Application of Biomimetics to Architectural and Urban Design: A Review across Scales

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sustainability

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Review

Application of Biomimetics to Architectural and Urban Design: A Review across Scales

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Received: 4 December 2019; Accepted: 1 November 2020; Published: 24 November 2020

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Abstract: Application of biomimetics has expanded progressively to other fields in recent years, including urban and architectural design, scaling up from materials to a larger scale. Besides its contribution to design and functionality through a long evolutionary process, the philosophy of biomimetics contributes to a sustainable society at the conceptual level. The aim of this review is to shed light on trends in the application of biomimetics to architectural and urban design, in order to identify potential issues and successes resulting from implementation. In the application of biomimetics to architectural design, parts of individual "organisms", including their form and surface structure, are frequently mimicked, whereas in urban design, on a larger scale, biomimetics is applied to mimic whole ecosystems. The overall trends of the reviewed research indicate future research necessity in the field of on biomimetic application in architectural and urban design, including Biophilia and Material. As for the scale of the applications, the urban-scale research is limited and it is a promising research which can facilitate the social implementation of biomimetics. As for facilitating methods of applications, it is instrumental to utilize different types of knowledge, such as traditional knowledge, and providing scientific clarification of functions and systems based on reviews. Thus, interdisciplinary research is required additionally to reach such goals.

Keywords: biomimicry; built environment; interdisciplinary collaboration; sustainability; biophilia

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1. Introduction

Biomimetics is defined as "the interdisciplinary cooperation of biology and technology or other fields of innovation to solve practical problems through the functional analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution" [1]. Biomimetics is an approach that develops solutions based on living systems, such as organisms or ecosystems. Although nature is mimicked, it is not re-productions but the requires further abstraction that solutions will derive from these models in nature and will align with life principles and potentially decrease the burden on the environment, as they may be less dependent on fossil fuels and more self-organizing and multifunctional, for example [2]

The range of applications of biomimetics is wide and promises to foster innovation [3]. Since 2000, biomimetics has been progressively applied beyond conventional chemistry and expanded into material science and engineering, mostly at the centimeter scale [4]. Furthermore, biomimetics is increasingly applied to design in architecture and urban areas, at the meter or kilometer scales [5] (Figure 1).

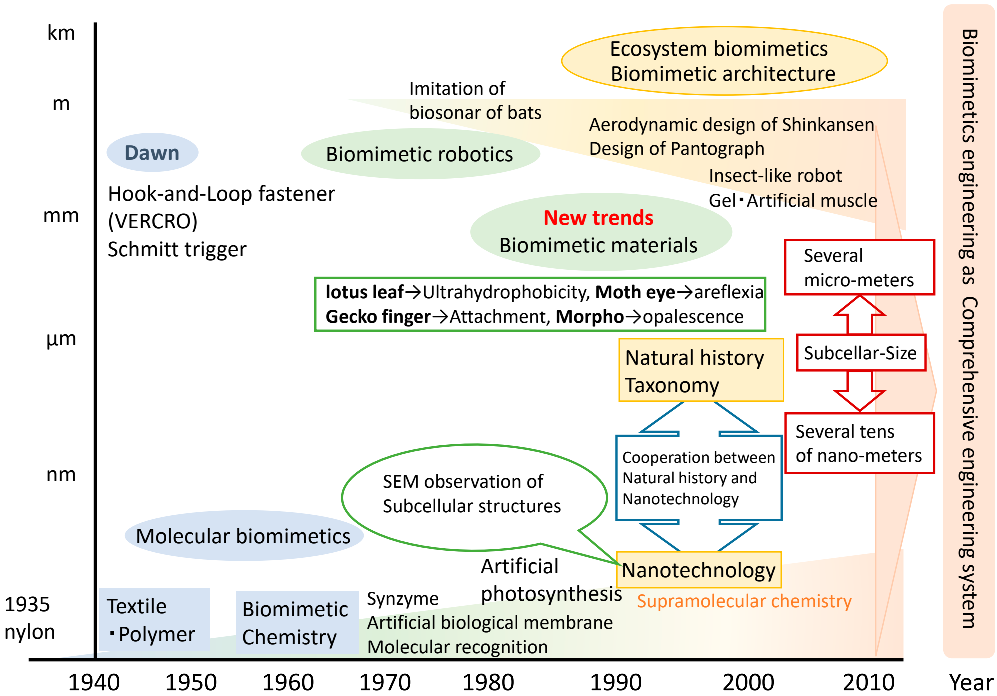

Figure 1. Historical trend of biomimetics. Source: Shimomura (2015).

