 2.43% increase from 2019. It now exceeds 100,000 systems in total.	[32]
Panels at bus stops and pedestrian walkways	Solar panels on bus stops as a reduction to the public grid energy system. The use of solar panels on pedestrian walkways in educational centers, government offices, shopping malls, parking lots, or public spaces, in general, is also being pursued.	They've been used as clean energy initiatives in China, Brazil, USA, India and more. For example, the Indian Institute of Technology, Kharagpur developed a successful 70m stretch of a pedestrian walkway with solar panels.	[33]
Solar sheets	Use of solar sheets, this innovation consists of triple laminated amorphous silicon glass. It can be used in those buildings that do not have enough space on the rooftops to install photovoltaic systems.	An implementation of solar sheets is seen in The Instituto Canario Superior de Estudios in Las Palmas de Gran Canaria, Spain. This building has a system of solar sheets on its façade, which function as windows.	[34]
Flectofin blinds	Adaptation of blinds in buildings, based on nature (bird of paradise flower). It works without hinges and with 90° displacements. It performs adaptive shading, efficiently covering buildings from solar radiation.	A Thematic Pavilion, which had been exhibited at Expo 2012 in Yeosu, Korea, was a kinematic façade that Soma architects designed. Individual kinematic fines have been applied in the façade for controlling daylight conditions.	[35]
Trees	Considers the use of trees and shrubs to improve the microclimate of urban areas through trees with dense foliage and light green, thick, rough leaves. In addition, by having a cool temperature, they will provide greater comfort while protecting from direct solar radiation.	In Taipei, Taiwan, the effects of twelve tree species were studied in subtropical urban areas. The most effective were *Ulmus parvifolia*, *Pterocarpu indicus* and *Ficus microcarpa*. In addition, the importance of leaf color, foliage density, leaf thickness and leaf surface roughness were concluded.	[36]
Sierpinski ceiling	The roof uses biomimicry to emulate the leaves of trees. The roof was made of fractals with a small exposure area that allows for better temperature distribution on the surface, thus obtaining lower temperatures. It is proposed for use in places, such as terraces, arbors, social or recreational areas, among others.	The National Museum of Emerging Science and Innovation (Miraikan) in Tokyo, Japan, built a fractal roof (Sierpinski forest) and compared the fractal prototype with a part of the roof made of PVC panels, concluding that the fractal surface had a much lower temperature.	[37]
Green hydrogen	The use of hydrogen as an alternative fuel in the country due to its zero-emissions benefit. In addition, it's expected to establish a hydrogen distribution hub in Panama, according to its geographical position and the opportunities brought by the Panama Canal.	Hydrogen refueling stations currently exist in countries, such as Japan, the United States and Germany. H_2 Energy Applications (in) Valley Environments (for) Northern Netherlands abbreviated HEAVENN.	[38]

Table 4. *Cont.*

Solution	Description	Application in Other Parts of the World	Ref.
Green walls and roofs	Implement green roofs/walls with native plants on buildings to cool the surrounding air through plant evapotranspiration. It converts any rooftop with more than 1300 square feet or at least 20% of the available space (for green or solar roofs) into green roofs. This would mean using natural barriers for CO_2 reduction, divided into three types of roofs: intensive, semi-intensive and extensive.	In Cordoba, Argentina, a law was enacted in 2016, making it mandatory to convert any rooftop more significant than 1300 square feet, including new or existing, into green roofs.	[39]
Purifying plants	Use of trees and plants that trap volatile organic compounds through the opening and closing of leaf pores. This will contribute to the reduction of toxic pollutants in the city's atmosphere and improve air quality.	In many places, mention is made of different species that could work as the most effective for sequestering emissions, such as VOCs, formaldehyde, benzene, carbon monoxide and trichloroethylene; these species are *Spathiphyllum*, areca palm, tiger tongue and *Chlorophytum comosum*.	[40]
Bio-filters	Implementation of microalgae-based biofilters in the busiest streets of the country, where traffic congestion levels are high and there is little space for planting large numbers of trees. Consideration is given to port areas where there are large logistical movements both at sea and land, industrial zones, etc.	There is the Biourban filter from Mexico. Its technicians assure that the models: BioUrban 2.0 and Bio Urban Industries, can supply the same amount of oxygen as 368 mature pine trees in a year, equivalent to the daily breathing of 2890 people. This filter has been incorporated in the Bus Terminal in Albrook Mall, in Panama City.	[41]
Photocatalytic cement	Composed of titanium dioxide, it is a coating used in avenues or sidewalks of public spaces and buildings with a large surface area exposed to sunlight. These can include constructing residential buildings, schools, bridges, hospitals and even monuments, especially in places with high pollution/odors.	In Milan, a 7000 m^2 road surface was built with photocatalytic cement, obtaining a 60% reduction in the concentration of nitrogen oxide (NOx) at street level.	[42]
Walk to work, walk to school, walk to park	It involves strategies to mobilize citizens to their destinations, without vehicles (more emissions), by walking to their places of work, education, leisure or socio-cultural activities. Part of this strategy focuses on distributing these places in the city center, making less distance between the pedestrian's home and its destination.	Lavasa Hill in India has a biomimetic design, which has land-use planning based on these concepts. Mobilization of residents through walking to their places of work, education, leisure or socio-cultural activities is implemented.	[43]
Sidewalks	Implementation of adequately designed and constructed roadways or sidewalks with permeable pavement and adequate space for pedestrians. Adequate and user-friendly measures, including the service strip (road signs, street lighting, street furniture, vegetation, among others).	Studies carried out on sidewalks in Cuenca, Barcelona, and Prague, consider the importance of using materials to construct sidewalks that can produce friction (cobblestones or concrete).	[44]

Table 4. *Cont.*

Solution	Description	Application in Other Parts of the World	Ref.
Green Corridors	It serves as a connection in the green areas of the urban zone, connecting different points of the metropolitan area using vegetation through its extension.	In cities, such as New York, Mexico City, Madrid, and Seoul, these corridors have been implemented along with flowers, trees, shrubs, walking paths, and bicycle lanes, thus improving the area's average temperature.	[45]
Electric Transport	It covers the use of electric vehicles, including recharging points in different country areas, i.e., those near parking lots of shopping malls, supermarkets, offices, hotels, universities, etc. It would also include discouraging internal combustion vehicles and raising awareness of decarbonization issues at the national level.	In Europe, for example, the advancement of e-mobility was foreseen with ABB, which is the main technology partner and supplier of IONITY, a joint venture between different groups, such as BMW, Ford, Volkswagen, Audi and Porsche, whose goal was to operate a network of at least 400 fast charging points in 24 European countries by 2020.	[46]
Bicycle lanes	It involves creating a network of bikeway infrastructure, which aims for its realization in the city's main roads and green areas. Its purpose is to serve as a connecting node to the rest of the city, which would increase the efficiency of mobility in the urban area in a sustainable and emission-free manner.	The countries with the most extended distances covered by cycling have been studied, determining this activity as the main form of urban mobility. It was concluded that the countries with the longest distances (600 km to 900 km) are: Netherlands, Denmark, and Belgium. Furthermore, in Germany, between 1994 and 2017, distance cycled per capita increased by over 150 km, consistent with an increase of over 50%.	[47]
Routing algorithm	Use of algorithms based on nature, focused on minimum use of resources and high efficiency, resulting helpful in the creation of future networks of the Panama Metro, by optimizing the city's roads. Its use is considered in those logistic services existing in Panama City.	In the cities of La Paz and El Alto in Bolivia, modeling work was carried out for the combinatorial optimization of transportation flow patterns by applying the ant colony algorithm and Dijkstra's algorithm (minimum paths algorithm).	[48]

3. Results Analysis

Regenerative urbanization seeks to develop a built environment that coexists with ecosystems and enhances their health instead of diminishing it. However, ecosystems' services to society are currently not adequately protected because of cities' poor regulation, solutions, and policies. Therefore, urbanization must contribute more than it consumes to ecosystems, while also remedying past and current actions in terms of environmental damage. This would allow moving towards truly regenerative efforts.

Since it is greatly difficult to replace all buildings and infrastructure for regenerative development, even with retrofitting techniques, an alternative would be to provide ecosystem services in humanity's own way, to reduce the existing pressure on local ecosystems [49].

In the previous section, different sustainable alternatives based on nature were discussed to contribute to Panama City's capacity to be regenerative. As a result, it is possible to respond to the problems arising from poor sustainable management and, in general, to the impacts of climate change, through biomimetic solutions and the so-called ecosystem services analysis (ESA). Figure 7 presents the trajectory of a roadmap proposal for regeneration in cities.

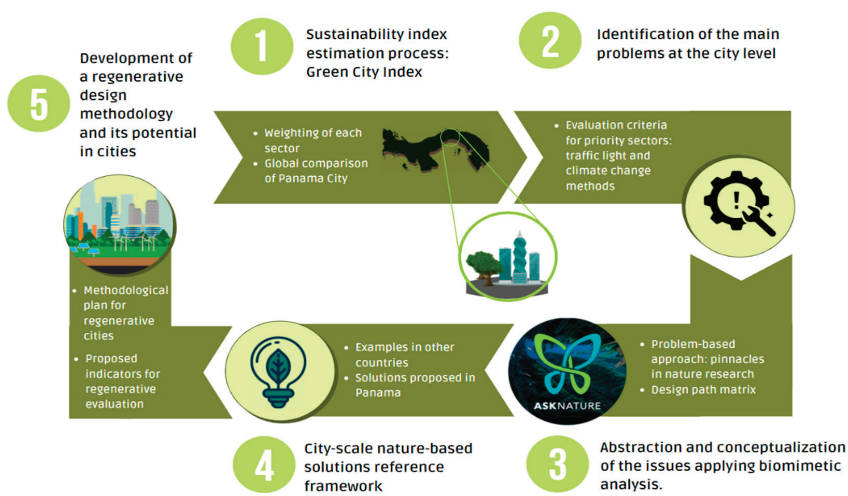


Figure 7. Roadmap for the development of a methodology towards regenerative cities. Own elaboration.

Ecosystem services analysis can work as a starting point for the creation of a regenerative design that is measurable. This is vital to establish the credibility of regeneration in urban design [49]. As a strategy to measure the sustainability of urban regeneration and ensure the principles of sustainable development, a set of indicators will be employed, which focus on the ecosystem services described above. These indicators are described and evaluated in Table 5.

These indicators could be considered for the objectives and targets established in the last Nationally Determined Contribution (CDN1) of Panama, for a circular economy, energy, resilient human settlements, sustainable infrastructure, forests, and biodiversity.

Table 5. Summary of methodological sheets of indicators based on Ecosystem Services Analysis. Own elaboration.

Indicator Name	Brief Description	Input Variables and Their Respective Unit	Indicator Calculation Formula	Indicator Evaluation (IR):	Data Source
Habitat provision	It shows the calculation of the number of existing trees in the land area of the townships of Bella Vista, Betania, Calidonia, San Felipe, San Francisco and Santa Ana.	-Number of tree units (NUA): Unit -Total territorial surface (STT): km^2 -Habitat Provision Indicator (IPH): Trees/km^2	$IPH = \frac{NUA}{STT}$	NUA = 22,334 trees STT = 12.3 km^2 IPH = 1815.77 trees/km^2	Municipality of Panama and National Institute of Statistics and Census [50].
Nutrient cycling	It shows the ratio of tons of recycled garbage (BR) to waste disposed of in landfills (BT) for the capital city.	-Recycled waste (BR): tons per year (ton/year) -Total waste disposed of (BT): tons per year (ton/year) -Recycling indicator (IR): Percent (%)	$IR = \frac{BR}{BT} \times 100$	BR= 11,700 ton/year BT= 583,576.60 ton/year IR = 2.00%	Urban and Household Cleaning Authority of Panama [51]
Climate regulation	Measurement of the amount of emissions absorbed (TCO_2e) by hectares of forest without change of use (HB) of the metropolitan area under study.	-Hectares of forested area in the study site (HB): hectare -Tons of CO_2e absorbed per year (CO_2e): tCO_2e/year -Emission absorption indicator (Iabs): tons CO_2e/hectare-year	$Iabs = \frac{tCO_2e}{HB}$	CO_2e = 948,863 tCO_2e/year HB = 178,850 ha Iabs= 5.31 tCO_2e/hectare	IDOM, Municipality of Panama [52].
Purification of air	Measuring the amount of green areas in the city of Panama (AV) over the total urban area (STU) excludes forests, mangroves, bodies of water, and agricultural land.	-Hectares of green areas in the city (AV): hectare -Total hectares of the urban area (STU): hectare -Air purification indicator (IP): Percent (%)	$IP = \frac{AV}{STU+AV} \times 100$	AV = 360.60 ha STU = 36,928 ha IP = 0.97%	Panama City Hall, IDOM [53].
Provision of freshwater	It shows the amount of rainwater used in buildings in residential areas, economic centers, shopping centers, and other urbanizations.	-Precipitation in Panama City per year (PCP): L/m^2 -Hectares of residential and non-residential areas (AT): hectare -Indicator of rainwater volume per year in the study area (VT): L/year	$VT = PCP \times AT$	PCP = 1850.20 L/m^2 AT =271,584,000 m^2 VT = 517,965 millions of liters	Regional Water Resources Committee, Panama City Hall, IDOM [52,54].
Provision of energy	Shows the calculation of the amount of renewable energy consumed compared to the total energy consumed in the province of Panama.	-Renewable energy consumed in the province of Panama (ERC): MWh -Total energy consumed in the province of Panama (ETC): MWh -Renewable Energy Indicator (IER): Percent(%)	$IER = \frac{ERC}{ETC} \times 100$	ERC = 391,381.8 MWh ETC = 3,266,682.7 MWh IER = 11.98%	National Public Utilities Authority (ASEP) [55,56].

4. Discussion

The distribution of the urban footprint, which began to increase with the construction of the Panama Canal, may have affected the city's position today. Considering other factors that were part of the urban growth, some studies point to the real estate explosion as an important cause, which began in the central banking and financial area of the city (Bella Vista and San Francisco); however, it has been moving to the north and east of the capital city [57]. The existence of multiple, poorly structured zonings in the city, where different land uses are dispersed, is part of the problem. This results in poor connections between areas with only a complicated network of roads, dense streets, deteriorated highways, and unfinished train lines, which increases the travel time of the inhabitants. This is due to the poor distribution of residential areas and economically unbalanced neighborhoods lacking basic services. Some authors and urban planners in [58] define Panama City with the words "half a city", "a divided city" or "two realities".

According to INEC data, in the 2010 census, 42% of households in the metropolitan area had a car. However, there were no initiatives to prioritize pedestrians until 2014, when the mayor's office started interventions for public space. Three restructured projects stand out and serve as an example: Via España, Via Argentina and Calle Uruguay [58]. Because of these and other problems, tools like the Green City Index [19] could estimate a starting point for describing the primary needs in terms of sustainability in cities and urbanizations. These needs can be adapted into biomimicry's different strategies, to seek better solutions, as has been seen in the literature. Furthermore, nature's opportunities for urban development offer an efficient way for human advancement in sustainability.

4.1. Evaluation of Proposed Approaches via SWOT Analysis

In Section 2, different solutions based on nature were proposed, however, it is not possible to know the suitability of such solutions to an urban and continuously developing environment, such as Panama City. For this reason, it is necessary to discuss or assess the potential for its adaptation; where strengths, weaknesses, opportunities, and threats are sought to be explored through a SWOT analysis for each approach studied.

A strength considers the resources involved in the urban area that make it possible to achieve the objectives considered in the area's social structure and physical conditions. On the other hand, a weakness focuses on the limitation that prevents the project from achieving the results or objectives in the urban environment. This analysis discusses the initiatives for the energy, air quality, and mobility sectors in Table 6, Table 7, and Table 8, respectively.

4.2. Experts Survey for the Evaluation of Regenerative Proposals

As a more exhaustive demonstration of the possibility of adapting the solutions presented for Panama City, a questionnaire was conducted among researchers and experts in different fields involved in the technological and sustainable development of cities. This could be done in collaboration with professionals in energy, environment, architecture, urbanism, among others.

4.2.1. Information Regarding the Participants

In August (2021), the survey was open for responses, and 13 participants gave their opinions through a set of evaluations. It was completed with a relative majority of participants who worked in the public sector, with 69.2% of respondents; the rest, 30.8%, belonged to the independent sector and none to the private sector. The work experience was distributed as follows: 30.8% for more than 20 years, 30.8% for both 10 to 20 years and less than 5 years, and at last, 7.7% for 5 to 10 years.

In addition, as a basis for their knowledge in biomimicry and regeneration, they were asked about their level of understanding, with 61.5% describing themselves as having low knowledge of biomimicry, 23.1% of medium, and only 15.4% having a high level. In the case of regeneration, almost half of them had a medium understanding with 46.2%, 23.1% had insufficient knowledge, 15.4% of them agreed to have high knowledge, 7.7% had a very high understanding, and just 7.7% had very low knowledge. When asked about what topic they considered to have more knowledge in, 76.9% answered in Environment, 23.1% chose Clean Energies, and only 7.7% said Urbanism and Mobility.

Table 6. SWOT analysis for energy initiatives.

SWOT Analysis	Strengths	Weaknesses
Internal	**Solar panels:** No emissions. It makes use of the available space in buildings, residences, etc. The sun is a usable and unlimited source of energy. **Panels with microalgae:** Uses the sun and CO_2 to produce biomass. Microalgae purify the air at a higher rate than trees [59]. **Renewable hydrogen:** Emission-free consumption and high calorific value, can be mixed with other gases, serves as electricity storage (green hydrogen). It can be obtained in different forms (blue, gray and green). **Sierpinski roof:** It allows a better temperature distribution on the surface due to its fractals with a small exposure area; lower temperatures are obtained [37]. **Flectofin louvers:** Operates without hinges and with 90° displacements. It performs an adaptive shading, efficiently covering the buildings. **Green facades:** It represents a natural barrier for the buildings against solar radiation and with the evapotranspiration of the leaves the surrounding temperature is reduced.	**Solar panels:** Requires an initial investment, needs direct solar radiation and no permanent shade. They occupy considerable space. **Panels with microalgae:** Requires solar radiation and equipment suitable for transforming it into electricity [59]. **Renewable hydrogen:** Probability of leakage, volatile, needs a lot of logistical and storage care. Green requires high renewable energy generation and is expensive to produce (electrolysis).Sierpinski roof: Partially transmits sunlight [37]. **Flectofin blinds:** They do not have automatic control, so they would have to be adapted. **Green facades:** Depending on the type of green roof, it can generate a lot of extra weight. Some types of green roofs or walls require maintenance, watering, and pruning.
	Opportunities	**Threats**
External	**Solar panels:** This would increase the distributed generation market in the region, contributing to the decarbonization of the energy matrix. Energy is in trend, so the cost decreases over time, making it more feasible. Therefore, energy savings are obtained. **Microalgae panels:** Can use the remaining biomass from the process to generate biogas. **Renewable hydrogen:** Growing global market, Panama's advantageous position in distribution. **Sierpinski roof:** Can be adapted to limited sites for planting trees, including terraces, pergolas, social or recreational areas, among others. **Flectofin blinds:** Studies and prototypes based on biomimicry are growing globally. **Green facades:** Diminish the heat island effect in the urban environment and purify the air. They can reduce rainwater reaching the street level and its flooding.	**Solar panels:** Buildings and trees generate shadows. Low performance in rainy or cloudy weather. **Renewable hydrogen:** There is no gas distribution network in the country. Lack of sufficient demand in industries. **Microalgae panels:** Shadows may be cast by buildings adjacent to the installation. Technology under development. **Sierpinski roof:** There is no record of its application in Panama. Designers and citizens do not know it. **Flectofin blinds:** There is competition in the local market, where biomimicry is unimportant for users. **Green facades:** Poor selection or maintenance of the species can lead to a deterioration of the roof or wall, in addition to dangers due to biological diseases and the climate present in the site.

Table 7. SWOT analysis for the proposed air quality initiatives.

SWOTAnalysis	Strengths	Weaknesses
Internal	**Trees:** Minimize air and noise pollution, sequester harmful compounds for living beings. **Green facades:** Filter pollutants and heavy metals from rainwater, grow fruits, flowers, or vegetables, atmospheric filter pollutants, such as CO_2 and act as an acoustic barrier. **Biourban microalgae filter:** They can sequester up to 2 tons of CO_2 per year and pollutants, such as CO and NOx. Their oxygen generation capacity is equivalent to that of hundreds of trees [60]. **Photocatalytic concrete:** Use of photons to neutralize organic and inorganic pollutants. It makes surfaces self-cleaning. Savings in maintenance costs due to their durable nature [42].	**Trees:** They require maintenance and inventory of their phytosanitary status. In addition, some have to rot in the heart of the tree trunk [61]. **Biourban microalgae filter:** The indoor model requires an investment due to its energy consumption. All models require maintenance every 3 to 6 months [60]. **Photocatalytic concrete:** For best performance, surfaces should preferably be exposed to direct sunlight [42].
	Opportunities	**Threats**
External	**Trees:** Plans have been presented that address their implementation in the city. There is a growing awareness among the population about tree planting and its benefits [61]. **Biourban microalgae filter:** There are various models for different sites, such as industrial, indoor, outdoor and ashtrays. They can be installed on the main roads most susceptible to vehicular congestion in the city. Other places to be considered are port areas, logistics centers and industrial areas [60]. **Photocatalytic concrete:** The construction sector can adapt these technologies to trends, such as bridges, office or residential buildings, hospitals, monuments, schools and drainage structures [42].	**Trees:** They can affect road infrastructure, power lines, buildings, and their roots can cause sidewalks or walls to rise. Lack of trees in some regions of the city [61]. **Biourban microalgae filter:** In indoor locations, it is necessary to consider the space required due to their size. In addition, they can weigh from 120 kg to 1 ton [60]. **Photocatalytic concrete:** There are several products for conventional concrete that are manufactured locally. Cement plants in the region do not produce this type of cement.

Table 8. SWOT analysis for the proposed mobility initiatives.

SWOTAnalysis	Strengths	Weaknesses
Internal	**Citizen mobilization strategies (sidewalks, walk to work, routing algorithm, bicycle lanes):** Greater efficiency in terms of citizen mobility. Properly constructed sidewalks promote walking and improve connectivity. Walking and bicycling will increase people's physical fitness. They consider the frequency of use and the space needed for different people, including those with reduced mobility, blind people, etc. They provide safe walking with their materials and add permeability to the routes [43]. **Green corridors:** Increase biodiversity, connect, and give continuity to green spaces. Can serve as a site for recreation and leisure, as they facilitate walking and cycling through bicycle paths. It reduces air pollution in cities [62]. **E-mobility:** Generates zero emissions, has lower noise levels, low maintenance due to fewer mechanical parts, and is lighter. The energy efficiency of the engine is higher than that of conventional combustion engines [63].	**Citizen mobilization strategies (sidewalks, walk to work, route algorithms, bicycle lanes):** The user prioritizes his comfort due to the city's changing weather, which prevents him from transitioning from his vehicle to walking.Not all people have the condition and motor capacity for long walks or frequent use of bicycles. The latter requires good care and maintenance [43]. **Green corridors:** Constant maintenance, pruning, fertilization, and irrigation are needed to strengthen the ecosystems where insects, mammals, and birds have arrived. Diseases can appear in selected tree species. **E-mobility:** Electric car technology is more expensive than a combustion engine car. Its autonomy is limited, serving only to move around the city and its surroundings. In addition, it requires a recharging point in the garage, where recharging can be slower [63].
	Opportunities	**Threats**
External	**Citizen mobilization strategies (sidewalks, walk to work, route algorithms, bicycle lanes):** They reduce the use of vehicles and optimize routes, i.e., they will contribute to fewer traffic jams, which will result in fewer polluting emissions. Permeable sidewalks minimize the frequency of flooding. Better sidewalks can accommodate more space for street furniture (stops, benches, trash cans) or necessary vegetation. Walking or bicycling would save on fuel use and encourage people to become aware of their emissions. Bicycles are trending worldwide, and cyclists are less likely to suffer from cardiovascular diseases [43]. **Green corridors:** They would allow an improvement of the urban synergy between nature and society. It can be used as a strategy to avoid heat island effects in small cities. It would take less time to walk between city squares and parks, thanks to the comfort it provides to pedestrians [62]. **E-mobility:** Panama is in the process of transition through the 2020–2030 energy plan. If implemented, incentives for the technology could increase in the trend, resulting in a considerable decrease in emissions [63].	**Citizen mobilization strategies (sidewalks, walk to work, routing algorithms, bicycle lanes):** The design of the city structure still represents a challenge to implement more efficient routes in the metropolitan area. It's not feasible to apply some or all of the strategies in certain parts of the city due to its distribution's lack of initial planning. Priority is given to vehicular space, limiting the pedestrian area. Weather is an aspect that can influence walking and cycling strategies. Sidewalks' condition (low friction/raised sidewalks) can result in pedestrian injuries, reduced walking performance, or accidents. Bicycling has a risk in cities with few bicycle lanes and a high flow of vehicles. Accidents can occur due to a lack of protective equipment, signaling, or irresponsible drivers [43]. **Green corridors:** It is challenging to implement green spaces due to the complexity of the original design of Panama City, where priority is given to vehicular spaces [62]. **E-mobility:** Public charging infrastructure is very low-Lack of current government incentives and trained technical professionals in the country. Due to its manufacture and the electricity consumption from conventional energy sources [63].