Biomimetics is an approach toward sustainable whole systems design [6,7] that has the potential to develop ecological solutions to a given problem. However, it does not necessarily contribute to ecological solutions; Gebeshuber et al. [8] argue that designing sustainable products is independent from the specific design method.

However, a notion getting reinforced by scientists and designers is that biomimetic innovation must be promoted to make the goal of a sustainable society real [9]. Contributions of the biomimetic approach not only to environmental sustainability but to economic sustainability have been demonstrated [10]. Speck et al. [11] argue that sustainability, as a concept, cannot be transferred from biology to innovation easily, but that living systems have characteristics that, if systematically studied and transferred, can help us to move toward sustainability. Pedersen Zari [12] lists three main motivations to apply biomimicry approaches in the design process. The first is related to the development of new technologies and materials, without concern for ecological performance, and is called "biomimicry-for-innovation"; the second, aligned with previous consideration, seeks better ecological performance and is named "biomimicry-for-sustainability". The last, and least explored, is related to the development of human psychological well-being, and mostly applies to biophilic design theories.

Although biomimetic approaches could have positive and negative effects on the environment and society, exploring a method to enhance the positive effects of the technology is urgently required [13]. Wanieck et al. [14] identifies and analyzes 43 tools related to biomimetics application and discusses the interconnection of these tools to facilitate a problem-driven biomimetic approach, but sustainability is not at the center of the discussion.

In urban and architectural design, biomimetic concepts can be applied to tackle global environmental issues [12,15] Architecture in modern cities requires a huge amount of energy for construction, maintenance, and operation, directly and indirectly causing global environmental issues, such as loss of biodiversity or climate change through greenhouse gas emissions [16]. Urban areas are responsible for 70% of global carbon emissions and are also the cradle of major current social problems [17]. It has been proposed that the biomimetic approach can address these challenges [15,18] at multiple scales, from single mechanical units (materials) to buildings, up to entire urban areas.

Living organisms and the natural world are regarded as the key source of ideas for functional design of sustainable built environments [19,20].

Alongside the view of the biomimetic concept as a promising approach to move toward sustainable architecture, there is, however, a lack of methodologies to facilitate its application in building and urban design [21,22]. In this paper, trends in the application of biomimetics in the fields of architecture and urban design are reviewed, to identify the issues that may surround and successes that may emerge from implementation. Overall trends of the reviewed papers are analyzed in Section 2, and the papers related to architectural design and urban design are reviewed in Sections 3 and 4, respectively.

2. Trends of Application of Biomimetics in the Fields of Architectural and Urban Design

To conduct the review research, the related papers were collected using Google Scholar with the keywords; city/urban, architecture, biomimetics/biomimicry, in 2019. In total, 107 papers including proceedings and book chapters were identified, and 72 papers of them were discussing mainly about application of biomimetics in the fields of architectural and urban design (see Appendix A). The remaining papers did not not focus on our fields of interest but on general trends of biomimetic design. At first we identified the research topics of the papers, and at second we identified the target scales (architecture/urban) addressed by the selected papers.

Regarding the research topics papers were categorized into four topics: Material, Structure, System, and Biophilia. Examples of the subjects addressed in each topic are: Materials: bio-inspired building materials; Structure: bio-inspired building structure as façades and building structural design; Systems: biological system and ecosystem level biomimicry; bio-inspired traffic systems design; bio-inspired urban infrastructure systems management; Biophilia: use of natural patterns and systems on buildings and urban design aiming to improve users well-being and to foster sense of nature.

Some papers were conducting research on several topics as shown in the table presented in the Appendix A. The number of papers published in individual years and their research topics is presented in Figure 2. The bar chart shows that the topic "Structure" was relatively frequently discussed, and "Biophilia" seems to be emerging recently in our sample. The trends of papers with the topics of Material and System are similar, still the number of papers with the topic of System is relatively large compared with that of the papers related to Material.

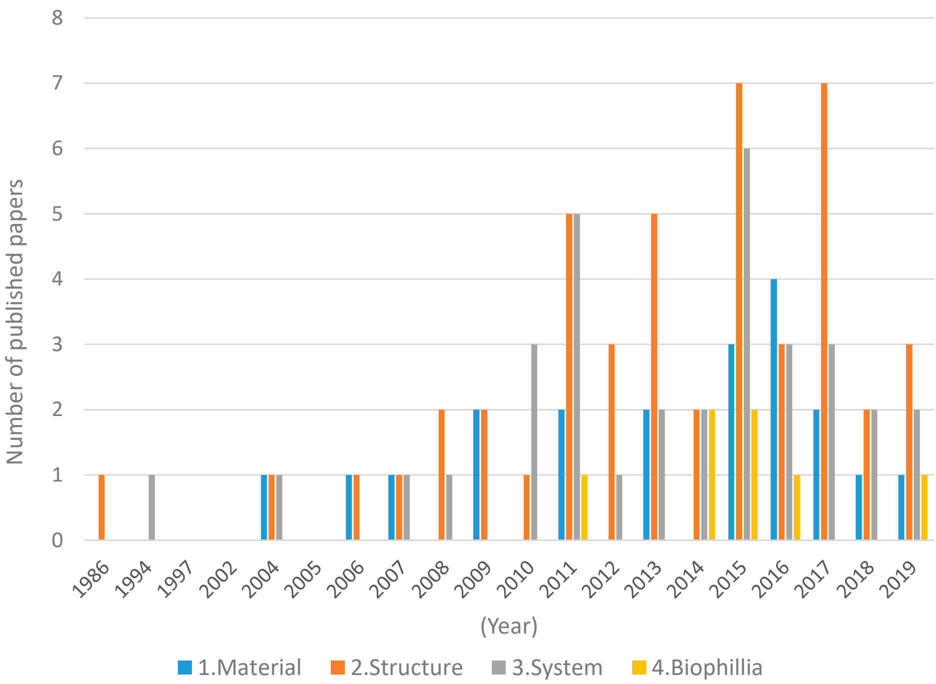

Figure 2. Number of papers published in individual years and research topics of the papers.

As for the concrete keywords in the research topics, subjects such as façades and buildings envelope were frequently mentioned and studied papers adressing the Structure topic. For example, structures of plants were mimicked in several research to design building envelope [23,24]. It's also important to observe that the energy efficiency of biomimetic design tended to be mentioned as a merit of application of biomimetics design in our sample.

Regarding the target scales (architecture/urban) of the reviewed papers, the trend of the publication is shown in Figure 3. The number of papers focusing on the architectural scale is much larger than papers adressing the urban scale. Papers adressing both scales are increasing, still the papers which are discussing and analyzing the application of biomimetics only at the urban scale are limited.

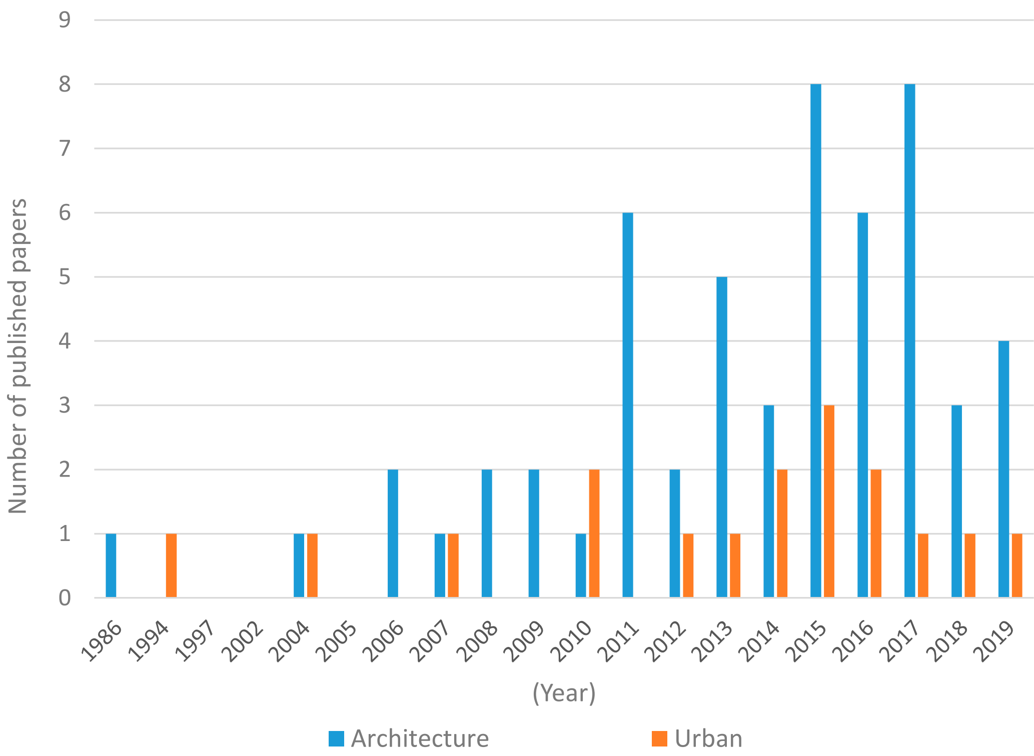

Figure 3. Number of papers published in individual years and target scales (Architecture/Urban).