4.2.2. Rating Questions and Answers

Local experts were asked which sectors they considered to be priorities for sustainable development in Panama City with the options of 1 (low importance), 3 (neutral), and 5 (high importance). A total of 61.54% considered the waste sector as high importance, making it the most relevant. For the energy and CO_2 emissions, 53.85% rated it as high importance, and the same happened for land use/buildings, water and sanitation, and transportation sectors. On the other hand, for air quality, only 23.08% considered this sector to be of high importance, 38.46% between very important and neutral, and 38.46% recognized it to be neutral.

Participants were also asked what aspects they considered the most relevant for developing a sustainable city. Their responses pointed to a greater appreciation for the integration of nature and the application of waste reduction measures, both of which were approved by 76.9% of the participants surveyed. This was followed by implementing clean energy with 69.2% and sustainable mobility where the participants indicated their approval with 61.5%. Furthermore, 46.2% valued compact urbanization, while 30.8% valued adequate care of air quality. Finally, a total of 23.1% considered the preservation of public spaces.

To obtain the experts' opinions for the evaluation of proposed solutions, it was explained what the initiatives consisted of. Then they were asked how they would rate the feasibility of those solutions on a scale from 1 to 5, where 5 denoted high likelihood, 3 meant medium likelihood, and 1 indicated low likelihood.

The results revealed that out of the 17 actions assessed by the respondents, nine of them were considered to have an average value of 4 and upon the scale presented, i.e., close to a high possibility of implementation. The solution that had the highest score for its positive application in cities was the adaptation of trees and plants for arborization. In the case of the remaining eight solutions, they all obtained an average value between 3 (medium) and 4, denoting a medium-high possibility of implementation. No solution had a value lower than 3.31, belonging to the Sierpinski ceiling. These results can be further seen in Table 9, along with the rank occupied by each solution, where rank 1 represents the best-voted option for adaptation, and the value 12 is the least voted one.

As an assessment of the limitations involved in applying these solutions, the respondents were asked which ones they considered as challenges and which ones as risks. Some of the limitations included the difficulties in technology and natural solutions, their implementation, maintenance, possible effects, and their adaptability in Panama City with the current policies. In total, it was found that from the 28 constraints, the participants voted 211 times for the challenge section with 59.94% of the total; on the other hand, the option of possible risk was selected 103 times, covering 29.26% of the constraints; at last, 10.80% of these were not considered a limitation or were not as relevant. Table 10 summarizes the results for this question, with the number of votes for each option.

As part of the research, respondents were asked what factors they considered that applied to Panama City. The most voted were the delay in government decision-making and resistance to change in the adoption of new practices, both with 92.30%. This was followed by the lack of government support and knowledge of sustainable planning practices with 84.60%. Figure 8 shows the results obtained:

Table 9. Feasibility of nature-based solutions for Panama City: expert opinion. Own elaboration.

Solutions	5	4	3	2	1	Possibility Score (1–5)	Rk (Rank)
Solar roofs	53.85%	23.08%	7.69%	15.38%	0.00%	4.15	4
Panels at bus stops/pedestrian walkways	38.46%	23.08%	15.38%	23.08%	7.69%	3.85	7
Solar sheets	23.08%	46.15%	15.38%	15.38%	0.00%	3.77	8
Flectofin blinds	7.69%	30.77%	53.85%	7.69%	0.00%	3.38	11
Trees	69.23%	23.08%	7.69%	0.00%	0.00%	4.62	2
Sierpinski ceiling	23.08%	23.08%	30.77%	15.38%	0.00%	3.31	12
Renewable hydrogen	30.77%	23.08%	7.69%	38.46%	0.00%	3.46	10
Green walls and roofs	38.46%	46.15%	15.38%	0.00%	0.00%	4.23	3
Purifying plants	76.92%	23.08%	0.00%	0.00%	0.00%	4.77	1
Biofilters	23.08%	53.85%	23.08%	0.00%	0.00%	4.00	6
Photocatalytic cement	23.08%	23.08%	38.46%	7.69%	7.69%	3.46	10
Walk to work, walk to school, walk to the park	30.77%	15.38%	30.77%	15.38%	7.69%	3.46	10
Sidewalks	46.15%	23.08%	23.08%	7.69%	0.00%	4.08	5
Green corridors	30.77%	46.15%	23.08%	0.00%	0.00%	4.08	5
Electric transport	46.15%	38.46%	7.69%	7.69%	0.00%	4.23	3
Bicycle lanes	38.46%	46.15%	7.69%	7.69%	0.00%	4.15	4
Routing algorithm	23.08%	46.15%	15.38%	7.69%	0.00%	3.62	9

Table 10. Limitations of the nature-based solutions for Panama City. Own elaboration.

Limitations	Challenge	Risk	None
Low panel performance on rainy or shaded days.	4	7	1
Solar panels require a high initial investment.	7	3	3
Microalgae panels require equipment suitable for biomass-to-electricity conversion.	7	4	1
Renewable H_2 production is very costly (electrolysis).	6	6	0
Hydrogen is volatile and has a high probability of leakage.	2	10	0
There is no gas distribution network in the country.	10	2	0
In the application of a Sierpinski roof and/or Flectofin louver, biomimicry is not so important yet for Panamanian users.	10	0	3
Trees require maintenance and inventory of their phytosanitary condition.	8	0	5
Trees can affect road infrastructure, power lines and cause sidewalks and walls to rise.	3	8	2
Lack of tree planting in areas of the city.	11	1	1

Table 10. *Cont.*

Limitations	Challenge	Risk	None
The Biourban filter requires an investment due to its energy consumption.	7	4	0
Filters require maintenance every 3 to 6 months.	6	5	1
Consider the space to implement the filter due to its size.	6	3	2
Photocatalytic concrete needs direct sunlight preferably.	3	4	5
Local cement plants do not produce this type of product (with titanium dioxide).	8	3	2
The user prioritizes his comfort when moving around.	7	2	3
The climate prevents the transition from using a vehicle to walking or cycling.	10	2	1
The current design of the city is inefficient.	9	4	0
Priority is given to vehicular space over pedestrian space.	10	3	0
Lack of land-use planning and urban distribution.	8	5	0
Sidewalks are in poor condition (raised, low friction).	8	5	0
The current signage of bicycle lanes, and the danger for possible accidents with cars.	7	5	1
Constant maintenance of green corridors.	11	1	1
Difficulty in implementing green spaces due to city design.	10	3	0
Technology for electric mobility is more expensive than traditional technology.	9	4	0
Limited autonomy (few electric charging points).	8	4	1
Requirement for government incentives.	10	1	2
Emissions still exist during electric charging if it comes from conventional sources.	6	4	3
Total results	211	103	38

Figure 8. Factors that apply in the Panamanian context, according to respondents. Own elaboration.

Finally, they were asked for their opinions regarding this work, and they recommended or commented on the following factors:

- The viability of the options by approach is correct when considering the barriers in the Panamanian context, such as environmental awareness, user demand for green alternatives, and governmental will and support.
- To rely on bills that consider sustainable projects, such as Executive Decree No. 205 of 28 December 2000, which considers the approval of the Urban Development Plan for the Metropolitan Areas of the Pacific and Atlantic; as well as Executive Decree No. 139 of 1 September 2000, which considers the approval of special rules to maintain the character of a garden city in the interoceanic region.
- To consider the implementation of the architectural designs used in the decade of the 1960s, where the wind direction and open designs that allowed air circulation was contemplated.
- Keep in mind that the effects of climate change are experienced disproportionately by people with lower incomes. So take actions in vulnerable areas to natural disasters, including not applying designs that benefit or improve the quality of life only for the upper class or the more affluent.

5. Conclusions

The purpose of this work is the proposal of solutions using biomimicry in the context of Panama City. Through the weighting obtained in the Green City Index, three aspects were covered: energy, air quality and mobility, for which a biomimetic abstraction was obtained with the problem-based approach. During this analysis, 11 pinnacles were identified, and 17 solutions were proposed and described. Their concepts and applications were studied through an extensive literature review.

Biomimicry of ecosystems is sustained on a design criterion that is based on sustainable and regenerative principles; therefore, the support of professionals with this knowledge is important. Accordingly, a survey for experts in the relevant sectors was conducted. The results revealed that among the 17 proposed solutions, the most supported or feasible in the experts' opinion were: arborization, green facades, solar roofs, e-mobility, green corridors, bicycle lanes, sidewalks and biofilters. In general, the concluding remarks from this paper and the final survey are following:

- Encouraging purification strategies can be achieved with the planning and use of natural adaptations: trees, green roofs/facades, green corridors and others, such as biofilters, titanium dioxide products, among others.
- Due to the heat island effect, it's necessary to optimize the comfort of the inhabitants, considering the importance of trees in regulating the temperature of the soil and surrounding air. At the same time, the opportunities for heat regulation and energy savings presented by the application of biomimetic designs in buildings are recognized.
- The use of solar energy through photovoltaic systems was considered a vital pillar towards progress in the energy transition and distributed generation.
- The population must be aware of the impact of motorized transport and emissions caused by mobile sources for a modal shift that considers sustainable transport (bicycles, walking and electric alternatives).
- With the incorporation of greener infrastructure and solutions, government initiatives will be needed to create laws that encourage local photovoltaic systems, green roofs and facades, and other solutions in buildings; as well as e-mobility laws new projects for low-density transportation (bicycles, sidewalks).
- There is a need for collaboration with several professional bodies to ensure regulations to prevent the notorious pollution from the built environment.
- To achieve a regenerative city, fundamental changes and comprehensive strategies are needed in the form of long-term policies, rather than temporary compromises, as is the case for most political decision-making schemes in the country.

For future works, it is recommended to test the different proposals through simulations or new evaluations before implementation in this case study. Although the problem-based biomimetic analysis can be extended to other challenges that encompass the unassessed systems, such as how nature uses water, the methods presented should be revised before application to other case studies due to the specific challenges and factors identified for the pinnacles analysis and selection.

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Appendix A

Table A1. Summary of the evaluation of indicators in the Green City Index. Adapted from [19].

Category	Indicator	Type	Data	Source	Weight	Standard	Calculation	Result
Energy and CO_2	CO_2 emissions from per capita electricity consumption	Quantitative	284.93 kg/person	[17]	25%	202.20 kg/average person	17.81	0.1781
	Electricity consumption per unit of GDP or per capita	Quantitative	2226 kWh/person	[64]	25%	<815 KWh/person	−43.28	0.00%
	Clean energy policy.	Qualitative	Official Gazette (Law 37 of 2013, 45 of 2004, 44 and 42 of 2011). National Energy Plan 2015–2050 2nd Biennial Report	[4,17,65,66]	25%	0–3	2.00	16.67%
	Climate Change Action Plan.	Qualitative	URRE Law National Energy Plan 2015–2050 Paris Agreement Montreal Protocol 2nd Biennial Report	[64]	25%	0–3	2.00	16.67%
Land use and Buildings	Green spaces per capita	Quantitative	8 m^2/inhabitant	[53]	25%	100 m^2/hab	2.00	2.00%
	Population density.	Quantitative	5867 hab/km^2	[53]	25%	<7000 hab/km^2	20.95	20.95%
	Green building policy.	Qualitative	Sustainable Building Guide Sustainable Building Regulations	[67]	25%	0–3	2.00	16.67%
	Land use policy.	Qualitative	National Land Management Policy National Forestry Strategy, REDD Forestry Incentives Law of 2017 Arborization Plan	[61,68]	25%	0–3	1.00	8.33%

Table A1. *Cont.*

Category	Indicator	Type	Data	Source	Weight	Standard	Calculation	Result
Transportation	Length of the public transport network.	Quantitative	0.03 km/km^2	[53]	25%	>0.3 km/km^2 <7 km/km^2	−1.01	0.00%
	Stock of cars and motorcycles.	Quantitative	0.22 vehicles/hab	[53]	25%	0.3 vehicles/hab	14.00	14.00%
	Urban public transport policy.	Qualitative	Comprehensive Sector Program Integral Urban Mobility Plan	[68]	25%	0–3	2.00	16.67%
	Congestion reduction policy.	Qualitative	Integral Plan for the Improvement of Mobility and Road Safety Panama Subway ATTT, MOP, MUPA	[69,70]	25%	0–3	1.00	8.33%
Waste	Proportion of waste collected and disposed properly.	Quantitative	92%	[53]	25%	>70%	32.86	25.00%
	Waste generated per capita.	Quantitative	456.25 kg/hab/year	[71]	25%	800 kg per person	10.74	10.74%
	Waste collection and disposal policy.	Qualitative	National Waste Management Plan 2027 Plan for Service Improvement (AAUD) Panama City Municipal Integrated Waste Management Plan	[53,72,73]	25%	0–3	2.00	16.67%
	Waste recycling and reuse policy.	Qualitative	Zero Waste Plan Cleaner Production Policy	[72]	25%	0–3	2.00	16.67%

Table A1. *Cont.*

Category	Indicator	Type	Data	Source	Weight	Standard	Calculation	Result
Water	Per capita water consumption	Quantitative	274 L/person/day	[53]	20%	Min: 60 lt/day Max: 126.9 lt/day	−43.98	0.00%
	Water leaks	Quantitative	40%	[73]	20%	<45%	17.78	17.78%
	Population with access to potable water.	Quantitative	96%	[53]	20%	>80%	24.00	20.00%
	Water quality policy.	Qualitative	National Water Security Plan 2015–2050 IDAAN Action Plan 2019–2024	[74,75]	20%	0–3	3.00	20.00%
	Water sustainability policy.	Qualitative	National Water Security Plan 2015–2050 Metropolitan Panama Action Plan IDAAN Action Plan 2019–2024 Government Strategic Plan 2020–2024	[53,74–77]	20%	0–3	2.00	13.33%
Sanitation	Population with access to improved sanitation.	Quantitative	68%	[53]	33%	93.70%	23.95	23.95%
	Proportion of wastewater treated.	Quantitative	31%	[53]	33%	Min: 10% Max: 100%	7.70	7.70%
	Sanitation policy.	Qualitative	Metropolitan Panama Action Plan Panama Sanitation Program	[53,78]	33%	0–3	3.00	33.00%

Table A1. *Cont.*

Category	Indicator	Type	Data	Source	Weight	Standard	Calculation	Result
Air quality	Nitrogen dioxide concentration levels.	Quantitative	36 μg/m^3 per day	[51]	25%	≤20 μg/Nm^3 per day	−20.00	0.00%
	Sulfur dioxide concentration levels.	Quantitative	-	-	25%	-	0.00	0.00%
	Concentration levels of suspended particulate matter.	Quantitative	49 μg/m^3 per day	[53]	25%	≤20 μg/Nm^3 per day	−24.00	0.00%
	Clean air policy.	Qualitative	Executive Decree No. 5 of 4 February 2009. Executive Decree No. 38 of 3rd June 2009. Technical Regulations DGNTI-COPANIT 43-2001. Panama Metropolitan Action Plan	[53,79–81]	25%	0–3	2.00	16.67%
Environmental Governance	Environmental management.	Qualitative	National Institute of Statistics and Census The National Climate Change Strategy 2050 Municipality of Panama Committee Against Climate Change 2nd Biennial Report 1st Nationally Determined Contribution	[15,50,81]	33%	0–3	3.00	33.00%
	Environmental monitoring.	Qualitative	National Institute of Statistics and Census National Climate Change Strategy Water Quality Monitoring (MiAmbiente, Ministry of Health and IDAAN) Panama's Urban and Household Sanitation Authority Air Quality Monitoring by the ACP	[15,18,50,81]	33%	0–3	3.00	33.00%
	Citizen participation.	Qualitative	Ministry of Environment National Assembly National Government	-	33%	0–3	2.00	22.00%

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biomimetics

Review

Developing a Method to Connect Thermal Physiology in Animals and Plants to the Design of Energy Efficient Buildings

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Abstract: The literature shows that translating the thermal adaptation mechanisms of biological organisms to building design solutions can improve energy performance. In the context of bio-inspired thermoregulation several worthwhile attempts have been made to develop a framework for finding relevant thermal adaptation mechanisms in nature as inspiration for architectural design. However, almost all of these have followed a solution-based approach despite the problem-solving nature of architectural design. Given this, this research set out to take a problem-based approach to biomimetic design. The aim was to investigate the most effective way of accessing biological thermoregulatory solutions to assist architects in finding relevant biological inspirations for the thermal design of buildings. This required the development of an optimal structure for categorizing thermoregulatory mechanisms that could then be used as part of a framework for finding appropriate mechanisms for a particular architectural design problem. This development began with a three-step literature review to find, study, generalize and categorize a comprehensive list of thermal adaptation mechanisms used by animals and plants. This article describes how this literature review was carried out leading to the identification of nine main themes which were analysed for their practicality in informing the structure of the proposed framework. The selected themes were built around the common aspects of biology and architecture, and hence facilitated the categorization of biological thermoregulation mechanisms. This article thus explains the steps taken to develop a structure for generalizing and categorizing thermal adaptation strategies in nature. This article does not report on the list of thermal adaptation mechanisms identified in step 2 of the literature review. Instead, it presents the literature review workflow with a focus on step 3. Given that, discussion of the thermal adaptation mechanisms falls outside the scope of this article.

Keywords: biomimetic design; sustainable design; biomimicry; thermal adaptation; thermoregulation

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1. Introduction

Architectural researchers are already turning to the solutions used by biological organism to adapt to their thermal environment in the hope these might lead to sustainable buildings [1]. Biomimicry has also been recognised as a way of achieving energy efficient design [2–4]. In the construction industry biomimicry has the potential to reduce greenhouse gas emissions because nature uses low energy processes [5] and this suggests there might be numerous examples of biological organisms which could be explored for the energy efficient processes they use as a means of solving human design problems.

There are two different approaches to bio-inspired design, these being bottom-up (solution-based) and top-down (problem-based), which have also been called 'biology push' and 'technology pull' respectively [6]. Using the former approach designers have the biological knowledge, and hence the solution, at the outset [7], while the latter begins with a design problem as the basis for exploration of the natural world to look for solutions.

Because biology and architecture are two different knowledge domains with no obvious overlap, for bio-inspired design (BID) to be successful there needs to be a way for designers to find the relevant analogies in biology and subsequently translate these into architectural design principles. As no-one has investigated the possibility of developing a bio-inspired design framework specifically focusing on thermal adaption mechanisms for energy efficient buildings [8], this research, of which this literature review is a part, aimed to fill this gap.

In a problem-based approach the bio-inspired design process begins with design challenges, which in turn need to be connected to solutions offered by biological organisms in a systematic way, in a process known as design by analogy [9,10]. Given energy use reduction is a building design problem, a problem-based approach would seem to provide a better response to bio-inspired energy efficient building design (BEEBD). Problem-based BID has been researched in engineering fields [7,11] but not yet fully investigated in architectural design. Examples of frameworks that enable problem based bio-inspired design in other fields are: 'Biomimicry 3.8′ led by Benyus, 'BioTriz' led by Julian Vincent [7], 'Biomimetic for Innovation and Design Laboratory' led by Li Shu [11], 'Design and Intelligence Laboratory' led by Goel and 'Plants Biomimetic group' led by Thomas Speck [12]. However, many of these efforts suffer from a lack of clarification in how to explore natural examples. One that is more detailed in how the investigation could be carried out is the *State-Action-Part-Phenomenon-Input-oRgan-Effect (SAPPhIRE)* model developed by Chakrabarti, Sarkar [13]. It contains several levels of abstraction of function through which the function of any biological system can be described. This framework also provides information about previously used biomimetic samples, and their structural, behavioural and functional aspects. In this software, textual representation of organisms is used as nouns, verbs and adjectives to describe engineering design problems. Biological engineering design is then achieved by matching the texts to the database. Mechanical engineers work with *SAPPhIRE* [14]. This model has been further examined by Sartori, Pal [15] by focussing on biological transfer mechanisms, and thus translating biological principles into design principles.

As shown in the *SAPPhIRE* example, knowledge is transferred from one domain to another through a link that is normally the abstraction of the functions, behaviours and processes of biological organisms. This was what the third step of the literature review described in this article was aiming to achieve. The intention was to examine the physiological functions and then match these to architectural processes used in designing energy efficient buildings. For each thermoregulatory solution, the functions, behaviours and processes were studied to allow for the translation of thermoregulatory principles from biology to architecture.

One architectural example of the problem-based approach is the framework developed by Badarnah (2012), although this was incomplete. Badarnah stressed the necessity of developing an optimal classification scheme accepting the fact that there could be various ways of categorising biological information, but did not do this, a goal that was addressed by this research, and which resulted in the development of the ThBA [8,16]. This is a tool that allows architects to find biological solutions relevant to the thermal problems in the design of a building.

Developing the ThBA required studying biology to find, classify and generalise the thermal regulation strategies used by living organisms. The intention was the ThBA would have two sides relating to the distinctive fields of biology and architecture with links between. These links would become the points through which the analogies identified from the natural world and their corresponding thermal adaptation principles could be transferred.

As noted earlier, developing the ThBA began with a three-step literature review. The first step involved studying methods of heat transfer found in nature. Step two comprised a comprehensive literature review on the behavioural, physiological and morphological thermal adaptation strategies used by biological organisms. However, neither stage suggested a structure for categorising or generalising the thermoregulatory strategies, which would be a vital step in creating the ThBA. Step three involved investigating the key themes of thermal physiology as suggested in the original glossary of thermal physiology revised by the Commission for Thermal Physiology of the International Union of Physiological Sciences (IUPS Thermal Commission, 1987) (Figure 1). Full explanation of the testing and final development of the ThBA can be found elsewhere [8].

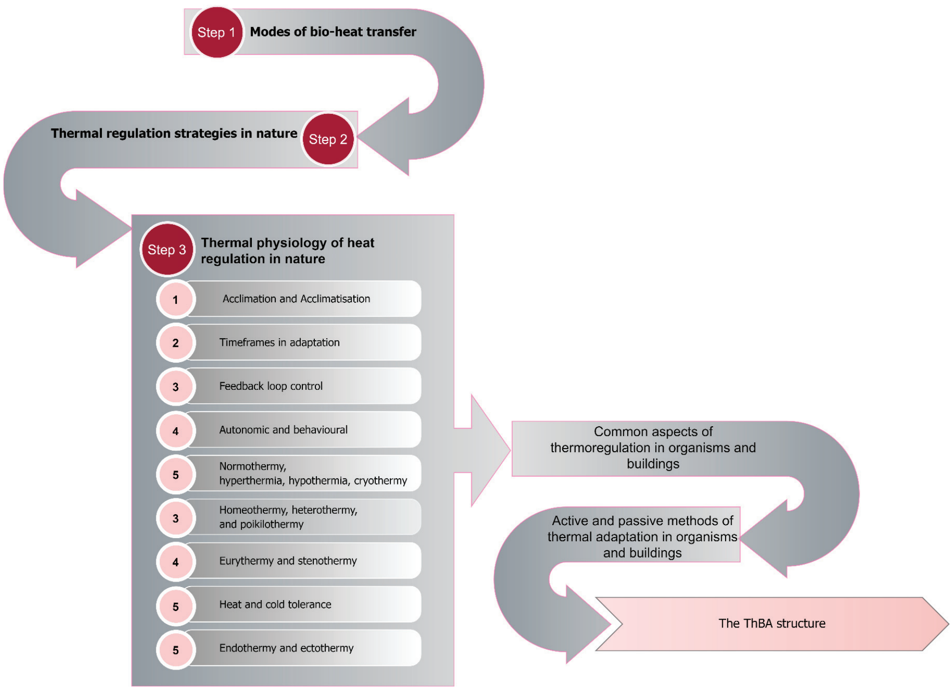

Figure 1. Steps in the literature review and their contribution to creating the ThBA.

2. Materials and Methods

In steps one and two, relevant literature was investigated by searching appropriate data bases using key words. Sufficient articles were examined such that key themes emerged. For step one, the methods of heat transfer are well known, as shown below. The same approach was adopted for step two but when that failed to produce a way of categorizing thermal strategies a different approach was used for step three, which only used the glossary of thermal physiology. The original glossary has been modified following numerous comments from experts during its development. This research used Version 3 of the IUPS which contains 479 terms. These were examined and grouped in ways that had parallels with the thermal behaviour of buildings, as described below.

2.1. Step 1: Modes of Bio-Heat Transfer

Dry heat exchange or sensible heat transfer [17] normally occurs in three ways through transfer via conduction, convection and radiation.

The rate and direction at which heat transfers through conduction is dependent on the temperature difference between an animal's body and the surface with which it is in contact. Some species of large mammals use behaviour to control conductive heat transfer by changing the temperature difference. For example, Chacma baboons (*Papio hamadryas ursinus*) in the Namib Desert do this by sand bathing [18]. This reduces their body temperature by facilitating conductive heat transfer to the cooler sand beneath the surface.