According to the trends observed in Figures 2 and 3, biomimetic research topics related to Biophilia and Material are topics which need to be further explored in architectural and urban design. As for the scales, the biomimetic research at the urban-scale, adressing urban design, urban forms and sustainable urban performance, is promising to facilitate the social implementation of biomimetics, but is still lacks of attention.

In the following sections, detailed review results of research on architectural and urban design are provided and discussed.

3. Architectural Design

Nature has inspired built space since antiquity, when natural proportions were borrowed for aesthetic purposes [25]. Mimicking biological morphology is one of many conventional applications of biomimetics in the field of architecture [26], and the subjects of this mimicry are not exclusively single organisms or organisms per se, but also the products of their biological behavior, such as nests [27–29].

In modern architecture, the geodesic cupolas introduced by the architect Buckminster Fuller are one example of biomimetics application [30], as is the art nouveau style, in which biological structures were frequently mimicked.

Currently, the focus is less on aesthetics and more on mimicking functional aspects of living systems. As a measure to reduce the environmental impacts of buildings, the biomimetic approach provides design elements that, for example, collaborate with the economics of materials and the optimization of lighting and heating [31,32]. Creating the potential for cost reduction in civil construction can be facilitated by using this approach [33]. Biomimetics is expected to be a comprehensive approach based on environmental technologies, including applying renewable energy and repurposing it to optimize the global environment [34,35].

Contemporary applications at this scale aim mostly to reduce environmental impacts or improve human well-being, topics that will now be explored.

3.1. Reduction of Environmental Impact

Energy-use optimization has been a central subject in biomimetic architecture. Buildings can rely on living systems' strategies to reduce energy-resources consumption related to illumination, heating, and ventilation [36], for instance. Passive cooling and ventilation systems are a major application field of biomimetics [37]. Ventilation performance of building ducts can be enhanced by mimicking the shape of joints between plant trunk and branch [38]. An example of a building-scale application is the Eastgate Center in Harare (Zimbabwe), which takes inspiration from termite mounds' passive temperature-regulation systems, and another example is the phototropic function used to optimize natural lightning on buildings, applied in the Heliotrope in Freiburg, Germany [36]. Solar cells for on-site energy production, deriving from mimicking photosynthesis, were also proposed. Artificial photosynthesis systems can improve global and local carbon-neutral cycles [39].

Further applications rely on building structures and materials. The structures of coral reefs and plants have been mimicked in architecture or materials aiming to reduce material use and make buildings stronger, lighter, and easier to construct [40]. Other studies investigated load adaptation of natural materials, like bones, to develop new lightweight materials that can be applied to architecture [41].

New building techniques have also been a field of application of the biomimetic approach. Gruber and Imhof [42] explore natural growth patterns and their application in architecture, such as in additive buildings that can be operationalized through 3D printing and can contribute to the reduction of resources demand on architecture.

Relatively large technologies related to the façade have been developed. As architectural envelopes, façades present several opportunities. They can be designed to suppress heat islands in the center of the city, as do, for example, surface structures designed by mimicking flower petals [43], or the use of green façades to improve local biodiversity [44] and to reduce heat islands and promote the reduction of noise [23]. Sheikh and Asghar [45] implemented a biomimetic façade inspired by the shape of the sorrel leaf. They found a significant decrease in building energy load (32%), without blocking visibility to the outside of the building. Moreover, façades mimicking animal fur [46], animal blood perfusion, to improve thermal performance of the façades [47], movable façades mimicking the structure of animal wings [48], and façades inspired by the human skin system [49] have been developed.

The features of plants and their leaves have been applied to the development of building envelopes [50–55], where envelopes with shading mimicked the supple structure of plants [56]. Another example is Flectofin technology, developed by the Institute of Building Structures and Structural Design (ITKE), at the University of Stuttgart, which seeks inspiration from the pollination mechanism of the *Strelitzia reginae* flower to develop an adaptative shading system, and the HygroSkin pavilion envelope model, which seeks inspiration in spruce cones to create an adaptative envelope that works in response to environmental conditions [54]. Furthermore, there is an example of design of building envelopes mimicking plant-cell walls [24]. Biomimetic building skins show the potential for energy savings; a conceptual building skin developed based on the African reed frog and the Hercules beetle led to potential total energy savings of 39% in small office buildings in Chicago [57].

In addition to the structures and functions of organisms, products of organisms are also mimicked. For example, air-conditioning and energy supply to individual small residential districts have been constructed and optimized by mimicking the natural structure of the nests of ants [58–60]. These studies focused exclusively on air-conditioning and, to continue the metaphor used at the beginning, can be said to be at the individual "organism" level.

3.2. Enhancement of Well-Being

Well-being can be improved psychologically by the incorporation of biomimetic patterns into the structure and decoration of buildings, and research on visual patterns in biomimetics has been conducted for this purpose [25,61].

Biophilic design, as a subcategory of biomimetic design, can be understood as a biomimetic application aiming at human well-being [12]. This concept focuses on the psychological connection of humans with the natural environment, to promote a sense of belonging [62]. Biophilic design has several strategies to enforce this psychological connection; some examples are the use of natural lightning, organic morphologies, and views to natural spaces. Biophilic applications have garnered several quantifiable pieces of evidence in humans, in areas like stress control and better concentration [63].

Conventionally, biophilic structures and decoration patterns are found in religious buildings, including churches and mosques, as well as in indigenous architecture in different regions of the world [26]. In such contexts, biomimetics serves as part of the focus of architectural and urban design in terms of the creation of a place for humans, fostering their well-being. Learning from, and evaluation of, historical buildings can facilitate understanding of functions of biomimetics in enhancement of well-being.

4. Urban Design

Cases of the application of biomimetics on the architectural scale were reviewed in the previous section, as individual buildings or materials, in the attempt to underpin their functions. At this scale, individual functions are frequently mimicked. In contrast, at the urban-design scale, discussed in this section, ecosystems are referred to and mimicked.

Cities are huge resource-consuming areas [64], and their growth, activity, and resource needs are responsible for major biodiversity loss and damage to natural ecosystems [65,66], compromising the ability of these ecosystems to contribute to the maintenance of life on Earth by providing a set of ecosystem services from which the human being benefits.

A characteristic of ecosystems is the tendency to optimize themselves for the good of the whole (total optimization), rather than for individual parts, while maintaining the diversity of elements. These characteristics are reflected in the concepts of urban design, so that mimicking ecosystem functions and processes serves as a strategy to develop more sustainable urban spaces [67]. Methods of quantitatively evaluating various ecosystem services of urban ecosystems have been proposed, as a tool to promote biomimicry at the urban-design scale [68,69].

Relevant models and their application on the production of supporting, provisioning, and regulating services in an ecosystem in urban areas are discussed below.

4.1. Application of the Concept of an Ecosystem and Its Components

If we use ecosystem services as guidelines for urban design, the artificial environment can contribute to global sustainability and even regenerate natural ecosystems [70]. For cities that are rapidly urbanizing, symptomatic technological solutions are not effective in the long term. Rather, the concept of sustainable urban ecosystems, seen from a long-term, integrated perspective, is necessary [71]. The Ecosystem Services Analysis method helps urban designers draw goals and actions for the redevelopment of urban spaces, understanding local ecosystems and emulating it on the urban scale [72]. As a case study, Pedersen Zari [72] applied this methodology to evaluate the provision of water and energy in Wellington (New Zealand). The approach allowed the author to measure environmental performance in the city based on ecosystem performance and not on politically decided metrics. Biomimetics is regarded as an ontology in future urban design, incorporating perspectives, including governance and the participation of residents [32]. From the viewpoint of biomimetic simulation and analysis, organically linking the various elements of the city can contribute to the optimization of the whole urban system, going beyond the optimization of individual elements, such as housing, transportation, and business.

In addition to recent research that adapts ecosystem concepts to urban design and ecosystems (functions), there are also studies that directly apply specific ecosystems or organism systems [70]. For example, amoebal networks can give engineers insights to design robust transportation networks which include solutions to problems related to trade-off relationships between cost, transport efficiency, and tolerance [73–75]. Concerning infrastructure networks, studies suggest that increased efficiency can be reached through biomimetics [76]. Self-organization as a concept for optimizing the network structure can also be applied to the design of traffic infrastructure; for example, an optimal operation algorithm for traffic lights, based on the principle of self-organization, has been proposed [77].