Convective heat transfer in contrast depends on the air temperature of the microclimate where an animal live [19–21]. Convective heat exchange is 'forced' when there is a wind and is 'free' in the absence of wind. An animal running quickly will force convective heat transfer but at the same time, heat is generated by muscular activity, so running may not be a way of cooling the body.

Although conductive and convective heat transfer occur, radiant heat transfer is the most significant method of heat exchange in large mammals [22], which is why large mammals, such as cows in a sunny field, seek shade ([23]. Animals will also change their posture or orientation [24] as a means of adjusting the heat received through radiation.

In a building conductive heat transfer will occur through the building envelope, which is why in cold climates buildings are insulated to slow the loss of heat from inside to outside. Convective heat transfer has been a traditional way of cooling buildings in hot climates, by allowing hot air to rise up and vent through a roof opening, drawing in cooler air from near the ground. Radiative heat transfer happens when sunlight enters the building through a window. However, stage one of the literature review did not suggest a useful way of linking examples of thermoregulation in nature to energy efficiency problems in buildings.

2.2. Step 2: Classification of Thermal Regulation Strategies in Nature

The second step involved looking for classification systems that might have parallels with thermal regulation mechanisms. The three systems investigated were taxonomy, climate conditions and the different scales at which thermal adaptation occurs (molecule, cell, organism).

The eight major levels of the taxonomic classification are domain, kingdom, phylum, class, order, family, genus and species. Each of these is then split into specific groups. For example, the six main kingdoms in nature are plants, animals, bacteria, archaebacteria, fungi and protozoa. The question for this part of the literature review was whether animals belonging to a particular genus, such as *Panthera* (snow leopard, tiger, jaguar, leopard and lion) used similar thermoregulatory strategies. Given that snow leopards have an enlarged nasal cavity to pre-warm the cold air they breathe in, something that lions living in a much warmer climate do not need, this seemed unlikely and was not pursued further.

When it came to classification by climate it also seemed that animals living in cold climates do not all use the same thermoregulation strategies. For example, reindeer have counter current heat exchange in their legs, polar bears have thick pads and fur on the feet to keep these warm, while other bears hibernate to survive the cold winter.

Classification by scale also failed to produce a way to generalize thermoregulatory strategies. Trees that are dormant in cold winters reduce the water in root tissue to avoid freezing (organism level), but some plants can also secrete anti-freeze proteins (molecular level).

Overall, stage two produced many examples of thermoregulation in nature but did not seem to help in organising the available strategies, so was abandoned and step three started.

2.3. Step 3: Thermal Physiology of Heat Regulation in Nature

As a third stage, the thermal physiology of heat regulation was studied in the hope this would create a foundation for categorising thermal adaptation strategies. As explained previously, the themes came from the 479 terms in the UIPS glossary and the many terms on which the experts have agreed were used [8]. The categorised biological thermal adaptation strategies were then used as a means of seeking analogies in architecture. Accordingly, for each mechanism, parallels in energy efficient building design were introduced, and used for the architectural side of the ThBA.

3. Results

The results of the three-step literature review are explained below as their findings were connected and together contributed to the development of the ThBA. The stage 2 investigation had provided many examples of thermoregulation, while stage 3 led to structuring and categorisation of the ThBA contents. Even though, step 1 did not directly contribute to the ThBA development it was useful for developing its architectural side.

3.1. Main Themes

The themes that emerged from stage 3 of the literature review are outlined below.

3.1.1. Acclimation and Acclimatisation

As suggested by The International Union of Physiological Science (IUPS), acclimation is the physiological and behavioural changes that occur within the bodies of organisms so they can endure environmental stressors. Thermal stressors in this sense are not the familiar aspects of a specific climate but rather a specific climatic factor that has been around for a short period. Acclimatisation, on the other hand, refers to changes that take place in the body during the lifetime of organisms as a response to normal climatic conditions [25].

The meaning of adaptation thus includes both acclimation and acclimatisation, and the changes that occur during both are genotypic and phenotypic adaptation respectively.

3.1.2. Timeframes in Adaptation

According to the IUPS glossary, another important aspect of adaptation is the time interval. The IUPS defines *Crepuscular* and *Nycthemeral* as adaptation activities. The former refers to adaptation strategies that take place at dusk or dawn while the latter indicates these occur on a 24 h basis.

3.1.3. Feedback Loop Control

In the glossary of thermal physiology, the negative-feedback loop forms the backbone of homeostasis, which is the ability of an organism to maintain equilibrium. This enables organisms to respond to environmental stressors in order to stabilise a changing variable. In a system, the comparator compares the received signal (the value of the variable) with a pre-determined set point and the process of adjustment runs until the received signal reaches the set point. In a homeostasis thermal balance mechanism, a sensor monitors the variables [26]. Responses to thermal stressors can be either physiological or behavioural and have been viewed as reflexes [27].

Figure 2 illustrates the principles of physiological feedback control in a simple and complex feedback system. The more complex system is associated with autonomic thermal regulation in which the set points detect thermal mismatches.

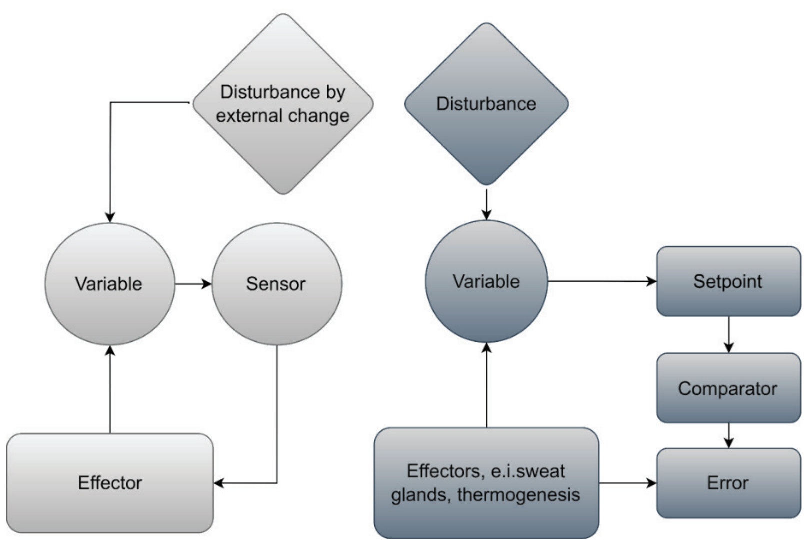

Figure 2. Principles of feedback control in a simple and complex feedback system, adapted from Willmer et al. (2009, p. 34) [28].

3.1.4. Autonomic and Behavioural

The IUPS suggested different ways of classifying thermal regulation mechanisms. Some that were obsolete have been replaced by new classification terms. This research used the new terms of autonomic (physiological) and behavioural thermoregulation as they seemed the most appropriate for categorising thermal adaptation strategies.

Autonomic thermoregulation has been defined as the regulation of body temperature through involuntary responses to thermal stressors. Changes in the rates of heat production and heat loss occur through physiological mechanisms such as sweating, shivering, non-shivering thermogenesis and circulatory mechanisms. Behavioural thermoregulation, however, does not happen involuntarily and requires coordinated movement of an organism towards a more favourable thermal environment. The movement in this sense provides the organism with a preferred condition for heat exchange.

According to the IUPS, thermotropism, where an organism such as a plant bends towards a heat source, cannot be recognised as behavioural thermoregulation as the latter is limited to specific behavioural patterns that are controlled by a nervous system.

Another criterion that affected the organisation of the thermal adaptation strategies in the ThBA was the need to reflect the classification of biological organisms as confirmed by the IUPS. Taking this into consideration, the following groupings were deemed important as these were achieved based on the characteristics, limitations and scope of responses of organisms to cold and heat stresses.

3.1.5. Normothermy, Hyperthermia, Hypothermia and Cryothermy

Normothermy, also known as cenothermy and euthermy, describes the conditions where the body temperature is maintained within normal limits. Hyperthermia is a condition where the core temperature is above the range of a species held in a normal state, whereas hypothermia occurs when the core temperature drops below that normal range of body temperature. For each species there is a specified range within which the organism holds a normal active state. Cryothermy refers to the thermal status of a supercooled organism, when the body temperature falls below the freezing point of the body tissue.

3.1.6. Homeothermy, Heterothermy and Poikilothermy

The IUPS glossary divides animals into the two categories of homeotherms—constant body temperature—and poikilotherms—variable body temperature. The two parameters that determine the body temperature are heat gain and heat loss. Homeothermy (homoiothermy) is a thermoregulatory pattern in which temperature variation occurs within defined limits except for conditions where the ambient temperature varies greatly. This means homeotherms regulate their body temperature within a narrow range. This type of thermoregulation happens in tachymetabolic species for which temperature variation takes place during nychthemeral or seasonal cycles. Heterothermy is when the pattern of temperature regulation exceeds the boundary of that of homeothermy. A specific type of the latter is local or regional heterothermy. While the pattern of temperature regulation is the same for heterotherms and poikilotherms, the former occurs only in the thermal shell of homeotherms.

In contrast to homeothermy and the two types of heterothermy, changes in the body temperature of poikilotherms occur over a broad range. This variation happens as a response to ambient temperature fluctuations. While poikilothermy does not include effective autonomic temperature regulation, there are temporary exceptions in some species. For example, several species of flying insects, and large crocodilians and turtles benefit from muscular thermogenesis to maintain their body temperature above the ambient temperature.

3.1.7. Eurythermy and Stenothermy

The IUPS glossary identifies the two distinctive groups of eurythermy and stenothermy. Eurythermy describes the tolerance of organisms to a wide range of environmental temperatures. Heterotherms and poikilotherms belong to this group. Stenothermy is temperature tolerance and happens when the accommodation of an organism to a wider range of temperatures is ineffective. This is the category that includes homeotherms, as the temperature variations in their bodies occur within a narrow range and are not influenced by the fluctuating temperatures in their environments.

3.1.8. Endothermy and Ectothermy

Endothermy and ectothermy divide animals based on the pattern of temperature regulation with a focus on the source of heat on which they are dependent. The skin of ectotherms (commonly called cold-blooded animals) is usually bare, and hence their body temperature tends to follow that of their immediate environment closely. In contrast, the body temperature of endotherms (commonly known as warm-blooded) might not be the same as the surrounding air temperature as they maintain a near constant body temperature. However, the division between ectotherms and endotherms cannot be achieved based on variable or constant body temperatures as a number of ectotherms, such as flying insects, are capable of generating internal heat (Section 3.1.6). This type of heat generation usually takes place through muscular thermogenesis [29].

Ectotherms do not generally generate heat and accordingly, face thermal challenges as they have a very low metabolic rate and do not have the physiological mechanisms to conserve heat. Endotherms use metabolic energy to keep a stable internal body temperature. Endotherms are also capable of adjusting their peripheral blood flow to conserve or dissipate body heat by reducing and increasing the blood flow respectively. Other thermoregulatory mechanisms concern water evaporation from a wet surface. The evaporation takes place if the skin of the animal gets wet either by sweating or spreading saliva (the latter is a habit of kangaroos) [30]. However, this evaporative cooling cannot be used continuously by endotherms as the water from their body has to be replaced, and this is especially critical for small endotherms [31].

Control of heat exchange in endotherms also occurs through physiological responses or physiological adaptation mechanisms. The latter involve strategies in which animals use either their body structures or physiological mechanisms to cope with thermal stresses. These can be viewed as three types, the first being circulatory mechanisms, such as altering blood flow patterns, the second being insulation, such as fur, fat or feathers, and the third evaporative mechanisms, such as panting and sweating [29].

Circulatory mechanisms can be further categorised into two types, these being vasoconstriction and vasodilation and countercurrent heat exchange [32]. In both, the flow of blood is a means of controlling heat gain and heat loss. The former occurs when the blood vessels near the skin surface narrow or expand respectively. Terrestrial animals also use evaporative cooling to lose water from their mouth, skin or nose.

While autonomic (physiological) thermoregulation is unique to endotherms, both endotherms and ectotherms use behavioural thermoregulatory strategies. However, there is a major difference between terrestrial and aquatic animals as the mediums that surround them have different heat transfer coefficients. The air surrounding land-based animals has low thermal conductivity while water permits rapid heat transfer. Relatively, terrestrial animals exploit their environment in order to adjust heat transfer. Davenport [29] states the behavioural adaptation mechanisms used by terrestrial animals to control body temperature (controlling heat gain and heat loss) can be categorised into the four groups of basking, posture, orientation and locomotion. He states animals use specific behaviours to prevent or produce heat and the behavioural means for producing heat can be categorised as clustering and huddling. Behaviours such as shading, migration and burrowing help in avoiding thermal stresses. Increased heat loss is behaviourally achieved by evaporative cooling [29].

3.1.9. Heat and Cold Tolerance

Cold tolerance or cold endurance is defined as “The ability to tolerate low ambient temperatures. This term comprises a variety of physiological properties” [25]. According to IUPS, certain homeotherms are cold tolerant. They are capable of balancing their body temperature when the ambient temperature is low. The relevant mechanisms they use for thermal regulation are either insulation or efficient metabolic heat production. In addition to these, they are able to protect appendages from freezing. For the latter, thermal tolerance is achieved either through vascular control of local heterothermy (protecting appendages from freezing), or general heterothermy such as hibernation. Poikilotherms are also cold tolerant if they can survive low and subfreezing body temperatures (formation of ice-crystals in the state of cryothermy).

Heat tolerance or heat endurance is defined as "The ability to tolerate high ambient temperatures. This term comprises a variety of physiological characteristics" [25]. Homeotherms are often characterized as heat tolerant. They are capable of balancing heat gain and heat loss in locations where the ambient temperature is high. Homeotherms are also considered a heat tolerant species if they can function normally even when their body temperature exceeds their normal range. Selective brain cooling is one of the mechanisms that make this survival possible [33].

In another way of looking at this, thermal adaptation mechanisms and the relative responses to thermal stresses can be approached by avoiding, conforming to or regulating these [34].

Avoiding thermal stress describes the mechanisms animals use to get away from the environment causing the thermal stress through avoidance by movement (e.g., seeking microhabitats such as burrows, or by migration) or avoidance by stopping normal activities (e.g., torpor) [28].

Conforming to thermal stress describes the mechanisms whereby animals undergo changes in their physiological and biochemical levels [35]. Using these mechanisms animals can function though at a very low level. In other words, conforming adaptation mechanisms do not involve huge physiological and biochemical changes but through them the potential damaging effects of a condition such as freezing are avoided [36]. According to the IUPS, thermotolerance or heat shock response (HSR) is a short and rapid action at the molecular level for the purpose of protecting cells and enabling survival for several hours in such a way so that the animal can retain its activity.

Regulating thermal stress requires significant changes in an organism and is a combination of both behaviours (e.g., basking, burrowing, huddling, erecting or concealing appendages) and substantial physiological and chemical transformations. The regulation of thermal stresses is also described as thermal tolerance [28].

3.2. Common Aspects of Thermoregulation in Organisms and Buildings

The next stage in the development of the ThBA was to look at the commonalities between thermal regulation in organisms (results of step 3 of the literature review as summarised above) and buildings. In the event, many of these proved inappropriate when it came to structuring the ThBA. However, as they were part of the process they have been briefly summarised below.

The rhythms of organism activities can be either crepuscular or nycthemeral [37]. The former happens only at dawn or dusk while the latter happens anytime during the day. In terms of thermoregulation, behavioural strategies take place on a diurnal basis to enable organisms to respond to the nycthemeral cycle of their core temperature [38].

For a building, variations in the operation of HVAC systems or other thermoregulatory activities such as the way the building occupiers use the space could have nycthemeral patterns. An analogy to crepuscular pattern of thermoregulation could be turning on cooling or heating systems when there are higher temperatures midday and early afternoon and lower temperatures in the early morning and late evening. However, while the analogy of a crepuscular pattern for running space conditioning systems might be valid for houses, it does not seem relevant for an office building or a school, which is less likely to be occupied at dawn and in the evening. This means the building type also governs the rhythms of the thermoregulation.

The concept of feedback loop control is similar for both buildings and the bodies of organisms but remained too general as a factor for organising the ThBA. The parallel to this concept in organisms is the temperature control mechanisms in a building. However, two aspects of the feedback control were relevant for further consideration. For example, the concepts of normothermy, hyperthermia, hypothermia and cryothermy [25] that describe the states of fluctuating body temperature have a parallel in free running buildings, and some energy efficient buildings, for example the zero energy houses at Hockerton [39] are free running. Similarly, homeothermy, heterothermy and poikilothermy [25] were considered applicable to buildings because they pointed to constant or changing body temperature, which could be achieved by running some type of HVAC system. Irrespective of whether the states above describe a range of temperature fluctuations or deviation from the set temperature, connection between the two groupings of normothermy, hyperthermia, hypothermia and cryothermy and homeothermy, heterothermy and poikilothermy emerged. Both groups rely on the mechanism of feedback loop control, which is a mechanism involved in both regulating the temperature in the body of an organism and that of a building.

Likewise, heat and cold tolerance were a potential means of structuring the ThBA. Each category of temperature tolerance had the three sub-branches of thermal adaptation, namely avoiding, conforming to, and regulating thermal stressors. This meant the ThBA could be structured based on the cold and heat endurance capabilities of organisms, broken down into these three sub-branches.

Other similar states to cold and heat tolerance were eurythermy and stenothermy, which are to do with temperature tolerance over a wide range of temperatures. A successful sustainable building in terms of responding to different temperatures and maintaining a satisfactory indoor temperature could be a parallel to eurythermy. Conversely, if the thermoregulatory systems in a building fall short in providing a comfortable environment for the occupants during the highest and lowest ambient temperatures, this is analogous to stenothermy, which is when thermoregulation strategies are only effective over a narrow range of temperatures.

Despite several similarities between thermoregulatory states in organisms and buildings, some thermoregulation concepts in biology cannot be transferred to architecture. For example, acclimation and acclimatisation had no parallel in building design. This is because thermoregulatory strategies in buildings do not evolve over building lifetimes or transfer to their next generations. Nor do buildings tend to move from one climate to another, although the use of portable structures such as tents and how these might be adapted for different climates is a potential link.

Thermal adaptation by definition explains the biological processes that organisms go through to adapt to their environment. However, during these species with poor functions might die while the best fits become prevalent through natural selection. Given this, the concept of distinction and fatality was irrelevant for building design. An imperfect analogy to this concept could be the accumulation of knowledge relating to sustainable building design achieved over the years and the fact that successful strategies would be used for designing the next generation of energy-efficient buildings.

3.3. Active and Passive Methods of Thermal Adaptation in Organisms and Buildings

From the thermal physiology terminologies suggested by the IUPS, endothermy and ectothermy emerged as the most appropriate for structuring the ThBA. Endotherms and ectotherms use different sources of heat when it comes to adapting thermally to an environment. The former generate heat within the body, and this has a parallel to running HVAC systems within a building to generate heat. In contrast, ectotherms regulate body temperature through behavioural strategies, such as basking in the sun to raise temperature, or retreating to a shady place to avoid becoming too hot. Parallels in buildings would be raising and lowering window blinds to let the sun in or keep it out. The voluntary (behavioural) and involuntary (autonomic or physiological) aspects of thermoregulation in organisms also seemed useful as a basis for the categorisation of thermoregulation strategies for the architecture side of the ThBA. For endotherms, the control of body temperature mostly takes place within or through organ(s), tissue(s), cell(s) or in other words their physiology, whereas ectotherms control their body temperature mainly through their behaviour. However, there are some exceptions where ectotherms use physiological thermal adaptation strategies to regulate their body temperature.

As a result, the thermal adaptation strategies that come from changes in the physiology of an organism were viewed as active thermoregulatory mechanisms when it came to organising the ThBA. In contrast those strategies that resulted in no change to the body of an organism because all that changed was a behaviour, were termed passive thermoregulatory strategies in the ThBA. For someone designing an energy efficient building if there is some form of change when temperature regulation happens then this is akin to active thermoregulation, whereas if there is no change to the building when there is a thermal change, such a sunlight falling through a fixed window causing a rise in internal temperature, that is akin to passive thermoregulation. Thus, where thermoregulatory strategies take place through circulatory systems or need energy for activation in buildings, they are active, while passive design strategies cause no changes to the building fabric, nor do they make use of HVAC systems. These ideas were embedded in the structure of ThBA. The following sections examine possible active and passive thermal adaptation strategies in organisms and their parallel in buildings.

3.3.1. Active Methods of Thermal Adaptation in Organisms

Penguins and reindeer both use countercurrent heat exchange to avoid excessive heat loss from their extremities. As feet are, relative to the size of the bird or animal, some distance from the body's core, the arteries taking blood to the feet lose heat to the veins returning blood to the heart, ensuring the blood reaching the feet is cooled.

3.3.2. Active Methods of Thermal Adaptation in Buildings

Buildings that rely on HVAC systems to ensure a comfortable even indoor temperature can be considered as analogous to active thermal adaptation in nature. In some climates in winter one side of the building can be too hot with sun shining through the windows while the other side of the building might be cold. The HVAC system needs to address this by using energy to cool one side and heat the other.

3.3.3. Passive Methods of Thermal Adaptation in Organisms

Behavioural change is a common method of heat regulation in animals. A cat will move into the sun to warm itself and out again when starting to become too hot. Apart from having to expend energy to move the cat remains unchanged. Many animals that live in hot, dry climates such as deserts make use of burrows to avoid midday heat. Using such thermally buffered microclimates is a survival tactic [40].

3.3.4. Passive Methods of Thermal Adaptation in Buildings

Buildings have also been buried or semi-buried in the ground as a passive strategy to reduce heat loss and gain, the Hockerton houses being an example. In earlier times when energy for heating was less readily available, bedrooms were often placed on the east side of the house so as to benefit from the morning sun, and in larger houses the morning or breakfast room would also be placed to receive the morning sun, while the drawing room would benefit from sun later in the day. In such houses, the people would move to make best use of the available energy, but the building did not change.

3.4. The ThBA Structure

The analogy between active and passive thermal adaptation strategies in organisms and buildings informed the primary structure of the ThBA, which had three parts. Two were related to passive and active strategies for animals and one for strategies used by plants. The latter had only one part since the main principles relating to active and passive strategies as provided by IUPS did not match properly with the thermoregulatory mechanisms used by plants.

As the aim of this research was to connect the thermal challenges presented by a building design to relevant inspiration(s) in nature, the ThBA needed an additional part for architecture. This meant adding equivalent energy-efficient building design strategies to the other side. Empty boxes were used where there was no parallel design strategy to an existing biological thermal adaptation mechanism. For example, 'vasodilation' does not have a parallel in architecture. The absence of an existing parallel was shown by an empty box on the architectural side of the ThBA, although there was no empty box on its biology side.

Figure 3 shows a section of the ThBA related to active strategies for animals. Each side of the ThBA consists of different columns. Column A has three main branches called 'parent actions' these being heat loss, heat gain and heat generation. As Figure 3 is only part of the ThBA it only shows heat loss strategies. Column B has the three sub-branches of 'parent actions', these being increasing heat loss, decreasing heat loss and avoiding heat loss, although only the first part is shown in Figure 3. Column C gives the relevant strategies for each 'action' in column B. These strategies then branch into 'types' in column D, and for each 'type', there is a 'means' that refers to the parts of animals or plants responsible for thermal adaptation. Column F gives examples of organisms using each particular strategy.

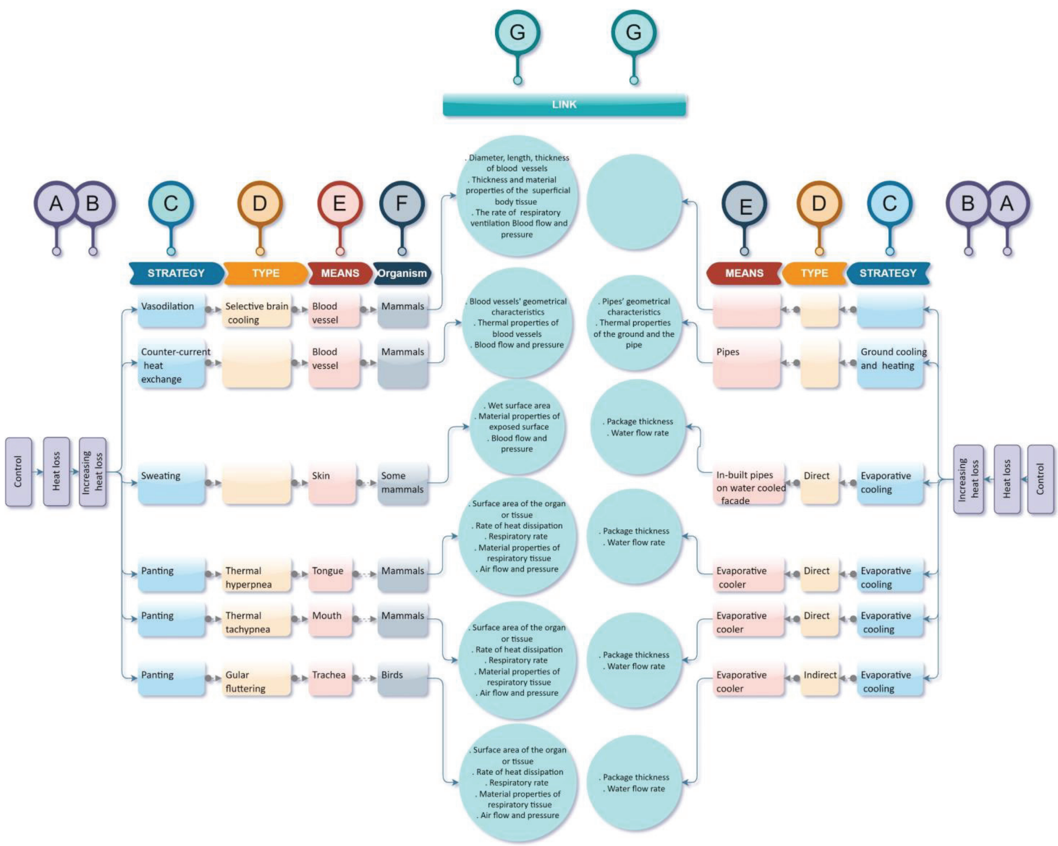

Figure 3. A section of the ThBA related to active strategies for animals, adapted from Imani and Vale [41].

The architecture side of the ThBA shows sustainable building design strategies presented in the same column types except for column F as the analogy between a building and an organism made column F irrelevant on the architecture side of the ThBA.

In the Design-by-Analogy process, a link should be made between source and target concepts. For cross-disciplinary research, these analogous concepts belong to different fields of knowledge.

Transferring knowledge from the source design domain into the target design field happens through documenting a series of parameters representing different attributes of the source design concept. The source and target domains were architecture and biology, and the main parameters contributing to each biological thermal adaptation strategy were derived and presented in column G.

Looking at the examples in Figure 3 shows that counter current heat exchange is equivalent to ground cooling and heating and that sweating and panting are related to evaporative cooling in buildings, both direct, as when water is used as the cooling medium in an evaporative cooler (equivalent to sweating), and indirect as when the outdoor air is cooled by a precooled air flow [42] (equivalent to gular fluttering).

Sweating is an autonomic (physiological) mechanism that functions under sympathetic cholinergic and adrenergic control in humans and the animal kingdom respectively. Skin releases water when thermosensitive neurones respond to any changes in the temperature by sending signals to the hypothalamus, which has been described as acting as a set point manager similar to the thermal management system of a building. Panting, which is another analogous strategy to evaporative cooling in buildings can be categorised into three types. In all three, thermoregulation happens through evaporative heat loss as a means of responding to the core temperature overheating. Heat loss is from the mouth area and lungs in mammals while the trachea is the principal organ contributing to gular fluttering in birds.

The links created in the ThBA can be used for translating the thermoregulatory principles in sweating and panting to parallels with the function of evaporative coolers. The ThBA thus lists the key parameters which are necessary for transferring mechanisms from biology to architecture, which then need to be explored by the building designer. For example, in thermal tachypnea the respiratory parameters, air sac properties and cooling efficiency of panting in birds affect their panting mechanism [43]. The designer similarly needs to consider the size and properties of a system of evaporative cooling so that it is suitable for the building. Obviously, the links between evaporative cooling in organisms and buildings are well known, but the hope was that the structure of the ThBA would lead to new opportunities for applying thermoregulatory systems found in organism to buildings. A full description of the creation of the final version of the ThBA and its testing can be found elsewhere [8].

4. Conclusions

This article details the development process of a bio-inspired design tool called the thermo-bio-architectural framework (ThBA) for energy efficient building design. The ThBA was developed through conducting a comprehensive literature review on thermal adaptation-associated concepts in biology. These involved exploring different modes of bio-heat transfer, thermal adaptation strategies and the thermal physiology of living organisms. Reviewing these, passive and active ways of thermoregulation linked to the concepts of endothermy and ectothermy emerged as the most appropriate for structuring the ThBA. Heat generation is the key to the concepts of endothermy and ectothermy and the fact that the heat source in nature is either inside or out of the body of organisms, meant there were exact parallels in energy efficient building design. Once created, the ThBA was used in a focus group where biology experts confirmed the inclusiveness, effectiveness and applicability of both the animal and plant parts of the ThBA [41]. This is the first time that a comprehensive framework has been developed to bridge the gap between biology and architecture. The ThBA could assist architects in finding relevant biological thermal adaptation strategies based on the thermal needs of a building.

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Review

An Inspection of the Life Cycle of Sustainable Construction Projects: Towards a Biomimicry-Based Road Map Integrating Circular Economy

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Abstract: According to the National Energy Plan in Panama, the construction sector is one of the most prosperous and impactful sectors in the economy and it is expected to expand due to population growth by almost 300% by 2050. However, this sector must work on the transition towards sustainability and resilience in the face of climate change, since its growth implies a high consumption of resources and the contribution of greenhouse gases. The need to establish practices and strategies that embrace the dimension of sustainability and a circular economy is imminent. Currently, there is little guidance in the reference framework beyond certifications in planning, management and evaluation tools for its implementation. Different studies vary in the number of phases and considerations for projects. Therefore, the present work proposes the development of a unified road map, with defined phases, practices and indicators based on principles inspired by nature, such as biomimicry (Greek words: "bio" means life and "mimesis", imitation), and focuses on a circular economy, validated by construction professionals, where strengths, opportunities, skills and threats are identified with a high level of acceptance. This contributes to strengthening the field of sustainable construction project management and a precedent for Panama.

Keywords: sustainable construction; project management; sustainability; circular economy; biomimicry; road map; life cycle phases

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1. Introduction

The construction industry has a great economic influence and presents great opportunities, unlike other sectors, to face the challenges of climate change [1,2] and global challenges. For this reason, it is essential to adopt practices based on sustainability and circular economy principles at all stages of the process, since it involves high consumption of resources and negative impacts on the environment [3]. Studies indicate that the construction industry is responsible for about 50% of carbon dioxide emissions into the atmosphere; further, 20–50% of its natural resource consumption and 50% of its solid waste generation cause environmental impacts [4]. It is expected to expand by 50% in global terms, due to population growth and the demand for buildings and energy [5]. In the case of Panama, this population increase will be almost 300% by 2050, according to the National Energy Plan [6], which would have a proportional impact on resource consumption and greenhouse gas emissions. Thus, it is imminent that the construction industry must act with commitment and responsibility, given its contributions to the environment, society and the economy.

There are various definitions of "sustainable construction", but it is positioned as a relevant contemporary issue and aligned with the efforts needed to achieve sustainability and development [7]. Sometimes its focus is limited to environmental dimensionality, but it must encompass all three pillars: environmental, social and economic aspects. The Construction Research Institute (BRE) specifies the approaches under the three pillars of sustainability [8]:

- Environment: reduction in negative impacts on the environment through the selection of renewable materials, management and minimization of waste and adoption of practices for improvement and environmental protection;
- Economy: increased efficiency and growth through the efficient use of resources (materials, energy, water, etc.);
- Social: meeting the needs of the population and social groups involved in the construction process, guaranteeing the satisfaction of all interested parties, including the inhabitants of the project's area of influence.

This integration of sustainability must occur in all the processes of the life cycle of construction projects and their management, such as initiation, execution, monitoring, control and shutdown [9]. The link of project management with the sustainable environment is an opportunity to explore and identify components, structure and defined integration processes. As found in [10], Silvius, G. supports the management of sustainable projects such as "the management of change-oriented to the project in policies, assets or organizations, taking into account the economic, social and environmental impact of the project, its result and its effect, for the present and future generations". Therefore, determining the management factors and processes in the framework of sustainable construction, in addition to having multiple benefits in terms of achieving prosperity without compromising the lives and resources of future generations, will respond to raising awareness of the feasibility of application and notion of both costs and risks [9,11].

The reasons for not investing in the change from traditional to sustainable construction is the complexity of design and increased costs [12], but, according to studies, this can be considered an additional success factor in terms of scope, time and costs [13]. In addition to the results already proven in operation, such as reducing 50% of energy consumption in green buildings, these tend to be more durable and have fewer maintenance requirements. The review includes a study that illustrates that an investment of 2% in sustainable construction can produce long-term savings of more than ten times the amount of investment [11]. Due to this profitability of implementation, it is important to contribute to the orientation in the construction process, essentially, in the initial phases (feasibility and design), to intervene less in the operation phase and avoid having to carrying out repairs, which causes low costs [2,14]. Similarly, we take into account the perspectives of administration, planning and the project and product life cycle [2,15].

The findings in the reviewed literature are varied, whereby the relevance of the topic has been recognized but different directions have been developed; some authors focused on the qualities of planning as well as aspects of control and leadership related to the "triple result" [14,15], while others examined preliminary proposals for decision-makers and outlined processes with variation in the quantity of the phases to be carried out and their factors or indicators. In addition, the latent presence of qualification systems for green buildings (LEED and BREAM, among others) and ISO international quality standards related to the "triple result" has been considered [13]. However, for the latter, emphasis has been placed on the inclination for the environmental dimension over the social and economical ones, its sustainable scope being questioned [2,16].

Considering previous studies and the diversity of frameworks and taxonomies found to integrate sustainability in construction and project management, the objective is to define a road map that includes the triple bottom line and extends through the concept of circular economy, which works with biological processes that emulate nature, for the transition from a linear to a circular economy [17,18]. In the articles here reviewed, the circular economy is considered to be a tool to be adopted in order to perform a successful transition to sustainable construction [19], since it is a restorative or regenerative industrial system by intention and design [20], thus complementing the triple factor balance or result approach.

Similarly, the biomimetic approach is included to solve challenges with innovative approaches that aim at making constructions sustainable [21]. This is based on the exploration of nature as a mentor, measure and model that influences both the theoretical or conceptual design-related decisions in any project and the way to approach the built and natural environment through design, materials and technologies [1,22].

The relevance of the topic is currently recognized, but the approaches researchers have employed over the years are diverse and the scope of sustainability is also debatable. Studies have been developed in different directions, such as the quality of planning, process schematization and international standards, as well as green building rating systems (LEED and BREAM, among others). That is why this research study aims to propose and evaluate a road map with a definition of phases, practices and indicators in terms of the triple bottom line (profit, people and planet), circular economy and biomimicry, to unify definitions, considerations and challenges for sustainable construction taking inspiration from nature for problem solving.

This document is divided into three parts. It starts by presenting a review of different frameworks regarding the methodologies used to design sustainable construction projects. This is followed by a presentation of the biomimicry methodology, linked to the circular economy concept, to address the challenge of unifying the diversity in the approaches relative to sustainable construction projects and process definition. Here, a road map based on a named "Biocircular Model" is proposed, with the biomimicry-based strategies' influence on the sustainable construction process and definition being highlighted. Finally, the "Biocircular Model" is applied to each phase in the construction project and evaluated by experts in the local field via a survey together with a SWOT analysis to support the proposed model and road map.

2. Inspection of the Methodologies Used for the Design of Sustainable Construction Projects

The inclusion of sustainability in construction is a topic of interest and great opportunities for the future in the face of global environmental challenges, but directions of its processes, indicators and factors have not been formally defined within the project management framework. For this reason, in order to define the road map, it is necessary to know the barriers and opportunities already identified in the field. How does the literary review define sustainability in construction? Is the process of its inclusion by stages analyzed? Are there metrics for its evaluation? These are the main questions that guided our the literary review, with the ojective of establishing the transition to sustainable construction, complemented with the biomimetic approach and circular economy.

2.1. Literature Search Strategy

Different databases were used to carry out the search on sustainable construction and link it with biomimicry and the circular economy, such as ScienceDirect, Google Scholar, SpringerLink, Academia and Researchgate, applying Boolean operators and the combination of keywords (see Figure 1). The main approaches were "sustainable or green construction", "project management or life cycle phases", "principles, indicators, criteria", "Biomimicry" and "Circular Economy". The filtration was first given by the title, then by the abstract and, finally, by the full text. For this study, around 49 documents were considered, of which those that only treated context and principles were useful for the state of the art and domain of the subject. The phases and metrics, biomimicry and circular economy were the most influential concepts for this project.

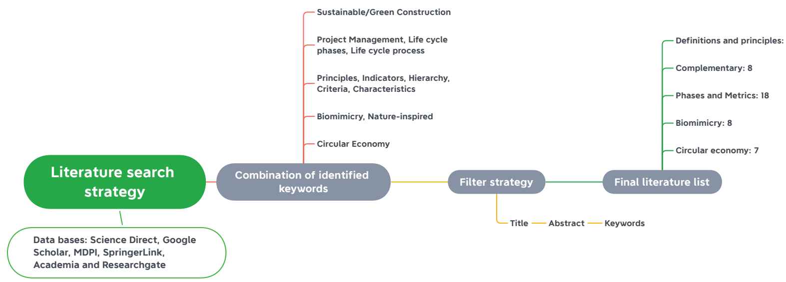

Figure 1. Literature search strategy.

In this way, we began by understanding how sustainability is defined in construction, analyzing a selection of 20 articles with phases and metrics (Table 1). There was no more than 80% agreement among the elements identified, which illustrates the variation in the orientation of sustainable construction. Occurrence from 55% to 75% was found for the following: the minimization of construction's impact on the environment [2], decision making considering green factors in all phases of a project [23] and the three pillars or "triple result" of sustainability—environment, economy and society. These are determining factors for construction activities to achieve sustainable development and minimize environmental degradation.

Table 1. Elements for defining sustainability in construction.

Elements	Occurrence * (%)	References
Impact minimization	75	[2,4,7,8,11,18,20,23–30]
Resources efficiency	50	[2,4,8,18,20,26,28,29,31,32]
Green aspects in each phase	75	[7,8,11,18,20,23–26,28,30,31,33]
Environment	75	[2,7,8,11,26–29,32–35]
Economy	75	[4,7,8,11,25–28,32–35]
Health	25	[7,11,25,27,28]
Energy	50	[7,11,20,25–27,32]
Safety	25	[7,11,27]
Social aspect	75	[4,7,8,25–28,32–35]
Waste	50	[7,8,18,25,26,29,30]
Triple Bottom Line	50	[4,7,8,26–28,32–35]

With a 50% frequency, we found resource efficiency and a new process approach [31], energy efficiency and consumption, and waste generation. Health and safety were found in the minimum range, which allows us to reflect on compliance with the dimensionality of sustainability with these mainly social factors.

2.2. Comparative Analysis of the Phases and Metrics Considered in Sustainable Construction Projects

In the literary review, few documents focused on the stages of the process. Therefore, it was considered necessary to analyze the phases involved, their quantity and definitions (Figure 2) in those studies which did so in the form of a proposal and to find patterns. In the 14 papers selected, there were only mentions of the phases involved, since the authors' focus was on factors or indicators.

The predominantly mentioned phase was duly execution (construction), while planning and design were viewed jointly. The monitoring and control phases, as well as the delivery phase, were mentioned less frequently. However, in [36], the necessary approach for the road map is linked to the management of imminent projects and the phases that monitor the performance and fulfillment of goals must be included.

Additionally, the vast majority of documents focused on buildings exclusively. This allowed them to explore a product's life cycle and its stages, such as operation and maintenance. Among the instruments used formally, there are certifications such as the green building qualification systems (GBRT), used to evaluate the sustainability of buildings and ISO management standards [5].

	Life cycle of the Construction Process						Product Life Cycle			Others	
References	Initiation	Planning	Design	Construction	Monitoring	Delivery	Operating	Maintenance	Abandonment	Process	Product
[2]			*	*			*			*	
[11]	*	*	*	*	*	*				*	
[18]			*	*			*		*	*	*
[23]	*	*	*	*			*		*		
[24]	*		*	*		*				*	
[25]	*		*	*	*					*	*
[27]			*	*			*	*	*		
[28]		*		*			*				
[30]		*	*	*			*	*	*		*
[31]		*		*			*				
[32]		*		*			*			*	
[33]		*		*			*	*	*		*
[34]	*	*	*	*	*	*	*	*	*		
[35]	*	*		*	*	*					

Figure 2. Comparison of phase inclusion for the process and product's life cycle process.

The need to integrate sustainability in the construction sector is clearly defined, but there are no defined reference frameworks for its implementation in project management, life cycle and objectives beyond certifications for evaluation.

For this reason, most of the articles make proposals and contemplate the triple factor or triple bottom line. These articles include a decision matrix with hierarchical analysis [23], proposals for quantitative and qualitative indicators with applicability to case studies [7], definitions of a phase approach together with the green supply chain [25] and the establishment of indicators by construction factors [28].

2.3. Applicability of the Biomimetic Approach and Circular Economy in Construction Projects

Biomimicry is the study of and inspiration from biological components and natural processes to solve problems, understanding how they survive, function and evolve in a self-sustaining way [12,21]. Serving as a "model, mentor and measure", biomimicry has three levels, namely, organism, behavior and ecosystem, and it can be applied in forms, processes and systems [1]. For a long time, biomicmicry has been employed trying to solve problems of food and shelter, as well as others; as a result, we have obtained models, patterns and solutions that have been tested and have successfully, creatively and sustainably solved challenges for humanity over time [37,38].

The motivation for the application of biomimicry in research has had a great increase in recent years, with the aim to find those innovative solutions hidden in nature—mainly in the architecture and engineering fields, whose goal is to employ sustainability for human development [38,39]. Two approaches are presented in biomimicry to solve problems. The "problem-based approach", which involves solving the design problem by identifying the principle with which another organism or ecosystem solves it. The second approach, i.e., the "approach based on the solution", consists in solving the problem through the identification of a particular behavior, function, or characteristic in an organism or ecosystem [12,21]. For this research study, the "design looking at biology" or "problem-based approach" is addressed and the "BioGen" design methodology [40] is applied, since this methodology has improved the investigation of the strategies of nature and the extraction of fundamental principles to establish design concepts, as well as the integration of strategies of different organisms to obtain enhanced solutions [40].

3. Materials and Methods

The methodology (see Figure 3) is divided into two parts. The preliminary design phase consists of conducting an exploration and investigation of organisms and ecosystems based on challenges, similar functions, extraction and abstraction of principles through the exploratory model, the pinnacle analysis matrix and the design path matrix. We look at the biological domain, where the analysis of solutions to deal with current problems and challenges in sustainable construction are managed and analyzed [41]. Then, the emulation phase is where the ideas are transformed into designs, constituting the biocircular model, where the resulting functions are identified and classified at both the target and application levels and then validated for decision making [40,41]. This validation is given through a survey distributed to 27 construction professionals with different positions and years of experience.

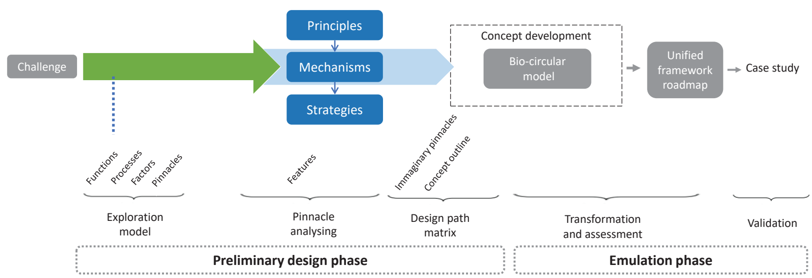

Figure 3. Schematic of the methodology implemented.

3.1. Conceptualization of a Frame of Reference with a View to Sustainability

To apply the methodology, the problem of diversity in the approaches to sustainable construction and the definition of its processes are presented. Therefore, "the three pillars of sustainability" or "triple result" are presented as challenges; environment, economy and society are oriented, in order, to protection, harmonization and well-being, to ensure that construction has a sustainable scope.

3.1.1. Biomimetic and Circular Economy Approach

The first stage within this phase is the exploratory model (Figure 4), which establishes four hierarchical levels for each challenge, establishing the functions in the first level, the relevant processes in the second, the influencing factors in the third and the biological entities (called pinnacles) are presented in the fourth. These represent an example of a specific function, process, or factor. The AskNature platform of the Institute of Biomimicry was used to find nature's solutions to the challenges.

The first challenge is the protection of the environment, where fundamental processes were identified. Firstly, the production of waste and the hierarchy of sustainable waste management was taken into account [30], with the following factors being prioritized: reduction in/prevention of the generation of waste; reuse of materials and recycling of materials; reduction in consumption of less natural and material resources; reuse of materials that are in good condition and fulfill their original function; and recycling to process materials to obtain the same or lower quality necessary to achieve the task [18]. For this process, searches were carried out with keywords such as "waste" and "build" and with the exploration of the category of innovations in construction; this returned more than 60 results in the categories of optimization of shape/materials and physical assembling, obtaining 12 preselected pinnacles, such as birds, hornets and bees. The use of resources, according to the efficiency and duration, was the second process considered, with the quality of "renewable" considered as a factor, taking into account ecological components and referring to the opportunities to have environmentally friendly materials; in the context of materials sourced from local regions, we considered the reduction in emissions from transport and the support of the local. For the search, logical connections were made with "materials", "resources" and "construction", obtaining 41 results for review; among these, a preselection of 8 pinnacles was made for analysis, among which we highlight the eastern oyster, ants and birds.

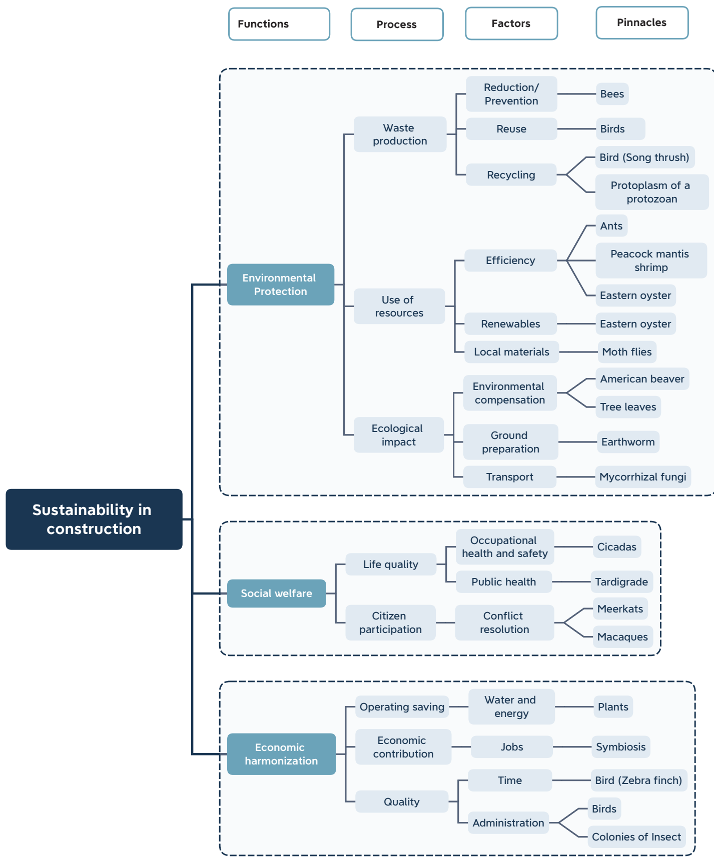

Figure 4. Exploration model connecting challenges and pinnacles.

The last process considered was ecological impact, which involves the existence of environmental compensation for the pollution generated and a correct preparation of the land and transport, which is obtained efficiently with low carbon emissions. In this, reviews of "solutions for climate change" and searches with logical connections such as "build and maintain the community" and "life-friendly transport" were carried out, with 18 results and 6 elements preselected for analysis, such as beavers, worksheets, trees, termites and worms.

These processes and factors have a great environmental focus, but working to protect the environment also affects social well-being; further, finding more efficient materials, reducing them and providing support with the selection of local sources support the economy.

In social welfare, the first process considered was quality of life, encompassing occupational safety and hygiene, aligned with the protection of employees, training and occupational safety; public health, focused on the impact of inhabitants within the project's area of influence, opportunities for improvement and well-being, was also considered.

As another process, the participation of the citizenry is itself part of construction and its orientation is aligned with the resolution of conflicts among interested parties [32,34]. Regarding the search for pinnacles, logical connections of words such as "build and protect from physical damage" and "build and maintain the community" were made with the focus of coordinating, resulting in 26 solutions and 4 preselected elements for analysis, such as cicadas, meerkats, macaques and tardigrades.

Finally, economic harmonization, with processes such as operational and water and energy saving processes, is part of the economic benefits of being sustainable. In addition, economic contribution implies the generation of jobs and that, in the same way, has to do with the social sphere and people's quality of life. Finally, we considered quality, in terms of administration, its performance and capacity [34]. To identify pinnacles, word connections, such as "efficient design," "fast build", "quality of construction" and "symbiosis" (the latter being an agreement to obtain benefits, applied to the concept of receiving income for work performed), were made. There were 86 results and quick filters were applied, with short descriptions of the strategies. As a preselection for analysis, there were six pinnacles.

The analysis of the preselected pinnacles continued through the identification of the strategy and its mechanism, extracting its main principle and the characteristic by which it is carried out [40].

For the selection of the fundamental pinnacles (Figure 5), the processes identified for the three challenges were maintained. Among the factors, priority was given, in the case of waste production, to the main factors in the hierarchy of integral waste management [30], highlighting reduction and reuse. For the ecological impact, the transport factor was discarded within the first challenge, since the choice of local materials applies its concept. In the case of the quality process for economic harmonization, the time process was discarded, since it is binding on management and the pinnacle had already been analyzed.

The number of pinnacles required depends on the challenges set and the corresponding solutions provided by the pinnacles, which may be entirely novel for generalities [40].

Functions	Process	Factors	Pinnacles
Environmental Protection	Waste production	Reduction/Prevention	Bees
		Reuse	Birds
	Use of resources	Renewables	Bird (Song thrush)
		Local materials	Protoplasm of protozoan
	Ecological Impact	Environmental Compensation	American beaver
			Tree leaves
		Ground preparation	Earthworm
Social welfare	Life quality	Occupational health and safety	Cicadas
		Public health	Tardigrade
	Citizen participation	Conflict resolution	Meerkats
			Macaques
Economic harmonization	Operating saving	Water and energy	Plants
	Economic contribution	Jobs	Symbiosis (ant/plant)
	Quality	Administration	Birds
			Colonies of Insect

Figure 5. Selected pinnacles from the exploratory model.

The strategies of the selected exploration model routes are covered by challenges and processes and, for each, the selected pinnacles are mentioned:

(a) Environmental Protection

- Waste production: birds and bees were chosen. Birds handle construction as a complex process due to their experience and observation, which includes the efficient use of the materials at their disposal and the use of decomposed wood for their nests. Bees forge their hives with the principle of storing the greatest amount of honey with the least building material (wax).

- Resource Utilization: The sacworm was selected for using environmental materials such as twigs, leaves and silk to construct boxes with spiral patterns for protection. On the other hand, the oriental oyster was selected for its creation of a kind of cement from calcium carbonate with softer and stickier proteins; they withstand strong tides and manage to hold their colonies together.
- Ecological impact: beavers, tree leaves and earthworms were chosen. Beavers were chosen for being ecosystem engineers, managing to model entire landscapes including habitats and damaged streams by constructing their dams. Tree leaves can absorb organic compounds from the atmosphere and break them down to be less harmful. Lastly, earthworms are decomposers that add air and disperse nutrients in the soil as they dig; these consume dead organic material, such as leaves and roots and, after consuming it, they break it down and excrete it in the form of nutrients.

(b) Social welfare

- Quality of life: For occupational safety and hygiene, we chose the pinnacle of cicadas, since they expel dirt and water through nanoscale protrusions surrounded by air pockets that attract water droplets. In public health, the tardigrade was selected for its characteristics of protection from extreme environmental conditions through cryptobiosis (i.e., quarantine).
- Conflict solving: Meerkats were selected because of how they manage conflicts—by taking turns in leadership—and macaques because they use a simple, clear and inclusive voting process to stay together as a group.

(c) Economic harmonization

- Operational savings: Plants were chosen as the pinnacle, since their antenna of light capture allows it to be efficient from a quantum point of view, thanks to the high density of pigments and the design of long states of excitation. An addition reason for this selection is the ability, in Bromeliaceae, to capture water and nutrients in a storage tank through hydrophobic leaf surfaces.
- Economic contribution: The symbiosis was selected and the plant/ants agreement was taken as an example; plants provide shelter and other services, while the ant provides nutrients.
- Quality: For the management context, birds were selected for handling and identifying the construction process as complex. Speed and construction materials are also important to them, as they influence their ability to reproduce.

With the pinnacles already selected, we proceeded with the pinnacle analysis matrix and with the design path matrix stages. The design matrix seeks to evaluate an imaginary pinnacle for each category, which are: process (identified for the exploratory model and selection), flow (if they do it actively or passively), adaptation of the process, the scale, the environmental context, that is, the climate, the morphological characteristics and, finally, the circular economy. Five actions of the ReSOLVE framework [17] were placed as characteristics, where:

- "Regenerate" refers to the change to renewable materials and energies, the restoration of ecosystem health and the return of biologically recovered resources to the biosphere.
- "Sharing" is about sharing assets, driving reuse or second hand and prolonging the life of products through maintenance, durable design and upgrades.
- "Optimize" consists of increasing the performance or efficiency of a product, removing waste in the production and supply chain, and alludes to optimization.
- "Cycle" refers to remanufactured products or components, digested anaerobically, recycled materials and biochemicals extracted from organic waste.
- "Exchange" refers to replacing old materials with advanced non-renewable materials, applying new technologies and choosing new products or services.

It should be noted that the action of virtualizing was not considered in the ReSOLVE framework due to its limited applicability for pinnacle analysis, but, together with the elements obtained from the design path matrix, support technologies can be identified.

The "X" symbols are placed when a characteristic is applied to each pinnacle in order to identify the imaginary pinnacle that has the most dominant characteristic by category. This procedure is utilized to reduce the complexity of the solutions found, where the imaginary pinnacle acquires its functions [40].

The environmental protection pinnacles analysis matrix is presented in Figure 6. The relevant features of this challenge are highlighted with the color pink. Their results show that the three defined processes coincided with pinnacles, with active flow and physiological and behavioral adaptations. The macroscale means the natural scale in which the solutions are carried and, since the application is for construction, all types of weather are applied in the environmental context. Within the morphological characteristics, there is that of housing and sticky network and, in circular economy, four of the five characteristics were applied—regenerate, share, optimize and cycle.

The social welfare challenge's pinnacle analysis matrix is presented in Figure 7, where the two processes were taken for the imaginary pinnacle and the active form and macro-scale dominated. In the environmental context, the arid, the tropical and the temperate climates were predominant. In morphological characteristics, the herd was emphasized and, in the circular economy, the characteristic of sharing was.

		Process			Flow		Adaptation			Scale				Environmental Context					Morphological characteristics						Circular Economy				
Challenge	**Pinnacle**	Waste production	Use of resources	Ecological Impact	Active	Passive	Physiological	Morphological	Behavior	Nano	Micro	Meso	Macro	Arid	Tropical	Moderate	Temperate	Polar	Hexagons	Housing	Sticky web	Spiral design	Pores (stomates)	Flexibility	Regenerate	Share	Optimise	Loop	Exchange
Environmental Protection	Bees	X	X	X	X		X		X				X	X	X	X	X		X		X				X	X	X		
	Birds	X	X		X				X				X	X	X	X	X	X		X					X		X	X	
	Eastern Oyster		X		X		X		X				X		X	X	X				X				X		X	X	
	Moth flies	X	X		X				X				X	X	X	X	X	X				X				X	X	X	
	Beaver	X		X	X				X				X				X			X					X	X			
	Tree leaves			X	X			X					X		X	X	X						X		X		X		
	Earthworm	X		X	X		X		X				X		X	X	X	X						X	X		X		
	Imaginary pinnacle	*X*	*X*	*X*	*X*		*X*		*X*				*X*	*X*	*X*	*X*	*X*	*X*		*X*	*X*				*X*	*X*	*X*	*X*	

Figure 6. Pinnacle matrix analysis for the environmental protection challenge.

		Process		Flow		Adaptation			Scale				Environmental Context					Morphological characteristics			Circular Economy				
Challenge	**Pinnacle**	Life Quality	Citizen participation	Active	Passive	Physiological	Morphological	Behavior	Nano	Micro	Meso	Macro	Arid	Tropical	Moderate	Temperate	Polar	Wings	Cryptobiosis	Herd	Regenerate	Share	Optimise	Loop	Exchange
Social Welfare	Cicada	X		X			X		X					X		X		X				X			
	Tardigrade	X		X		X		X		X			X	X	X	X	X		X			X			
	Meerkats		X	X				X				X	X							X		X			
	Macaques		X	X				X				X	X	X						X		X	X		
	Imaginary pinnacle	*X*	*X*	*X*				*X*				*X*	*X*	*X*		*X*				*X*		*X*			

Figure 7. Pinnacle matrix analysis for the social welfare challenge.

The results for the pinnacle analysis matrix in the economic harmonization are presented in Figure 8. Operational savings processes predominated over quality. In adaptation, behavior was predominant and, in scale, macro was dominant. All morphological and environmental context characteristics coincided with the imaginary pinnacle, contrary to the circular economy, where only "sharing" applied.

Challenge	Pinnacle	Process: Operating saving	Process: Economic contribution	Process: Quality	Flow: Active	Flow: Passive	Adaptation: Physiological	Adaptation: Morphological	Adaptation: Behavior	Scale: Nano	Scale: Micro	Scale: Meso	Scale: Macro	Environmental Context: Arid	Environmental Context: Tropical	Environmental Context: Moderate	Environmental Context: Temperate	Environmental Context: Polar	Morphological characteristics: Pores (stomates)	Morphological characteristics: Locks	Morphological characteristics: Housing	Morphological characteristics: Distribution	Circular Economy: Regenerate	Circular Economy: Share	Circular Economy: Optimise	Circular Economy: Loop	Circular Economy: Exchange
Economic harmonization	Plants	X			X			X					X	X	X	X	X	X	X	X		X	X	X		X	
	Symbiosis (ants/plant	X	X		X				X				X		X				X	X	X			X			
	Birds	X		X	X				X				X	X	X	X	X	X			X			X	X	X	
	Colonies of insects			X	X				X				X	X	X							X		X			
	Imaginary pinnacle	*X*		*X*	*X*				*X*				*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*		*X*		*X*	

Figure 8. Pinnacles Matrix Analysis for the Economic harmonization Challenge.

Based on the pinnacle analysis matrix, we established the specifications for the design path matrix, where each imaginary pinnacle was classified and categorized with its corresponding trajectory [40]. Each vertical column represents a category and its various characteristics. The pink, light blue and green dotted lines in Figure 9 denote the trajectory of the imaginary pinnacles. The orange nodes emphasize the dominant characteristic of each category, representing the design concept's trajectory to address the problem and its approaches. These nodes contain the highest number of connections in the "challenge" trajectory, with the highest number of connections being the most dominant per category.

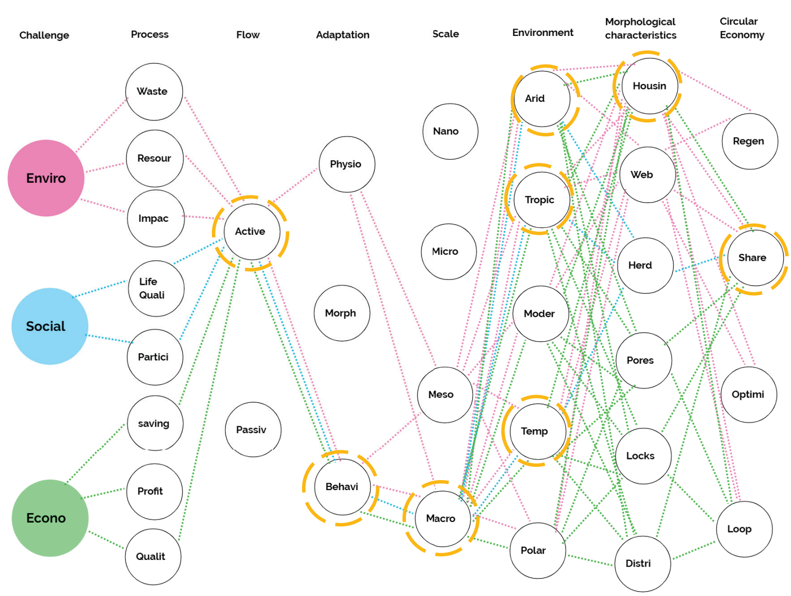

Figure 9. Design path matrix.

3.1.2. Road Map Definition

The design pathway matrix established the dominant characteristics in each category, considering the challenges of sustainability and circular economy. The active flow was predominant in the face of environmental protection (1), social welfare (2) and economic harmonization (3), indicating that the processes that would lead to sustainable construction must be dynamic, efficient and effective to meet the challenges presented. Likewise, for the three challenges, the influence of behavior prevailed, giving significance to the management of administration, technical knowledge and skills for construction, with the macro scale being the natural one. For the environmental context, all the elements were reviewed, highlighting the arid, tropical and temperate climates, pointing out the safety considerations that would change according to the type of project, location and attributes. In the morphological characteristics, housing was dominant, where its interpretation would be the provision of facility or service for which it is built. Finally, for the inclusion of the circular economy, sharing stood out from the ReSOLVE framework [17]. This emphasizes asset sharing, reuse and durability through maintenance, design and retrofitting. The inclusion of these elements would complement the definition of phases of the sustainable construction process, the evaluation of indicators in the literature and the relationship with technologies to support the process (Figure 10).

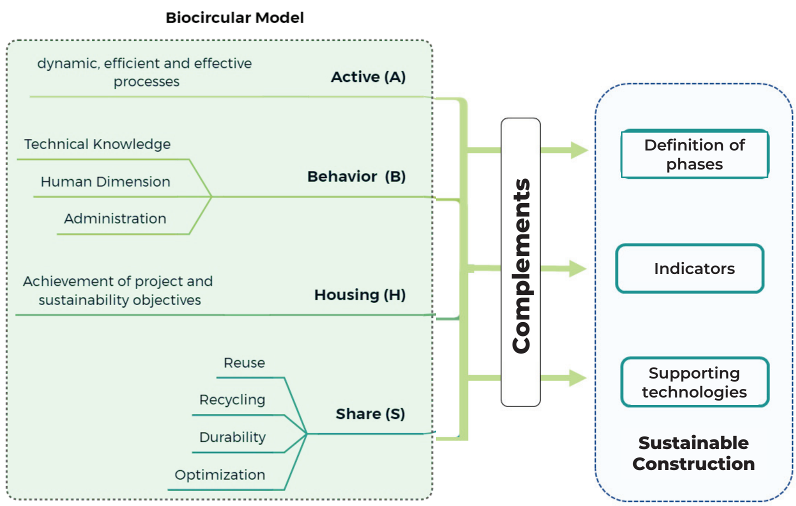

Figure 10. Biocircular model and its influence on sustainable construction.

(a) Supporting technologies

These tools enable better collaboration between stakeholders and multidisciplinary teams, reducing uncertainties and decreasing contingencies, risks and costs [32].

The new emerging technology of "Building Information Modeling (BIM)" has been promising for architecture, engineering and construction. This tool allows stakeholders to make decisions regarding sustainability in the early design and pre-construction phases by its concept of collaborative design of a universal computational model, which handles multidisciplinary information to be integrated into a model and motivates the analysis of environmental performance and sustainability metrics with a life cycle approach in these areas [32]:

- Construction orientation;
- Shape of construction;
- Natural lighting analysis;
- Water supply;
- Sustainable materials;
- Site and logistics management.

Geographic Information Systems provide opportunities for sustainability and cost saving in extending, operating and maintaining the built environment. The most widely used technologies in the industry are BIM and other traditional technologies, such as computer-aided design (CAD) systems for designing and storing building information. However, GIS complements BIM or CAD files in connecting relevant information at the site, municipal, or regional level [32] due to the following:

- It enables a more coordinated view and increases collaboration and understanding while reducing risks and associated costs.
- It provides visualization, analysis and comparison of possible alternatives to improve performance.
- It contains analytical tools necessary for stakeholders to decide which solution is the best to achieve in the short and long term.
- It supports the construction industry in the transition to sustainability, identifying green practices and patterns.

(b) Project Management for Sustainable Construction

To achieve the expected results of the project, three types of indispensable variables must be harmonized [36]:

- Technical dimension, namely, the areas of knowledge relevant to the nature of the project to be executed for its proper fulfillment, given a team of professionals to apply it.
- Human dimension, namely, aspects that can condition the success or failure of the project among all stakeholders. These include coordination, negotiation, participation, motivation and integration.
- Management, namely, where the work of the various resources is integrated and reconciled decisively for the production and fulfillment of results.

The success factors for any project, traditionally, include the final result, costs and time. Nevertheless, our route with the biomimetic and circular economy approach integrates sustainability challenges as another success factor in construction [13,36].

It is also essential to identify the stages of a project, since the motivation in this field of research is that not only the final products are green but so are the process [32] and what it entails, i.e., the identification of activities, deliverables and allocation of responsibilities among the executing team. In such a way, the abstraction of the dominant elements in the design path matrix is given, along with the definition of what each stage entails in sustainable construction. These descriptions are supported by the exploratory review of the stages described above in Figure 10.

3.2. Case Study Definition: Expert Assessment

A survey was distributed to construction professionals within the emulation phase to assess the level of acceptance of the phased definitions with the considerations of the biocircular model, by initially identifying the following at a personal level:

- Job position (director, designer, engineer, project manager, or contractor).
- The sector to which they belonged (public, private, or independent).
- Years of experience (less than 5 years, from 5 to 10 years, from 10 to 20 years, or more than 20 years).

Then, the first section, regarding consulting with professionals for knowledge in sustainable construction, biomimicry and circular economy, was presented for control. This included eight questions consulting the phases they identified for a construction project; the measurement by scale, from null to very high, of the knowledge of construction, biomimicry and circular economy; the most important attributes required to define sustainability in construction among those suggested; and the selection of the aspects considered the most important for the challenge to achieve sustainability in construction.

A second section regarded the proposed road map with the biocircular approach, in order to obtain evaluation and degree of acceptance of the proposal along with recommendations. A comparative table of the stage definitions was presented conventionally on the left and the right, with the biocircular approach highlighting the elements that sustainable construction contributes.

The third section was the SWOT analysis, presenting possible barriers found in [42] for selecting respondents, such as challenges, risks and difficulties of implementation, in the context of Panama. For opportunities and strengths, as well as perceived challenges, factors [43] were presented to be select the importance of which had to be established.

In addition, a final section for additional comments and recommendations was provided in a non-binding manner.

4. Results Analysis and Discussion

The following section presents the analysis of the results of the biocircular model implementation in each of the life cycle phases in sustainable construction projects, along with a brief discussion regarding the acceptance of such biocircular approach by experts in the field.

4.1. Application of the Biocircular Model to the Sustainable Construction Phases

As a complement, the biocircular model (Figure 10) approach was applied to the sustainable project phases' definition. Table 2 shows how each approach of the biocircular model impacts and complements each phase of the sustainable construction project phases.

(a) Initiation

During this phase, the groundwork is laid for proper project management and for the establishment of a common understanding of the critical elements for all stakeholders (from owners to community representatives) [2,36]. These elements would be the goals, objectives, scope, site selection and budget, along with the consensus to integrate sustainability for specifications and practices [11,23]. Therefore, it implies hiring relevant human resources for planning, design and management, as well as for feasibility and risk studies [2,11].

The budget should emphasize life-cycle costs, shifting the focus from short-term return on investment to long-term gains in green and local materials, material reuse, eco-efficient design and operational savings [2,25,43].

It is important to highlight the role of stakeholders, those who can influence or be influenced by the project, the conditions established by these stakeholders in the objectives and the risks to be considered for its completion [25].

(b) Planification

This consists of the detailed preparation of the regular work plan of the project staff, recognition of collaboration between technical sectors and the definition of tasks and milestones for the design. More detailed management plans are developed in terms of resources, quality, time, budget and procurement. In the sustainable context, the environmental impact assessment study in the area of influence is included, where the direct and indirect environmental consequences of the project's activities on the physical, biological and socioeconomic environments are recognized. This includes an environmental management plan that includes recommendations for mitigating impacts, preventing risks, providing environmental education and establishing mechanisms to include the public in decision making. Complementing the sustainable efforts, a waste management plan must be implemented, aligned with recovery and recycling. The main guidelines of the detailed project specifications, the green factors and the correlation with environmental policies that apply [11,23] are also constituted in this phase.

To achieve the defined, a solid understanding of the project specifications, factors and green benefits must be provided to the work team, since a critical green capability must be developed for the selection of sustainable materials, which is based on durability, costs, maintenance, local and recycled components— where sourcing locally would mean to reduce emissions from transportation and the promotion of reuse and recycling [11,18,23,43]. Social aspects include occupational health and safety programs for implementation and collaboration with suppliers to achieve environmental objectives [33].

Table 2. Biocircular Model Approach to each Sustainable Construction Phase.

Phases	Biocircular Model Approach			
	Active (A)	**Behavior (B)**	**Housing (H)**	**Share (S)**
Initiation	Organization among stakeholders on critical elements and productive capacity at the stage		Economic and social benefits of the project (opportunities to improve quality of life)	Considerations and scope of the sustainable engagement project
Planification	Organization in construction and occupational safety in terms of quality, control and maintenance		Identification of actions to be achieved	Selection of materials for the circular economy considering costs and ecological footprint
	-	Planning of the work team in the areas of knowledge with responsibilities		
Design	Integration of BIM as a decision-making tool, allowing the following to be performed: for energy design guidelines, environmental performance assessment, cost estimation according to the variety of design options, etc.			
	Effective communications among designers, clients, environmental specialists and government to ensure that all requirements are incorporated		-	-
Construction	Stakeholder meetings before project milestones are initiated or completed		-	-
	Compliance with occupational health and safety measures		-	-
	Execution of the schedule of activities on time and compliance with quality standards			-
	Collaborative emission monitoring among all members (including subcontractors) on-site through BIM and optimization of rolling equipment routes to decrease emissions			
Monitoring and control	Identification of issues through performance indicators and BIM, as well as management responsiveness.			Performance monitoring of measures related to the reduction oin emissions, solid waste, wastewater, material consumption and environmental risks.
Delivery	-	Compliance with environmental objectives, correct operability, delivery of maintenance descriptions and stakeholder satisfaction.		

Similarly, project progress and quality metrics should be defined, which could be qualitative or quantitative for the monitoring and control stage, to optimize the path of milestones and activities necessary to meet the scope.

(c) Design

This phase contains the use of best practices to maximize the design results of the construction project, the evaluation of the costs of sustainable strategies for environmental benefits and the accuracy of combinations of design strategies [23]. Among its categories for reducing environmental impact there were variations according to the type of construction project, but the following stood out: materials and resources, waste reduction, energy efficiency, water savings, comfort, site management, recycling and reuse—with a view of adaptive and environmentally friendly designs [7,23,24,32]. Design considering the most efficient use of natural light and ventilation, safety in case of environmental accidents and the legal requirements that apply are among the most prominent [7,11,32]. Thus, the integration of qualified contractors and subcontractors is essential to reach a common design vision and avoid future problems [11].

Considerations at this stage [18,25,43] are as follows:

- Increase in or maintenance of green space;
- Reuse, recycling or recovering of materials or parts of materials;
- Design for reduction in material, water and energy consumption;
- Avoidance of using materials that become hazardous waste;
- Consideration of the use of renewable energy;
- Adaptation of design options to environmentally impactful scenarios (waste production, emissions, etc.);
- Recovering of water and energy;
- Long-term planning for climate change risks and their effects;
- Modular design;
- Innovation capacity.

(d) Construction

This phase consists in the execution of construction and general mobilization work in an effective manner, with a focus on minimizing resources, waste and emissions to reduce ecological impacts [11,25,32]. It is important to contemplate periodic environmental education and training on the sustainable construction strategies that apply, including the specifications and technologies that would be used to optimize processes [2,11,43]. Compliance with the work schedule, quality management systems, safety and health in construction are other factors in this phase [24].

For construction, the environmental management plan containing the environmental management procedures must be carried out, particularly, the management of air and noise pollution, water and energy use, occupational health and safety, resource utilization, transportation and emissions, solid waste, quality standards and legislation [7,25,31]. For solid waste, waste quantity reduction and sorting for recycling or sale to recycling facilities need to be considered [11].

Some sustainable actions that can be carried out are [4,18] the following:

- Reuse of elements—building components, rubble, concrete, steel and wood;
- Having containers for waste sorting on site;
- Installation of efficient plumbing for water use;
- Purchase of nearby available material to reduce air pollution produced by vehicles;
- Reuse of excavation materials for backfill;
- Increase in or maintenance of green areas;
- Limitation of tree, soil and habitat disturbance.

(e) Monitoring and control

In the framework of project management, this is a decisive phase for the success of a project and its implementation is continuous from the beginning, since it allows stakeholders to verify whether the project plan is being implemented as planned or whether certain actions need to be corrected. It includes receipt and authorization of work, change and version management, analysis and performance reports on integrating sustainable factors and corrective and preventive actions [36]. Thus, meetings among project stakeholders, as well as inspections, should be performed with high frequency to identify progress over time, verify the performance of sustainable actions to minimize impacts (emissions, waste and material consumption), quality assurance, risk prevention and problems to be addressed on time [2,11,43].

(f) Delivery

This stage is where the project is finalized and ready to be handed over to the owner. A checklist and tests are performed to ensure compliance with criteria and the project's environmental objectives to verify operational performance and quality. It is important to obtain the satisfaction of all stakeholders [2,11,23]. For the sustainable construction context, the lessons learned and the capacity of building with this process, its proper completion and the milestones it would bring in terms of reputation are all important [43].

Now, the continuation stages are no longer of the process but the product. In general, these stages are intended to provide a guide for operation and maintenance according to the type of project that applies. These plans should combine cleaning, work practices, training and surveillance [25]. Emphasis should also be placed on the constant monitoring of environmental and social performance metrics to be applied to environmental management, energy, carbon footprint reduction, solid waste, landscape, water and environmental education campaigns [24].

If abandonment is included, options for transformation and adaptive reuse should be evaluated, as well as the use of materials to recover energy and prioritize disassembly and transformation over complete demolition [18].

4.2. Application of the Biocircular Model to the Sustainable Construction Metrics

Complementing the road map with the biomimetic and circular economy approach, 12 articles with indicators were identified in the literature review for the construction life cycle. These were filtered from the general to the specific, giving 7 articles with proposed indicators for the evaluation of the biocircular model: 11 quantitative indicators and 19 qualitative indicators, presented in Tables 3 and 4.

Table 3. Quantitative Indicators evaluated by the Biocircular Model.

Reference	N°	Quantitative Indicators	Phases						Biocircular Model			
			I	P	D	C	M	De	A	B	H	S
[8]	1	Job creation (N°)	*			*			*	*		
	2	Rate of return (cost-benefit) ($)	*	*						*	*	
	3	Net income ($)	*	*					*	*	*	
	4	Complaints (N°)				*	*	*	*	*		
[28]	5	Training of staff in environmental awareness (N°)		*	*	*			*	*	*	
[29]	6	Monitoring and compliance inspections (N°)				*	*		*	*	*	
	7	Equipment maintenance (N°)		*		*	*		*	*		*
[34]	8	Amount of water saved (m^3)		*	*	*				*	*	
	9	Amount of water recycled (m^3)		*	*	*				*	*	*
	10	Amount of energy savings (kWh)		*	*					*	*	
[42]	11	Follow-up of the Environmental Management Plan, ratio of objectives reached		*	*	*			*	*	*	

Table 4. Qualitative indicators evaluated by the biocircular model.

Reference	N°	Qualitative Indicators (Yes/No)	Phases						Biocircular Model			
			I	P	D	C	M	De	A	B	H	S
	1	On-site waste separation		*		*			*		*	*
	2	Reuse of construction elements (earth, concrete, steel, wood and other components)		*	*	*			*	*	*	*

For these, only four qualitative indicators complied with the four concepts of the biocircular model, namely, reuse of construction elements (earth, concrete, steel, steel, wood and other components), reuse of excavation materials for backfill, use of local material to reduce emissions and water reuse system. These account for 21% of the total qualitative indicators. Within compliance of three concepts, five indicators were found, giving 47% among the qualitative indicators. For the quantitative indicators, no indicators were found that complied with the four concepts; however, 6 of the 11 (54%) complied with three concepts. For future studies, indicators that comply with the biocircular model can be defined.

4.3. Experts Assessment to the Proposed Biocircular Model

Twenty-seven responses were received from professionals (Figure 11), with the most predominant among the defined options being the positions of engineer, with 12 respondents (44%), and designer, with three respondents (11%). The other option was the second most frequent, with 30%. The majority were from the public sector and were present in all the established experience ranges. The most frequentely selected option, among professionals, was 5–10 years of experience.

The classification of attributes considered the most important to define sustainability in construction, presented in Figure 12a, was highly pronounced and coincided among professionals, regardless of their knowledge in sustainable construction (high, medium, or low). The most influential, for the definition, was the minimization of impacts, environment, waste and energy. The least considered for the definition was the economy. This reflects the need to join efforts to raise awareness of the benefits for investors of sustainable construction and its concepts of savings in materials, design and operation.

Dividing by sustainability challenges considered for the biomimetic methodology (Figure 12b), social welfare and citizen participation predominated, this being the fundamental social aspect for construction, since it is linked to the acceptance of projects in the influenced area. Economic harmonization was more closely contested among respondents, with economic benefits being the most popular by only one-tenth. This means that the aspects placed were considered of equal importance and influence. Finally, for environmental protection, the perception was equal for the factor of waste production (minimize, reuse and recycle) and resource utilization (optimize). These factors are important for reducing the ecological impact of construction. Additionally, they were asked if they would consider the inclusion of sustainability and unanimously agreed.

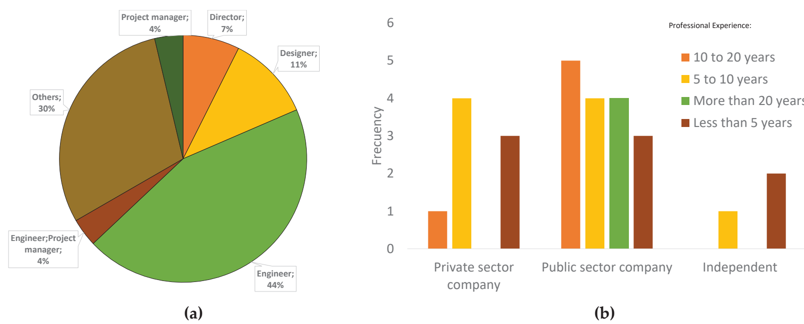

Figure 11. Professionals surveyed: (**a**) by job position and (**b**) by job sector according to years of experience.

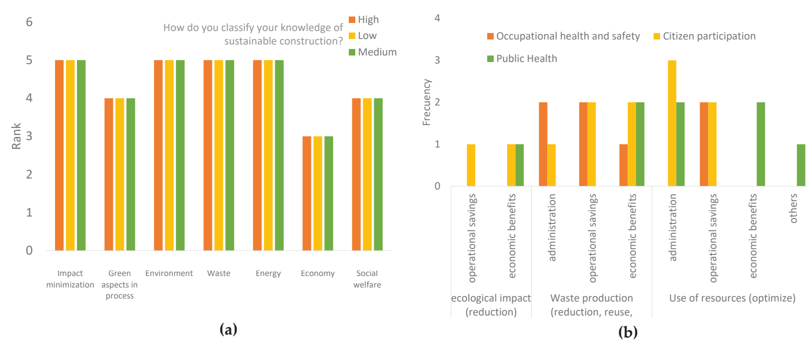

Figure 12. Results for: (**a**) attributes considered the most important for defining sustainability in construction and (**b**) the most important aspects considered to achieve sustainable construction.

The levels of acceptance of the phases with the biocircular approach are presented in Figure 13. It should be noted that the definitions presented in the comparative table are a summary of the complete text for each one in this article.

As depicted in Figure 13, the phase with the best reception was the initiation phase (a), with 93% agreeing, including high, low and medium knowledge in sustainable construction. Only one professional stated that he disagreed and, by his own consideration, his knowledge in sustainable construction was low. This means that the importance of establishing early on the objectives and reaching a common vision among the stakeholders is of great interest for the approval of the professionals.

The phases of design (b), monitoring and control (e) and delivery (f) had 85% approval. One professional disagreed and four were neutral. There were variations in the distribution between agreeing and strongly agreeing. Delivery was the one with the highest frequency and the highest approval score, which could be due to the definition with the objectives and procedures. However, the participant with high knowledge weighted his perception as neutral.

For the planning phase (c), there was an acceptable 81% and, as it was identified among the patterns by the literature review, planning and design were binding; perhaps the summary presented should have shown more justification in the activities. Among the knowledge of sustainable construction, agreeing had a greater presence of levels, including high.

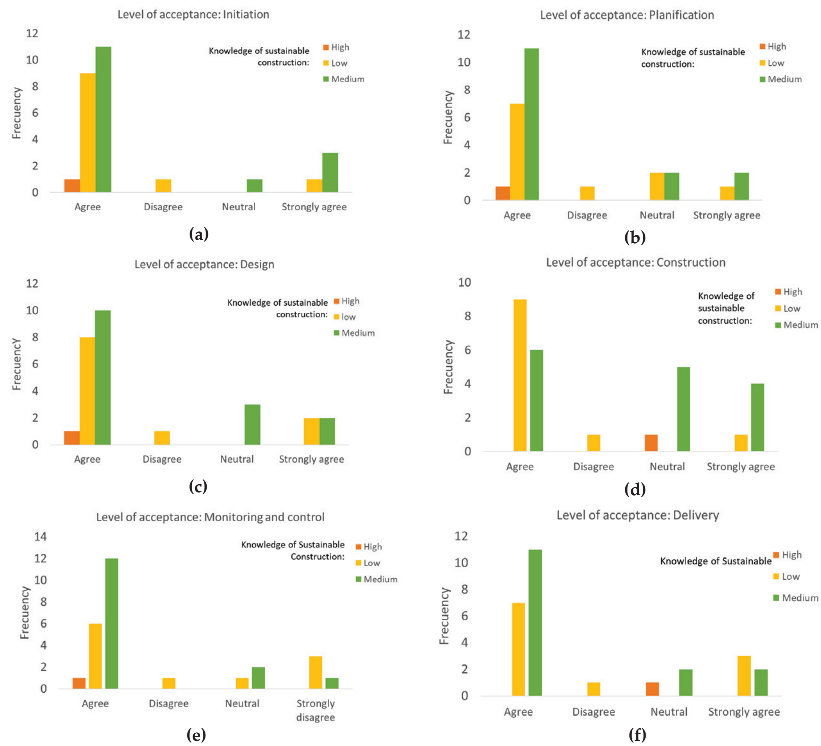

Figure 13. Results of phase acceptance based on the level of knowledge about sustainable construction: (**a**) initiation, (**b**) planning, (**c**) design, (**d**) construction, (**e**) monitoring and control and (**f**) delivery.

With 73%, the definition of the construction stage was the lowest among the six and, according to professionals with high and medium knowledge, a neutral position was maintained. Therefore, the activities and the sustainability factor in these activities should be studied in greater depth.

In general terms, the definitions of this road map with a biocircular approach had a 83% acceptance among those consulted (Figure 14). Among the recommendations, there were the following:

- Give greater publicity to sustainable construction and circular economy issues, addressing designers, builders and investors;
- Consider design and material safety standards to be implemented;
- Present BIM opportunities in more depth (general aspects were included in the survey, but not the technology itself and its opportunities).

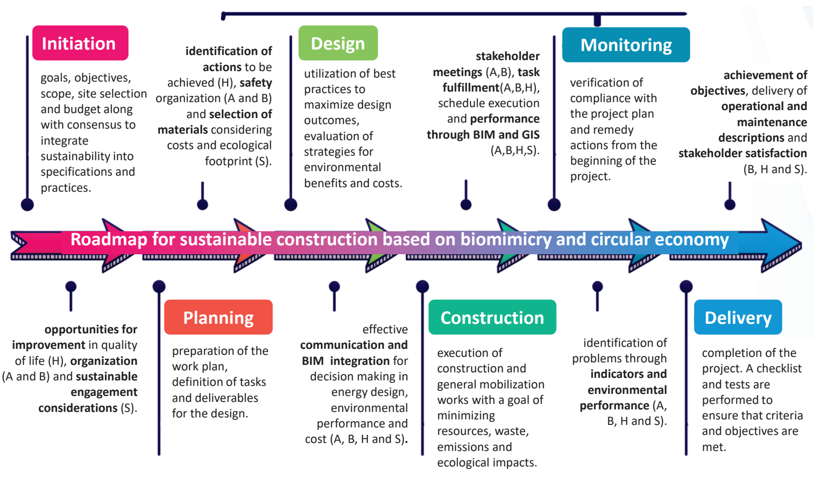

Figure 14. Summary of the road map phases definition with the accounting for the biocircular model approach.

4.4. SWOT Analysis of Proposed Biocircular Model

The survey included a bank of suggestions for sustainable construction in terms of barriers and opportunities. In these, the professionals categorized them into strengths, opportunities, skills and threats, which are shown in Table 5. It was emphasized that the professionals identified these challenges in the context of Panama, in consideration of the lack of knowledge of sustainable construction practices, the lack of governmental support and human attitudes towards change. Similarly, the strength in terms of reputation, automation in strategies and waste optimization were highlighted and the opportunities presented in terms of economic benefits and training.

Table 5. SWOT analysis obtained from the survey.

Strengths	Opportunities
1. Automation in design estimation, costs and strategies (BIM) 2. Motivation to apply green technologies and methodologies 3. Optimization of processes reducing environmental impacts 4. Good reputation 5. GHG emissions monitoring (GIS and BIM)	1. Focus on reduction in material and energy consumption 2. Waste reuse, recovery and recycling 3. Automation in design estimation, costs and strategies (BIM) 4. Cooperation with staff and suppliers to meet sustainable goals 5. Motivation to apply green technologies and methodologies 6. Choosing quality and environmental design certifications 7. Economic benefits from eco-efficient materials 8. Training of personnel in environmental issues 9. Reduction in contamination in physical media (air, soil and water) 10. Waste reduction 11. Reduce frequency of environmental accidents

Table 5. *Cont.*

Strengths		Opportunities	
		12. Improve the company's operational capacity 13. Improving personnel skills 14. Socio-environmental responsibility 15. GHG emissions monitoring (GIS and BIM)	
Risks/Threats	**Rank**	**Challenges**	**Rank**
1. Variation in material prices.	3	1. Lack of knowledge of sustainable construction practices.	5
2. Lack of technical knowledge.	4	2. Lack of environment-friendly materials.	4
3. Delay in decision making.	3	3. Lack of accessible guidance.	4
4. The price of the internship application.	4	4. Resistance to change in the adoption of new practices.	3
5. Lack of customer demand.	4	5. The application price of sustainable practices.	4
6. The fragmented nature of the industry.	4	6. The customer is concerned about profitability.	4
7. Poor management and communication.	4	7. Lack of knowledge of the benefits.	4
		8. Time for implementation of new practices.	4
		9. Lack of government support.	5
		10. Human attitudes to change.	5
		11. Poor management and communication.	4

5. Conclusions

This study represents a valuable opportunity for the field of project management and sustainable construction, because it includes the application of the biomimetic methodology to unify its definitions and elements and it allows the circular economy to be innovatively and creatively included in the activities by emulating nature and its self-sustainability. In this way, a defined framework is obtained for all stages of construction, the considerations to be taken within their practices and evaluation of quantitative and qualitative indicators applicable in the phases. Likewise, the exposure of benefits for the environment, investors, designers and contractors through the optimization and automation of the process itself, the costs, risks and success are considered.

In the context of Panama, this study symbolizes a precedent in the field and sensitization of professionals with experience in the country on the relevance of the topic, concepts and components to influence the construction and transform it towards sustainability. In line with this, relevant recommendations can be stated as follows:

- Give relevance to each stage of the sustainable construction process, mainly the earliest ones and those of follow-up and control, to take corrective measures and evaluate performances.
- Invest in green technologies for waste management, water and energy savings, as well as their sources.
- Train personnel in sustainable construction, health and safety practices and sensitize them with ongoing environmental education, e.g., as in [44,45].
- Maintain collaboration among all project stakeholders and ensure that they master the benefits of sustainability and circular economy.

Finally, future work could validate the biocircular model within a case study of construction and make improvements, as well as contemplate specific practices within the phase definitions. Among the limitations, we report the summary of the context of the research and the definitions of each phase for the survey distributed to professionals with low background in the subject and its applicability to the different types of existing construction.

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Review

Bio-Inspired Electricity Storage Alternatives to Support Massive Demand-Side Energy Generation: A Review of Applications at Building Scale

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Abstract: This work has its origin in the growing demands of energy regulations to meet future local targets and to propose a global implementation framework. A literature review related to conventional electrical energy storage systems has been carried out, presenting different cases analyzed at building scale to deepen in nature-inspired processes that propose reductions in environmental impact and present improvements in these storage devices. The use of batteries, especially lithium-ion batteries, is the most prominent among the electrical storage applications; however, improvements have been proposed through hydrogen batteries or the implementation of more environmentally friendly materials to manufacture the electrodes. In this sense, oriented to creating systems designed to protect the environment, important advances have been made in the development of storage systems based on biomimetic strategies. The latter range from the generation of energy through the respiratory processes of microorganisms to the recreation of the generation, storage, and release of energy using the thermoelectric and thermoregulatory characteristics of some insects. These facts show that the trend in research towards improving existing systems continues but reinforces the idea that new solutions must be environmentally friendly, so there is still a long way to improving the processes established thus far.

Keywords: biomimicry; buildings; electricity; energy; storage systems

1. Introduction

Globally, increasing demands are identified within their energy regulations, and in order to meet future goals, renewable energy systems have been implemented to supply the amount of energy required in a timely and environmentally friendly manner. These renewable energy sources need a storage system to supply the demand when the source cannot supply electricity. Although these systems already exist, they are not entirely "green" for the environment.

Energy storage systems (ESS) convert electrical energy from power systems into a form in which it can be stored and subsequently transformed into electrical energy when required by the consumer. Energy systems play a key role in collecting energy from various sources and converting it into forms of energy needed for various applications in various sectors such as utilities, industry, transportation, and construction [1]. Energy storage can provide several advantages for energy systems such as allowing higher penetration of renewable energy, reducing energy losses in the distribution system, increased reliability and customer satisfaction, better economic performance, among other factors. Even energy storage is of great importance in power systems as it allows load leveling, peak shaving, frequency regulation, damping of oscillations, and improvements in power quality and reliability.

The operation of energy storage systems, according to [2], is categorized into:

- Charging period: the power grid is used during off-peak intervals when electric power is at a lower cost.
- Discharge period: at peak demand time, the stored energy is used. During this period, the grid has a higher cost, so the use of distributed generation makes it more economical. Consequently, storage systems are applied to reduce or eliminate the uncertainties of distributed generation.

In terms of capacity, these systems are divided into:

- Large-scale storage (GW): reversible hydro (pumped), thermal storage.
- Grid and generation asset storage (MW): cells, batteries, condensers, superconductors, flywheels.
- End-user storage (kW): batteries, superconductors, flywheels.

Before, this originated the present qualitative and descriptive study to highlight all those advantages and disadvantages, among other technical aspects with the different conventional electrical energy storage systems. An extensive literature review of the different conventional electrical storage systems was carried out, together with an application at different scales, such as residential and commercial, to compare them.

Taking these factors into account, we searched for mechanisms inspired by nature that have the capacity to generate and store electrical energy in order to have a set of pinnacles that serve as a basis for the design of an electrical storage system that reduces the environmental impact. Among different studies reviewed, the criteria, principles, and characteristics of how such biomimetic approaches could be used in conventional systems are presented.

2. Materials and Methods

This research is based on developing a descriptive and qualitative methodology of both the different types of electrical energy storage systems and the organisms ("pinnacles") that generate or accumulate electricity naturally.

The EBSCO, MDPI, Elsevier, and Google Scholar databases were used to investigate conventional storage systems, while, for the part of the mechanisms inspired by nature, databases such as Springer US, Journal of Biological Engineering, and Ask Nature were used.

The Boolean operators (AND, OR, NOT) combined with the keywords electrical storage systems, buildings, nature, and biomimicry were applied as a search strategy (Figure 1). The search period was based on the last five years (2016–2021).

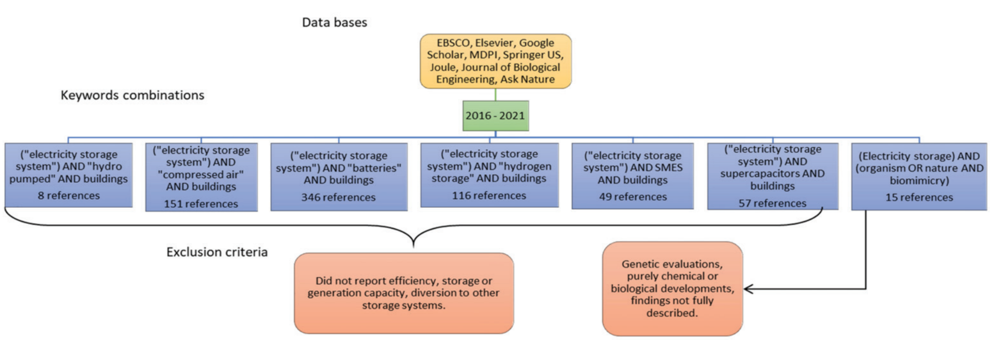

Figure 1. Literature search strategy. Own elaboration.

For the conventional section, there were no problems since there were indeed several studies related to electrical energy storage applied to both residential and commercial buildings; even so, those articles that involved other types of storage such as thermal storage were discarded. Likewise, with the section on mechanisms inspired by nature, articles in which the topic was more focused on aspects such as genetics of living beings, totally chemical or biological approaches were discarded.

3. Conventional Electricity Storage Strategies: Concept and Applications at Building Scale

Energy storage systems have been a fundamental piece for renewable sources since they can supply the energy demands when the system cannot. In this section, different study cases are presented applying each configuration at a building scale in different types of climates. At the end of this section a summary of the studies encountered including advantages and disadvantages of each conventional electricity storage systems is presented.

3.1. Pumped-Hydro Energy Storage (PHES)

Pumped-hydro energy storage (PHES) has two reservoirs or basins (one high and one low) connected via tunnels and shafts through which water can be passed from one point to the other. Hydro turbines, pumps, and valves are found to control water's flow from one reservoir to the other and generate electricity when necessary [3]. In this type of system, electrical energy accumulates electricity in hydraulic potential energy form by means of an electric pump that carries water from a lower level to a higher-level during hours of low energy demand. The turbine is connected to an electricity generator. The inlet flow of water can be controlled using gates to allow a variable power output. In addition, variable-speed drives can be used to provide regulation during the charging state [1].

Today's metropolitan cities have a natural height difference for potential energy, an advantage that has not been fully exploited. This gives rise to improving the use of renewable sources in a photovoltaic configuration co-connected to the grid together with hydro-pump storage. For example, a study was conducted in 2020 (Shanghai, China) based on the city's electricity pricing policies to develop the feasibility of renewable technology applied in residential villas and apartments [4].

Figure 2 illustrates the array of this system equipped with photovoltaic panels for its generation and the pumped-hydro energy storage. Its control, apart from acting as an inverter, also behaves as a control for electricity distribution. The study focuses on the fact that the pumping system can store excess energy from the photovoltaic (PV) system by pumping the water to the upper reservoir, where it will be used when it does not meet the required demand [4].

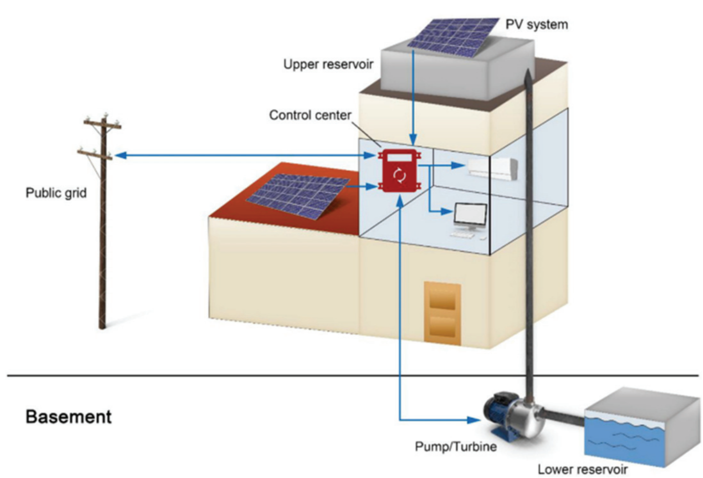

Figure 2. Configuration of the PV arrangement with the hydro-pump system [4]. No changes were made to the original figure.

The installed capacity of the whole system is 5 kW, according to Shanghai applications. The villas are three stories with a height drop of 13 m, an upper reservoir with a volume of 100 m^3 was installed, the pumping coefficient of the storage system was 24 m^3/kW, and that of the generation turbine, 0.0319 kW h/m^3. For this case, the consumption of the villa load is defined as twice the electricity consumption of an apartment household. The apartment consisted of seven floors with a height drop of 22 m, the same volume was used for the upper reservoir of the system, and the pumping and turbine coefficients were 14.19 m^3/kW h y 0.0539 kW h/m^3, respectively.

As a result, it was shown that the system is more viable for an apartment building than for the villas since, comparing the state of loads of both, the pumping system in a villa only operated in a so-read period (10 a.m.–6 p.m.); after this time, the water storage is null so it does not provide energy to the residents, In addition, the villa depends on the national grid after 7:00 p.m., while the case of the apartments reflected a longer duration to supply energy (10:00 a.m.–10:00 p.m.) and its storage maintained more than 10–30% of the water volume during the days demonstrating that the pumping system has enough potential to ensure the generation of electricity. However, for both cases, the power generated from the PV systems on cloudy or rainy days was ineffective for water storage in the reservoir. The self-consumption and self-sufficiency rates for the apartment were 59.69% and 76.47%, while, for the villa, they were 66.25% and 45.13%, respectively, concluding that, in the energy balance, the results show that the apartment absorbs more surplus energy from the PV system rather than selling it to the grid. In addition, the system is able to feed the appliance load compared to the villa by reducing the proportion of energy supplied directly from the grid [4].

3.2. Compressed Air Energy Storage (CAES)

In compressed air energy storage systems, also known as compressed air energy storage (CAES) systems, the air is compressed and stored in an underground reservoir as long as there is excess energy. Usually, underground reservoirs are caverns drilled in salt or rock formations, abandoned mines, or existing cavities of minerals or aquifers. If energy is needed, stored air will expand to a turbine which generates electricity [1,5].

In 2018, a study of a prototype system was presented, which consisted of the use of a photovoltaic array coupled with CAES to compress air and, when expanded, generate the demanded electrical energy. This small-scale system was located in an unoccupied basement of a building in Cittá di Castello (Perugia, Italy). The system associated with the residential photovoltaic plant is shown in Figure 3. The study carried out three scenarios for its energy storage: small-scale CAES using 30 bar compressor pressure, small-scale CAES at 225 bar, and, finally, a lead-acid battery in order to make a comparison between them [6].

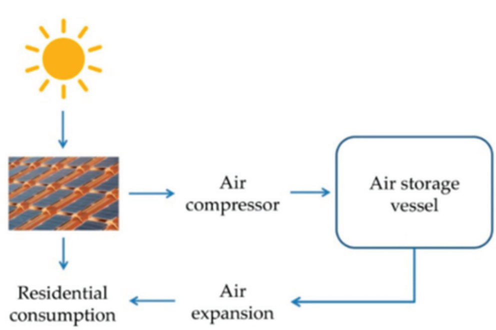

Figure 3. Compressed air energy storage system (CAES system) connected with the residential photovoltaic (PV) plant [6]. No changes were made to the original figure.

The photovoltaic energy production used for air compression is between 26.9 kWh/day in terms of average energy consumption of a residential building on a summer day, and a compressor with a flow rate of 4 Nm^3/h was considered for the results below:

- With a pressure of 30 bar, the compressor absorbed 8702 kWh of excess PV energy in a 1.7 m^3 vessel. Expanding through the turbine generated 1008 kWh in 38 min which covered 21.9% of the residential energy demand.
- At a pressure of 225 bar, 96% of the excess PV energy was absorbed within a 0.25 m^3 enclosure. The expansion generated 1273 kWh, which covered 26% of the residential energy demand.
- Using the lead-acid battery with 80% charge efficiency was able to cover 100% of the total demand, which was equivalent to 4.6 kWh, demonstrating that, in terms of overall efficiency, the CAES system is less than any electrochemical battery system.

3.3. Flywheel Energy Storage System (FESS)

This type of system consists of a mechanical energy storage form that is suitable for achieving the smooth operation of machines and providing high power and energy density [1]. A flywheel uses a rotating mass to store energy which is held in the kinetic energy of rotation of the rotor. The amount of stored energy is proportional to the moment of inertia of the rotor; hence, increasing rotational speed will increase storage capacity, but higher speeds offer a more efficient way of raising capacity. However, high speeds can make severe demands on the materials used in flywheel construction [7]. This kinetic energy is transferred in and out of the flywheel using an electrical machine that acts as a generator or motor depending on whether the system is in charge or in discharge mode. Generally, permanent magnet machines are common for this type of system due to their high efficiencies, high densities, and low rotor losses [8]. Flywheels convert the electrical energy surplus into motion in a high-speed rotating disk that is connected to an electric motor [9]. The main components of the FESS systems are shown in Figure 4.

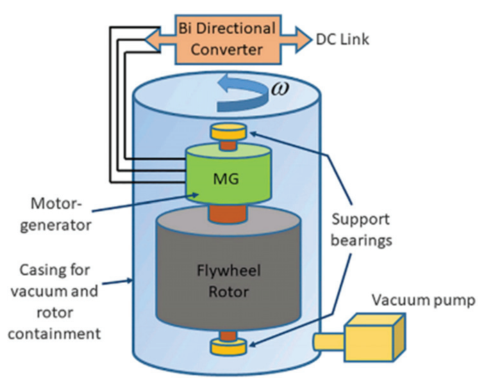

Figure 4. Components of a flywheel system for electrical storage based on [8] reproduced by [10].

3.4. Battery Energy Storage System (BESS)

Electrical energy can be stored electrochemically within batteries or capacitors. Batteries are the most used devices for electricity storage purposes. They can react instantaneously to changes in energy demand, and the type of cells used together to generate electricity can deliver and absorb energy quickly. During the chemical reaction of batteries, 80% or more of the energy is released to convert it into electrical energy, but this percentage varies with the type of battery, discharge rate, among other aspects [11].

Currently, there are several types of batteries, such as lithium batteries, including lithium-ion and lithium hydride batteries which represent the most popular battery type among consumer electronic devices due to their low weight, low self-discharge, high energy density, and long cycle life. Lead-acid batteries were one of the first batteries to be developed and were used for load leveling in some power distribution systems. There were also nickel-cadmium batteries that had high energy densities and were lighter than lead-acid batteries, and were even used in cell phones and laptops; however, they were replaced by lithium-ion batteries [11]. Continuing with the nickel battery family, nickel-metal hydride batteries function as another substitute for nickel-cadmium batteries due to their high energy densities and the absence of toxic metals representing less impact on the environment. Unlike lithium-ion batteries, this type of battery has a longer life cycle and better price [12]. Table 1 presents a comparison between the characteristics of the different types of batteries in terms of nominal voltage, life cycle, energy density, and self-discharge.

Table 1. Comparison of characteristics between the different types of batteries according to [13].

Battery Type	Nominal Voltage (V)	Life Cicles (N° of Cicles)	Energy Density (Wh/kg)	Self-Discharge
Lithium-ion (Li-ion)	3.6	500–1000	110–160	Very low
Lead-acid	2	200–300	30–50	Low
Nickel-cadmium (Ni-Cd)	1.25	1500	45–80	Moderate
Nickel-metal hydride (Ni-MH)	1.25	300–500	60–120	High

In 2016, a comparison was made between different types of batteries (Lead Acid, NaNiCl, Lithium) for energy storage together with a photovoltaic configuration for residential buildings in Sweden where the average peak consumption was in February with a value of 2419 kWh and average production of 5.20 kWh while the lowest consumption was in June with average consumption and production of 1224 kWh and 0.51 kWh, respectively. Among the battery comparisons, the lithium battery with a modular capacity of 7 kWh and efficiency of 92% was highlighted, concluding that this type of battery provides a high self-sufficiency rate, which made it quite convenient for the case study due to its seasonal changes, storing excess energy in summer for consumption in Winter [14].

Vanadium-redox batteries (VRBs) are also available in the market since, thanks to their attractive characteristics in terms of a long-life cycle, high energy efficiency, and low maintenance cost, the use of these batteries has been employed in the residential sector together with photovoltaic generation, and it has proven to be cost-effective to date. In 2016, the authors in [15] proposed an optimal sizing method for vanadium redox battery systems in residential-scale applications considering aspects of cost, battery efficiency, time-varying electricity price, solar feed-in tariff, user consumption, and PV profiles. It provided guidance for capital cost calculation, maintenance of the system itself, and an approach to charge/discharge efficiency evaluation of these batteries. These types of systems are based on the scheme in Figure 5.

Recently, new electrode and electrolyte materials have been developed to improve the advantages, cost, and safety of these devices. Batteries and supercapacitors are usually compared to each other, with batteries having better storage capacity by more than 30 times the charge per unit mass than supercapacitors; however, supercapacitors are able to deliver up to thousands of times the power of a battery of the same mass because they accumulate energy by adsorption reactions on the surface of the electrode material [1].

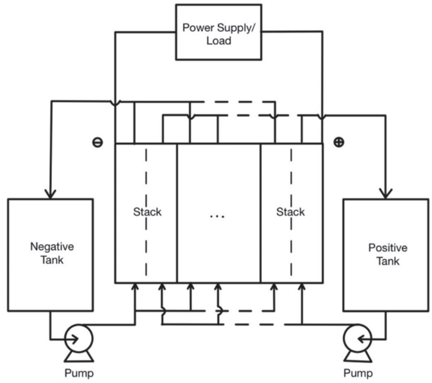

Figure 5. Basic configuration of the vanadium-redox system which consists of electrolyte tanks (positive and negative), stacks, endplates, and pumps [15]. No changes were made to the original figure.

3.5. Supercapacitor Energy Storage System

Capacitors are electronic devices that store electrical energy directly in the form of electrostatic charge. The simple arrangement of a capacitor consists of two metal plates separated by a small air gap. When voltage is applied across the device, the plates become statically charged; when the voltage is removed, the charge remains until a short circuit between plates occurs. The amount of charge accumulated on each plate creates an electric field that balances the charge generated by the voltage [16].

A conventional capacitor operates in the order of millifarads. A supercapacitor stores energy in the order of farads and more, whose fundamental characteristic is denoted by its ability to charge and discharge in seconds or less time. One application of this device is the electric car since the charges and discharges of a supercapacitor allow the car to recover part of its autonomy faster and more efficiently [17]. On the other hand, they have limited storage capacity. Current supercapacitors have a storage energy density of about one-tenth that of a lithium-ion battery. The voltage of these devices drops as their charge also drops, while that of a battery remains about the same for most of its de-charging cycle. This affects how each can be used [16].

There are three types of supercapacitors according to [17] as these are classified according to the composition of the dielectric material or conductor used:

- Electrochemical double-layer supercapacitors (EDLC): this electrochemical double-layer capacitor uses its two charge layers when a voltage is applied to an electrode (made of highly porous carbon) immersed in an electrolytic substance. Its slight charge separation generates capacitances on the order of 40–60 F/cm^3. Unlike conventional capacitors, the energy required to enter the breakdown field is very high and is usually calculated in V/cm.
- Supercapacitors with pseudocapacitance: this type of supercapacitors store charges in a faradic form rather than electrostatical by means of a charge transfer between an electrode and an electrolyte. They can be composed of polymer materials or metal-oxide compounds and, therefore, have different costs, conductivity, pseudocapacitance, and application characteristics. A supercapacitor based on metal-oxide composites has a high energy storage density and therefore is very similar to EDLC capacitors.
- Hybrid supercapacitors: they are a mixture of EDLC supercapacitors together with pseudocapacitors since this system combines both faradic and non-faradic processes to store the charge. Currently, several tests have been carried out with different elements such as ruthenium dioxide (RuO_2), cobalt oxide (Co_3O_4), nickel oxide (NiO), vanadium oxide (V_2O_5), nickel hydroxide ($Ni(OH)_2$, and manganese oxide (MnO_2), the latter having the best qualities since it is abundant and friendly material on

Earth. This type of supercapacitor is widely used in battery systems to improve their efficiency.

3.6. Superconducting Magnetic Energy Storage (SMES)

To achieve magnetic superconducting energy storage (SMES), a large superconducting coil can be used with almost no electrical resistance near absolute zero temperature and yet is capable of storing electrical energy within the magnetic field generated by direct current flowing through the field. SMES coils present large amounts of energy instantaneously and upon discharge, as well as an unlimited number of charge and discharge cycles with high efficiencies. Their energy discharge capacity is less than 100 ms, which presents a faster response time than batteries; however, the system requires constant cooling [18]. The main parameters for SMES design that could affect its storage are coil configuration, energy capacity, and operating temperature [1].

Some of the applications that include SMES are load leveling, system stability, voltage stability, frequency regulation, transmission capacity improvement, power quality improvement, automatic generation control, and uninterruptible power supply [1].

According to [18], SMES systems can stabilize the power grid by providing power quality to consumers even though such systems are costly. The same comprises distributed generation (DG) structures connected to the grid. The power generation plant, the conversion, and the storage unit are the main components of a commercial distributed generation facility. The conversion and storage components consist of an electrolyzer, fuel cell, tanks capable of controlling the rapid variations of electrical power, and its sudden demands from consumers. Resistance losses in SMES after its charging period are almost zero due to its superconducting coil. The cooling mechanism serves to keep the temperature of the superconducting coil below its critical value, such as Niobium–Titanium (NbTi), a superconducting material used for coils and liquid helium or superfluid coolants whose temperature is around 4.2 K to cool the system. SMES can release quantum energy during their discharge momentum to the power grid in fractions of milliseconds. Through a SWOT analysis, it is concluded that this new technology has many strengths: high energy capacity, stability, quality, fast response, and high stored efficiency without high risk of environmental impact. On the other hand, it has weaknesses as it is a system that demands high constant cooling, high-cost materials for its manufacture, high operating and maintenance costs, among other factors [18].

3.7. Hydrogen Energy Storage

Unlike other energy storage systems, that comprised of hydrogen offers a wide range of applications that can be used in various ways. The gas is attractive because of its low-carbon energy source and therefore does not generate carbon dioxide emissions during use. This reason is what makes hydrogen energy storage a high potential for energy storage.

Today, hydrogen is produced chemically from fossil fuels by electrolysis of water since water is a major component of the Earth; another feasible alternative is using renewable energy sources with a surplus of energy to produce hydrogen, which can be used in different applications.

Its principle is based on using the excess electricity produced by renewable sources to store it in the form of hydrogen, and, when an energy demand arises, the reserved hydrogen is used as a fuel in power plants [19]. Their systems are composed in their production of hydrogen by excess electricity by electrolysis, storage of the pro-produced hydrogen, and conversion of this stored element back to electricity in a controlled time [20].

Hydrogen storage represents a challenge for automotive applications. Hydrogen has a characteristically low energy density by volume, unlike other fuels such as petroleum and diesel. In addition, hydrogen is the lightest element of all and the most difficult to liquefy compared to methane and propane.

Fuel cells are low energy density devices like batteries that are capable of converting chemical energy into electricity. These cells show efficiencies around 70–80%, while, in some power plants, they reach efficiencies of 60%. Fuel cells use oxygen and hydrogen; these can be combined with super capacitors to increase their energy densities [1]. Photovoltaic and other solar systems depend on solar radiation and ambient temperature, wind turbines depend on wind direction, and hydroelectric plants depend on river flow. However, there are cases where the aforementioned renewable sources cannot provide the required amount of electricity, so the use of fuel cells becomes a good solution to the aforementioned problem because the cells are not dependent on weather conditions [21].

Moreover, it has been proposed to use photovoltaic systems together with hydrogen-based fuel cells as they present a great opportunity to achieve self-sufficiency in electrical energy. In 2020, the proposal was developed by adding a battery storage system for a pilot building located in Slovenska Bristica, Slovenia. The system consists of photovoltaic modules placed on the roof of the building and has energy storage with lithium-ion batteries and an inverter. It is connected to the grid. Figure 6 shows the configuration of the system developed. Employing energy equations, aspects such as the balance of a hybrid system connected to the grid of the photovoltaic system and fuel cells with battery storage and its consumption through time “t” and the efficiencies of the batteries, hydrogen cells, inverter, and inverter electrolyzer were calculated. By means of modeling, the charging and discharging of the batteries were considered. With the fuel cell output, the system can operate when there is no sun exposure or when the batteries are not in optimal function. The hydrogen is stored in a tank, and, when it passes into the cell, it is recombined with oxygen, and electricity is generated [21].

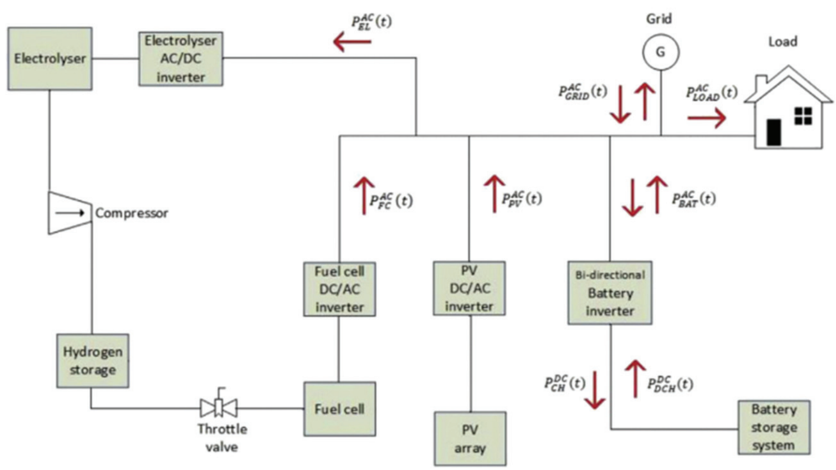

Figure 6. Scheme of the system configuration, fuel cells, and battery storage system used on [21]. No changes were made to the original figure.

For hydrogen production, the excess energy is used with electrolysis instead of extracting it from the grid. The study was carried out during one year where 202 days were of higher energy production than consumption, 162 days consumption was higher than production, and one day where consumption and production were equal.

As a result, the self-sufficiency of the fuel cell hybrid photovoltaic system was around 62.13%, which shows that it is not possible to complete the self-sufficiency of the pilot system. The hydrogen shortage was 144.24 kg. To achieve the desired self-sufficiency would require a larger photovoltaic system which would fit the correct dimensions and achieve the desired goal; even so, it would require an even larger hydrogen tank presenting high initial costs for its implementation. Battery storage is very effective for summer time, but, for winter time, hydrogen cells meet the shortcomings of conventional batteries (Table 2) [21].

Table 2. Evaluation of conventional storage systems.

Type	Description	Advantages	Disadvantages	Scale of Application	Storage or Generation Capacity	Efficiency	Reference
Hydro-pump	It has two reservoirs or basins connected through tunnels and wells through which water passes from an upper point to a lower one. Inside this system, turbines, pumps, and valves will generate the necessary electrical energy and control the water flow.	• High energy storage capacity. • Long service life of about 50–100 years.	• Location constraints. • High capital cost. • Low power and energy density. • Potential for environmental impacts; however, these systems have been built underground to avoid such impacts.	Buildings with photovoltaic installation for an apartment and villa building, Shanghai (China).	5 kW for both cases (villa, apartment).	• 76.47% (apart-ments). • 45.13% (villas).	2020 [1], 2018 [3], 2020 [14]
Compressed Air	The air is compressed and accumulated inside a subway reservoir as long as there is excess energy. Then, when an energy demand arises, the accumulated air expands into a turbine which generates electricity.	• High energy storage capacity. • Decreased energy losses since the system uses substantial fractions for the power supply, which has receivers that reserve the compressed air without the need to use an energy conversion machine.	• Geological limitations tend to lead to the installation of steel tanks that can withstand high pressures underground, thus increasing the cost of the system. • Variable efficiency. • Safety problems. • Not suitable for small-scale systems due to the large size of the installations and associated costs.	Residential building with photovoltaic system, Cittá di Castello (Italy).	• Pressure 30 bar, generation 1008 kWh. • Pressure 225 bar, generation 1273 kWh.	• 21.9% @30 bar. • 26% @225 bar.	2020 [1], 2016 [4], 2018 [15]

Table 2. *Cont.*

Type	Description	Advantages	Disadvantages	Scale of Application	Storage or Generation Capacity	Efficiency	Reference
Flywheel	The flywheel uses a rotating mass to store energy held in the rotor's kinetic form. This kinetic energy is transferred in and out of the flywheel with the help of an electrical machine that acts as a generator or motor, depending on whether the system is in charging or discharging mode.	• High energy storage capacity. • Environmentally friendly. • Does not require large space areas. • Long service life, depending on the bearings selected (non-contact, non-wearing magnetic bearings tend to have a service life of 20 years).	• Noise problems. • Safety issues are considered due to high speeds, depending on the robustness of the container. • High cost per stored unit. • Maintenance. • In the long term, the system presents difficulties for energy storage.	Buildings with photovoltaic installation (Germany).	N/D	67% in the short term but decreases to 40% in the long term.	2020 [1], 2018 [5], 2017 [6], 2016 [18]
Lithium Battery	Lithium batteries, including lithium-ion and lithium hydride batteries, represent the most popular battery type among consumer electronic devices due to their low weight, high energy density, and long cycle life.	• High efficiency. • High power and energy density compared to other batteries. • Short response time.	• Life cycle depends on discharge levels (5000 cycles (10–15 years)). • High cost.	Residential building with photovoltaic installation, Sweden.	7 kWh	85–95%	2020 [1], 2018 [7], 2016 [16], 2016 [18]

Table 2. *Cont.*

Type	Description	Advantages	Disadvantages	Scale of Application	Storage or Generation Capacity	Efficiency	Reference
Nickel Cadmium Battery	• Nickel-cadmium batteries belong to the nickel battery family, including nickel-metal hydride, nickel-iron nickel, and nickel-zinc-based batteries. Inter-cell reactions vary depending on the second component added to the nickel electrode.	• Good performance under low temperature. • High efficiency. • High power density.	• High cost.	Commercial buildings, India.	40 MW	70–85%	2020 [1], 2018 [7], 2017 [22]
Lead-Acid Battery	Their cells are based on the reaction between lead, lead oxide, and sulfuric acid. Their cells have a water-based liquid electrolyte that operates at room temperature.	• High efficiency but may vary depending on duty cycle and ambient temperature. • Low cost.	• Low power and energy density. • Short response time. • Short life cycle (3000 cycles (7–10 years)). • High maintenance requirements. • High level of toxicity and relatively heavy. • Material consumption.	Residential building with photovoltaic system, Cittá di Castello (Italy).	4.6 kWh (total demand of the installation).	70–80%	2020 [1], 2017 [6], 2018 [7], 2018 [15]

Table 2. *Cont.*

Type	Description	Advantages	Disadvantages	Scale of Application	Storage or Generation Capacity	Efficiency	Reference
Vanadium-Redox Battery	They consist of two electrolyte reservoirs where the electrolyte circulates through an electrochemical cell comprising a cathode, an anode, and a membrane separator. The energy density depends on the stored electrolyte volume and is independent of the electrochemical cell size and design.	• High energy storage capacity.	• Complex construction. • Low energy density.	Residences with photovoltaic installations (Australia)	40–80 kW	75–90%	2020 [1], 2016 [15]
Supercapacitors	It consists of two metal plates separated by a small air gap. The amount of charge accumulated on each plate creates an electric field that balances the charge generated by the voltage.	• High energy density. • Suitable for high peak power work. • Compensate for energy release during short time interruptions.	• Cell independency. • Safety issues. • Life cycle depends on voltage imbalances between cells and maximum voltage thresholds. • Environmental impacts.	Power Electronics	8 kWh	95% or higher	2018 [8], 2020 [9]

Table 2. *Cont.*

Type	Description	Advantages	Disadvantages	Scale of Application	Storage or Generation Capacity	Efficiency	Reference
Magnetic Super-conduction	A large superconducting coil has almost no electrical resistance near absolute zero temperature and yet can store electrical energy within the magnetic field generated by direct current flowing through that field.	• Immediate response. • High efficiency and reliability. • Lifetime is independent of duty cycle.	• High cost as they have to consider components such as cryogenic vessel, refrigeration, protection, control equipment, coil, and conductor structures. • Requires large magnetic fields.	Grid-connected distributed generation structures.	3 MW	95%	2020 [1], 2020 [10]
Hydrogen	It uses excess electricity produced by renewable sources to store it in the form of hydrogen, and when an energy demand arises, the reserved hydrogen is used as a fuel in the power plants.	• Low carbon energy so no CO_2 emissions to the environment. • Hydrogen cells satisfy systems during winter seasons. • Hydrogen is the lightest element of all.	• High initial cost. • Hydrogen production is not fully effective.	Building with photovoltaic system (Slovenska Bristica, Slovenia).	N/D	62.13%	2020 [1], 2018, 2017, 2020 [11–13]

4. Bio-Inspired Electricity Storage Strategies

Nature is the principal source of life for many living beings. Therefore, it is interesting to visualize different behaviors, ecosystems, and anatomic aspects that can be useful as an inspiration to improve or create many new technologies. Members of both the animal and plant kingdoms exist because of energy—whether this comes from the sun stored in the form of sugars in plants, or from ingested food that is stored as fat in some animals. Within the animal or plant, energy is transferred at the electron level. A battery works in a similar way as the electricity is both taken in and discharged via the battery electrodes [23]. For instance, species such as electrical fishes are animals that manage to generate a certain amount of electrical energy through their bodies; they have certain points on their body's special arrays similar to voltaic batteries, which allows these animals to produce an electrical discharge. These arrays are usually found in areas such as from the back to the belly, lateral parts of the fish's body, tails, and sometimes almost cover the whole body. Figure 7 illustrates examples of this kind of fishes.

(**a**) (**b**)

Figure 7. Fishes that can generate electrical energy in their bodies to search for food and navigate thorugh their habitat (**a**) Elephantnose fish ("*Gnathonemus petersii*") [24] and (**b**) Electric eel ("*Electrophorus electricus*") [25]. No changes were made to the original figures.

In the following subsection, a review of different organisms or pinnacles was made where each of them is related to energy storage or electricity generation. Table 3 presents the principal characteristics, mechanisms, and principles of each pinnacle.

4.1. Energy Storage, Photosyntesis

Photosynthesis is a biological mechanism that serves as an inspiration for the field of energy storage. Globally, it is estimated that photosynthetic organisms absorb an average of about 4000 EJ/year (130 TW) of sunlight. This capture is equivalent to 6.5 times the current global primary energy consumption of about 20 TW. Even so, photosynthesis is not perfect; it extracts carbon from the atmosphere at an average annual rate of 1 to 2×10^{18} CO_2 molecules/m^{2}s, which is 25 to 70 times less than the maximum possible rate of carbon absorption from the atmosphere of 5 a 7×10^{19} CO_2 molecules/m^{2}s. The overall and average annual efficiency of photosynthesis is between 0.25% and 1%, with the best efficiencies seen in the field at 2.4% for C3 plants (three carbon pathways), 3.4% for C4 plants (four carbon pathways), and 3% for algae grown in bubbled photobioreactors. The inefficiency of photosynthesis is because everything occurs within the same cell. Several alternatives have been developed to improve this aspect where photosynthesis is reconfigured by spatially separating each of the tasks performed within a photosynthetic organism and replacing some of them with a non-biological equivalent. These schemes have been termed "microbial electrosynthesis" or "rewired carbon fixation" by [26] with the object to capture and store solar energy from biofuels with higher efficiencies than photosynthesis; however, this separation allows storage of any electrical source.

From the configuration (Figure 8), two mechanisms for long-range electron transport and capture are highlighted: hydrogen transport to hydrogen oxidizing microbes and solid matrix extracellular electron transfer (SmEET) enabled by electroactive microbes. These microbes (Geobactor sulfurreducens, Sporomusa ovata, Ralstonia eutropha) are genetically engineered. In the same way, sulfur transport is developed along with its oxidation [26].

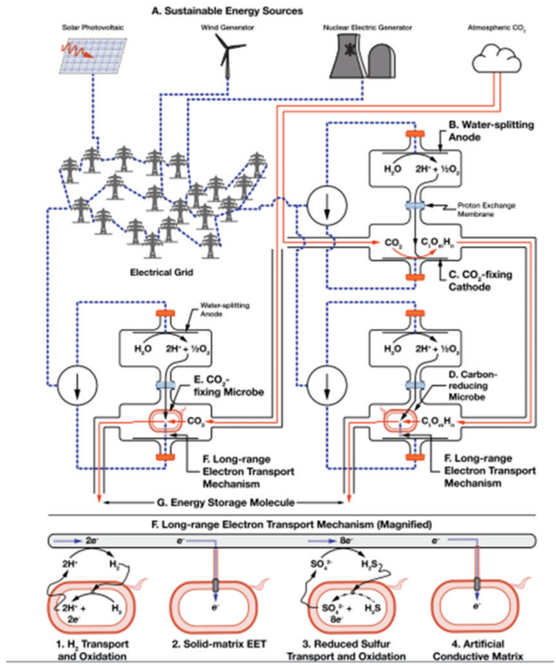

Figure 8. Fixation rewiring system consists of: (**A**) sustainable energy capture, (**B**) water splitting, (**C**) electrochemical CO_2 fixation, (**D**) additional biological reduction (**E**) or biological CO_2 fixation, (**F**) long-range electron transport to biological metabolism, and (**G**) synthesis of energy storage molecules [26]. No changes were made to the original figure.

These biological advances in microorganism systems are becoming evolutionary tools in developing synthetic enzymes, autotrophic metabolisms, and self-assembling and self-repairing biological nanostructures, the latter being very useful in renewable energy systems [26].

4.2. Battery Electrode Materials

Lignin is a biopolymer abundant in the soil which is extracted from trees. This material is characterized as an important structural material in the supporting tissues of plants, some algae, and insects. Lignin has quinone as a substructure, a polymer of interest for energy storage through oxide-reduction (redox) reactions by which protons and electrons are absorbed and released. There are obstacles such as: short life cycle, low cyclic efficiency, and high self-discharge rate. The problem with using lignin is that the electrodes tend to degrade in the electrolytes.

The Venus flytrap has characteristic leaves divided into two movable halves. Once the prey lands inside the open leaves, these halves are closed, imprisoning the prey inside the plant. As a biomimetic strategy, the capture form of this living creature is mimicked by means of a reconfigurable graphene cage. This confines the lignin within the electrode to prevent dissolution while acting as a three-dimensional current collector to provide efficient electron transport pathways during the electrochemical reaction. This bio-inspired design exhibited 88% capacitive retention for 15,000 cycles and 211 F/g layer-cytance at a current of 1.0 A/g. This study demonstrates the effectiveness and solves the problem of the cyclic lifetime of the electrochemically lignin-based species to make use of this material as effective, economical, and renewable [27].

4.3. Energy Production, Anatomy of Plants

Plants are the most efficient light scavengers in existence. Their behavior has opened doors for creating new photovoltaic cells that can be applied in urban systems. Plants have the advantage of adapting to any environment. The orientation of their leaves is generally towards the light and not in a vertical position because the crown of the leaf surface is wide, and the inclination limits the light needed for photosynthesis, which makes this structure optimal for the collection of indirect and scattered illumination. Photosynthesis is a slow chain reaction. The leaf anatomy balances the number of photon incidences to those consumed by photosynthesis to maximize its efficient collection. Figure 9 shows the analogy of leaf anatomy used to recreate the solar cell arrangement [28].

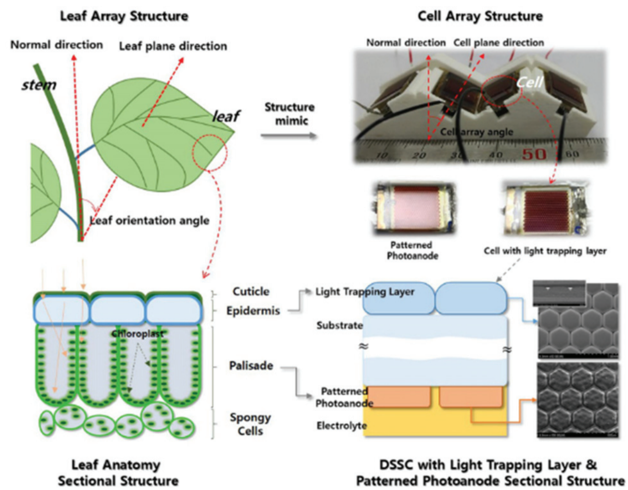

Figure 9. Anatomical structure of plant leaves as a basis for dye-sensitized solar cell (DSSC) configuration [28]. No changes were made to the original figure.

Mimicking plant leaves' structure and anatomy, one study created a light-capturing layer on top of the cells that mimic the epidermis. For the palisade structure, microscale photoanodes were used. One of the findings of the study was that, using 2D ray tracing, the trapping layer absorbed the incident light omnidirectionally and distributed it homogeneously across the photo-anodes. The current densities and light distribution were analyzed using the finite element method (FEM). The light-trapping layer and photo-anode tracing doubled the efficient conversion of dye-sensitized solar cells (DSSCs) from 4% to 8% by modifying the light distribution and improving the charge collection efficiency. Taking this study to the module scale, it was shown that DSSCs are much more efficient when illuminating the cells obliquely. To improve the efficiency of the system module, they connected in clusters of four DSSCs in parallel, mimicking the way plant leaf crowns exhibit a phyllotactic arrangement. The electrical power output improved by almost 55% by introducing the light-trapping layer designed in the study compared to the cells used in conventional designs [28].

4.4. Energy Generation by Respiratory Reactions of Microorganisms

From 2003 until today, BioGenerators have been developed, which are bio-electrochemical systems that use the respiratory reaction of a microorganism (*Leptospirillum ferriphilum*) as an electron collector for the generation of electrical energy. It is also a negative emitter of CO_2 consumed from the atmosphere as part of electricity generation. In 2017, three BioGenerators were built whose bioreactors varied in volume, dimensions, and fabrication material, but with the same culture of microorganisms. Their electro-chemical cells were built in different sizes, but the material for the anodes, cathodes, and bipolar plate were the same (graphene). Two types of membranes were used for the device membranes: cation exchange membrane and polyvinyl alcohol-based membrane. The microbial culture was obtained from acid mine drainage samples from four sites (USA, Spain, Bulgaria, Finland). Air was injected into the bioreactors to supply the microorganisms with oxygen and carbon dioxide [20].

The biological oxidation of ferrous ions by *Leptospirillum ferriphilum* is essential for the operation of this device since these ions were used as cathode electrons in the electrochemical cell where the anode electron donor was hydrogen gas. After the main biological and electrochemical reactions, the microorganisms act as biocatalysts increasing the rate of oxygen reduction. It is worth mentioning that these microorganisms were treated by analytical and genetic engineering techniques. *Leptospirillum ferriphilum* as autotrophic organisms (producing their food) use CO_2 from the atmosphere as a sole carbon source, making the BioGenerators commercially viable as CO_2-negative systems. For this case, the ferrous ions did not need electro-catalysts based on precious metals since the cathode was made of carbon felt, which makes it more economical than a conventional proton exchange membrane (PEM), for the oxidation of the hydrogen-based anode, PEM fuel cells were used with a quantity of black platinized carbon. As a result, a current density of 1.35 A/cm^2 and a maximum energy density of 1800 W/m^2 were achieved. The cell voltage was 650–800 mV with a voltage efficiency of 46–57%. Its overall efficiency reached 70%. These Bio-Generators have gradually evolved starting with small laboratories with 300 W scale up to the present time where the construction of biotechnological power plants is planned since they are low cost, stable, and large energy storage systems; however, it is quite bulky, so more development and more precise control are still required [20].

4.5. Thermoelectric and Thermoregulatory Properties of the Oriental Wasp (Vespa Orientalis)

The oriental wasp is the first insect that absorbs solar energy to generate electricity. It has pigments in its tissues that allow it to perform this production, being yellow, the one that traps light, and brown, the one that generates electricity. It is not yet understood how these insects use the generated electrical energy, but it is assumed that the absorbed energy is used in flight and temperature regulation, among others [29]. Studies have been made about the thermoelectric and thermoregulatory properties of the silk produced by the larva of this living being creating a kind of cape. The nest of the oriental wasp is maintained at temperatures of 28 °C while the ambient temperature varies between 20–40 °C. The silk layers help regulate temperatures in the nest by storing excess heat as an electrical charge so that, when the temperature decreases, the energy is released as heat. The wasp nest cocoon consists of fibroin, which is a protein with elastic properties, surrounded by a second protein known as sericin. Together, these make up the silk of the cocoon.

The fibroin core tends to be double-stranded and can be compared to a semiconductor material where the inner strand of this protein performed the function of p (positive) bonds, and the outer sericin envelope performed the function of n (negative) bonds. The closest engineered materials to hornet silk are electrically conductive polymers, such as polyaniline and polythiophane with lodin [30].

To develop an electrical cell capable of generating electricity, storing energy, and releasing it into heat, tests were conducted with the hornet silk layers within a single cell. The silk was obtained from nests in the field. The samples came from the eastern hornet queen with a diameter of 12 mm. They were kept refrigerated until the time of the experimental test. They designed an experimental platform to test the silk samples under varying environmental conditions, including temperature, relative humidity, among others. The tests were performed both in daylight and in the dark [30].

The platform consists of a cylindrical chamber for the control of temperature, relative humidity, light, and darkness. This chamber comprises aluminum with dimensions of 64 mm in diameter, 3 mm thick, and 148 mm high. A 12V DC axial fan at the bottom provides air circulation in the chamber. A 67 W thermoelectric module for cooling control. A 55 W AC radial fan for ventilation airflow and to dissipate heat from the thermoelectric module. Finally, a saline solution container was placed for relative humidity control [30].

As a result, it was obtained that the silk layer presented a voltage of 20 V in 5 s. As soon as the voltage source was turned off, the current was discharged. The capacitance obtained was 21.7 mF. The variation of the resistance along with the temperature had a range of 15.8 MΩ to a minimum of 2.6 MΩ remaining constant in the intervals between 28–35 °C. It was concluded that this is consistent as a material acting as a semiconductor whose performance and functionality depend on temperature and relative humidity. In the dry state, the silk layers act as insulators and, therefore, can be used as capacitors. The proteins that make silk can generate current by applying heat to them; however, moisture plays an important role in electrical transport and converts it from an insulator to a conductor. These fibers are suitable materials for constructing composite walls that could act as electricity generators or capacitors, insulation systems, heat transfer devices, and air filtration systems due to their thermoelectric, thermo-regulating, and storage properties [30].

4.6. Sucrose Modification of $Li_4Ti_5O_{12}$ Anode Material for Lithium-Ion Batteries

Lithium-ion batteries have made energy storage a broadly developable aspect due to qualities such as high voltage, high energy density, long cycle life, and low pollutants. However, the conventional carbonaceous materials used in the anodes present safety problems because of their low Li intercalation potential, which is close to 0 V. In [31], they improved the electrical conductivity of $Li_4Ti_5O_{12}$ (LTO) material through the transport properties of the material with sucrose as a source of organic carbon, thus obtaining a battery with sucrose-modified LTO material with improved electrical conductivity.

After elaborating the LTO with sucrose, the respective electrochemical impedance spectroscopy measurements at E = 1.55 V were performed. The frequency range was between 0.001–100 kHz under alternating current (AC) stimuli with ten mV amplitude. The experiments were carried out at a room temperature of 25 °C. Figure 10 presents the more detailed spectroscopy analysis where a conventional LTO and the test LTO without sucrose had almost equal resistance to each other and presented three times the resistance of the LTO with sucrose. These results indicated that the modified LTO reduces the charge transfer resistance.

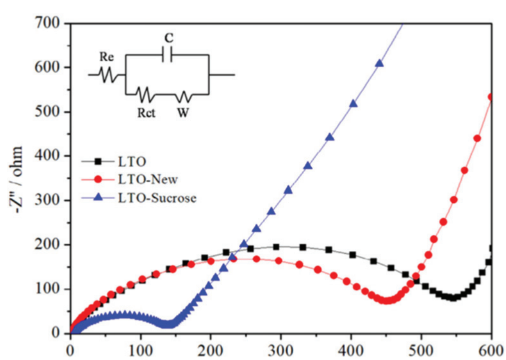

Figure 10. Electrochemical impedance spectroscopy between conventional LTO, LTO manufactured without sucrose, and LTO modified with sucrose [31]. No changes were made to the original figure.

The initial charge–discharge curves of sucrose-modified LTO and LTO samples developed in ranges of 100–200 mA/g showing efficiencies of 90.2% and 92.1%, respectively.

The ranges of the charge–discharge voltage platform were 1.7 V and 1.5 V, being close to the theoretical voltage (1.55 V). This was due to their redox reaction. They concluded that using sucrose as a material for LTOs reduces the charge transfer resistance, making it feasible for electron and Li+ transport to benefit charge–discharge cycling.

4.7. Improvement of Microbial Cells for Electron Transfer

Microbial fuel cells (MFCs) use bacteria as catalysts to convert chemical energy into organic matter and then into electrical energy. These cells are considered green, efficient, and sustainable technology to recover electricity from wastewater treatment. MFCs have been used in many fields such as wastewater treatment, soil remediation, biosensors; however, the low power output of these cells limits their applications. The electron transfer pathways are spatially and mechanically heterogeneous for electroactive bacteria on different parts of the electrode surface. Different materials (quinone, riboflavin) have been used to improve the physicochemical properties of the electrode. These properties correspond to stability and electrical conductivity since both are involved in the electron transfer at the interface between the electroactive bacteria and the electrode. However, as the biofilm grows, most of the electroactive bacteria move away from the electrode surface. Consequently, the electron transfer becomes inefficient, and energy production is limited. This is why, in this study, we use magnetite sprayed on an electroactive biofilm with the help of a magnetic field and also doped a biofilm inside it to facilitate the delivery of electrons from electroactive bacteria away from the electrode surface. Magnetite is a good conductor based on iron oxide for the enhancement of extracellular electron transfer. With the incorporation of magnetite, the electron transfer efficiency improved by 12% and 37%, respectively. The energy density of the MFC doped inside presented results of 764 ± 32 mW, this being a considerable increase with respect to the MFCs with biofilms doped on the surfaces that presented results of 604 ± 22 mW. Figure 11 presents a small scheme of the proposed mechanisms for the simulation of the biofilm doped inside and on its surface [32].

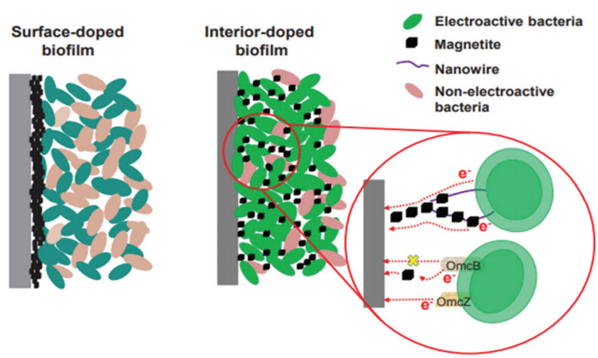

Figure 11. Rough sketch of the study, biofilm doped on the surface (left) and biofilm doped inside (right) [32]. No changes were made to the original figure.

It is worth mentioning that magnetite facilitates the enrichment of electroactive bacteria and helps to increase the proportion of electroactive bacteria to stimulate their production of electrons. Good conductive magnetite allows the collection and transport of more electrons produced by electroactive bacteria even if they are far from the electrode surface. This study demonstrated an effective method for improving bio-electrochemical systems leading to further improvements in the area of batteries and other storage systems to make them less polluting to the environment [32].

4.8. Bio-Electrocatalysis for the Production of Green Chemicals, Fuels, and Materials

One way to make bio-based chemicals, biofuels, and biodegradable man-made materials is through bio-electrocatalysis. Such a method can be efficient and more sustainable than conventional methods. It presents an alternative within the area of modern biomanufacturing technology as it combines biocatalysis and electrocatalysis to produce efficient and green products from electricity. It is important to remember that the redox reaction of biocatalysis requires two substrates (electron donor and electron acceptor) and electron transfer between these substrates.

For microbial cell-based biocatalysis, its diversification in terms of metabolic pathways provides the ability to produce various products. The equivalent residue is able to regenerate through the metabolic activities of the cells. Electrochemical reactions can be used to safely provide redox equivalents for biocatalysis with the consumption of electricity from renewable energy sources such as solar and wind.

Bio-electrocatalysis has been used for the fabrication of biosensors and biofuel cell devices. For this method to be feasible for the preparation of biofuel, chemicals, and other materials, the problem of electron transfer between the electrode surface and the bio-electrocatalyst must be overcome. The bio-electrocatalyst is the main function of the bio-electrocatalysis system and is classified into oxidoreductase and electroactive microbial cell. Oxidoreductases are usually cofactor enzymes with or without metal bases. These oxidoreductases have the advantage of transforming the reduction and oxidation states within the cofactors so that electron transfer is achieved. In contrast, electroactive microbial cells can catalyze a wide range of reactions because the microbial cells act as tiny bioreactors. Other cells have developed the ability to transport electrons as their mechanism to achieve electronic communication between electrodes. The most studied microorganisms for these aspects are "Geobacter sulfurreducens" and "Shewanella oneidensis."

Currently, better electrode materials are being developed that will allow better performance towards future bioelectrocatalysis devices and systems to be used in the field of chemicals, biofuels, and bioplastics. However, many factors still require further research [33].

Table 3. Mechanisms inspired by nature for both storage and generation of electrical energy.

Pinnacle (Strategies)	Mechanism	Principle	Primary Characteristic	Ref.
Venus Flytraps It has leaves divided into two movable halves. Once the prey lands inside the open leaves, these halves close, imprisoning the prey inside the plant.	Confine the lignin within the electrode to prevent dissolution by acting as a current collector to provide electron transport during the electrochemical reaction.	Reconfigurable graphene cage to capture lignin.	Environmentally friendly battery electrode materials	2017 [27]
Photosynthesis Being an inspired mechanism for electrical energy storage, a strategy (microbial electro-synthesis) capable of absorbing and storing energy from any electrical source is presented.	Use of the modified microbes for long-range electron transport and uptake.	Electroactive microbes are useful for moving hydrogen to microbes which can oxidize it and for a process called SmEET (solid matrix extracellular electron transfer)	Energy storage	2018 [23], 2019 [26]
Anatomy of leaves	Based on their structure, dye-sensitized solar cells were used to improve the efficiency of charge collection.	Layer capable of capturing light at the top of the cells (which mimics the epidermis) and photoanodes in the microscale palisaded structure.	Absorption of sunlight	2019 [28]
Plants adapt to any environment, and the orientation of their leaves towards light allows for light-harvesting and photosynthesis.				
Leptospirillum ferriphilum	Given the biological oxidation of ferrous ions, they are used as cathode electrons within the electrochemical cell together with hydrogen, which provides the anode electrons.	By utilizing CO_2 from the atmosphere as the sole source of carbon, they make BioGenerators commercially viable as CO_2 negative systems.	Power generation	2017 [20]
Iron oxidizing bacteria that have influence as electron collectors for electric power generation in biogenerators.				
Oriental Hornet (*Vespa Orientalis*)	Special silk layers of the insect larvae provide thermoelectric and thermoregulatory properties that protect the wasp nest by releasing energy in heat.	The silk created by these insects has fibers suitable for constructing composite walls that could act as electricity generators or capacitors, insulation systems, heat transfer devices, and air filtration systems.	Generation, storage and transfer of energy	2017 [29], 2015 [30]
First organism has the ability to absorb sunlight, store it and then generate electrical energy. Its use of electricity is still unknown.				

Table 3. *Cont.*

Pinnacle (Strategies)	Mechanism	Principle	Primary Characteristic	Ref.
Sucrose	Comparison between conventional LTO and sucrose modified LTO in which the sucrose modified battery with the abovementioned material provided a reduction in charge transfer resistance, making it feasible for electron and Li+ transport to be beneficial for charge and discharge cycling.	Improvement in the electrical conductivity of $Li_4Ti_5O_{12}$ (LTO) material through the transport properties of the material with sucrose as organic carbon source, thus obtaining a battery with sucrose-modified LTO material with improved electrical conductivity.	Anode material for lithium-ion battery electrode and improvement of electrical conductivity	2019 [31]
A proposed material for the improvement and modification of $Li_4Ti_5O_{12}$ anodes for lithium-ion batteries.				
Electroactive Bacteria	A good conductive magnetite allows the collection and transport of more electrons produced by electroactive bacteria even if they are far from the electrode surface.	Magnetite sprayed on an electroactive biofilm with the help of a magnetic field is used, and a biofilm was also doped inside to facilitate the delivery of electrons from electroactive bacteria away from the electrode surface.	Electron transfer at the interface between the electroactive bacteria and the electrode	2018 [32]
The application of magnetite facilitates the enrichment of electroactive bacteria and helps to increase the proportion of electroactive bacteria to then stimulate their production of electrons.				
Geobacter sulfurreducens and Shewanella oneidensis	Electroactive microbial cells can catalyze a wide range of reactions because the microbial cells act as tiny bioreactors.	The redox reaction of biocatalysis requires two substrates (donor and acceptor) and electron transfer between these substrates. Biocatalysis presents a diversification of metabolic pathways and provides the ability to produce a variety of products. The residue is regenerated.	Electron transport and electrode enhancement	2020 [33]
Used in bio-electrocatalysis systems, which is a sustainable way to make certain products as chemicals, biofuels and biodegradable man-made materials.				

5. Conclusions

With this study, it was possible to contemplate the evaluation of the different conventional electric energy storage systems detailing advantages and disadvantages of each one, applied to building scale visualizing that currently the most efficient storage system contemplates batteries. As a result of this, alternatives have been sought to improve battery elements, such as hydrogen cells, finding new materials for battery electrodes, among others. Starting from the point of improving elements in these systems, strategies observed in nature or "pinnacles" that are related to the storage or generation of electricity are sought, demonstrating that, although the immediate possibilities of increasing the technical aspects of these systems have not yet been fully investigated, their field of development is quite high, giving way to possible designs of these systems based on biomimetic strategies. Thus, a comprehensive analysis of the available research on biomimicry-based approaches to improving building design, driven by the increasing demands of energy regulations to meet future local goals, has been presented.

Energy storage systems have played a relevant role in applications in different areas, and, for this reason, proposing improvements to these systems continues to be a focus of scientific interest. In this work, it was emphasized that energy storage systems had worked favorably until nowadays, providing great benefits to the consumer or to the applications, but it is necessary to develop environmentally friendly solutions, thus establishing a culture of awareness. Along this line, oriented to the creation of "green" systems with the environment, biomimetic strategies for the development of storage systems have achieved significant advances, ranging from generating energy through the respiratory processes of microorganisms to recreate the generation, storage, and release of energy using the thermoelectric and thermoregulatory characteristics of some insects. These facts show that research and new policies aim to improve existing systems but reinforce the idea that new solutions must be environmentally friendly, so there is still a long way to improve the processes established so far.

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Abbreviations

Abbreviations

BESS	Battery energy storage system
CAES	Compressed air energy storage
DSSC	Dye-sensitized solar cells
EDLC	Electrochemical double-layer supercapacitors
ESS	Energy storage system
FEM	Finite element method
FESS	Flywheel energy storage system
LTO	$Li_4Ti_5O_{12}$
MFC	Microbial fuel cells
PEM	Proton exchange membrane
PHES	Pumped-hydro energy storage
PV	Photovoltaic
SMES	Superconducting magnetic energy storage
VRB	Vanadium redox battery

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