In regard to urban infrastructure management, biomimetic materials have various self-organizing functions, such as self-cleaning, self-repairing, water repellency, and so on. Such functions are commonly discussed in the field of civil engineering, which focuses on large-scale (e.g., urban- or national-scale) infrastructure [78]. These functions contribute to the reduction of energy required for cleaning and restoration, while simultaneously enhancing amenities in urban areas. For example, Biocement is a self-repairing cement based on living processes [60].

As an advanced example of urban design, the structure of ant nests was applied to reduce the impact of flooding in an area of India with frequent floods, in an approach that can potentially be tailored for individual local contexts [79].

Biomimetic products that are compatible with urban environments have also been developed. For example, a small UAV designed by mimicking pterosaurs is expected to be usable in densely built environments [80,81]. Such products are developed based on the assumption of conditions like those in current urban environments.

4.2. Improvement of Socioecological Functions of Cities

In addition to functions like the reduction of environmental impact and food production, positive mental effects can be provided by mimicking ecosystems, as they can by mimicking organisms. Cultural ecosystem services provide psychological restoration and improve well-being, and they should be supplied by urban ecosystems. Biomimetics holds potential applications for planning and managing cities, districts, and architectural projects, to contribute to the enhancement of ecosystem services, including cultural ones [82].

As stated in Section 2, positive mental effects are expected in architectural designs deriving from biomimetics; such effects are expected in biophilic urban design, eco-city design, and green urbanism as well [62,83–85]. Such urban design concepts are being proposed, for instance, in countries undergoing rapid urbanization which need to avoid urban sprawl. Urban design by biomimetics has become a part of the trend of ecosystem-based environmental design, which is leading designers and engineers to rethink human–nature interaction and improve the socioecological functions of cities [86].

At the European level, the GREEN SURGE Project was conducted by researchers in a European region covering 11 countries, who proposed a policy to utilize socioecological linkages and biodiversity for urban environmental management, identifying and applying nature-based solutions. Based on the concept of biophilia, which, as noted, aims to reconstruct close relationships between nature and human society, the conservation of biodiversity in cities is implemented from a cultural point of view. Nature-based designs and biomimetics are practices that share and disseminate the concept of biophilia [87].

Biomimetics is expected to be a promising approach, as it supports a paradigm shift toward a sustainable society because of its effectiveness in improving well-being and its environmental efficiency at both architectural and urban scales [12] Based on this review at the urban scale in particular, it is possible to see biomimetic design as a driver to change our urban environment.

5. Future Challenges in the Application of Biomimetics in Urban and Architectural Design

The application of biomimetic approaches to urban and architectural design is driven by the development of methods leading to discoveries in biology and to innovation in engineering [88]. Cross-linking biological and engineering knowledge is globally urgent in these fields [24,89–92], as it allows innovations that are not merely or solely representations of living morphology [93]. Simultaneously, the establishment of biomimetic design methods is required [94]. In the promotion of a biomimetic approach, development of educational programs can serve as a fundamental aspect of enhancing awareness of the importance of cross-linking biology and engineering [95].

A database aimed at cross-linking these two fields has been proposed and is highly necessary [96–98]. Furthermore, methodologies that can be used in the design process to bridge the two fields have been proposed [99]. Examples of such methodologies are Bio-TRIZ [100,101], Design Spiral [2], Typological Analysis [102], and Nature Studies Analysis [103]. Bio-TRIZ is a database of technical contradictions in patented technology. It has a possible application in biomimetics for proposing problem-solving systems [101].

Innovation in information technology also contributes to the implementation of biomimetic solutions, including in urban and architectural design. A digital model for analyzing individual aspects of urban design and architecture, including the structure of buildings, external environments, and transportation systems, has been proposed from a biomimetic perspective; in addition, the necessity for an integrated model based on biomimetic concepts for analyzing urban and architectural systems has been identified [9] Digital tools are also being developed to help architects and urban designers bridge biological and architectural knowledge based on Bayesian Networks [21].

In recent years, it has become possible to design highly complex building structures because of innovations in information science which can analyze and reproduce the form and movement of an organism [104,105]. As a further step, a model of system dynamics developed for the analysis of ecosystems has also been applied to the analysis of architectural systems [106]. Ways of analyzing artifacts, including buildings and cities, have been proposed, using methodologies from biology and ecology.

Further, development of assessment tools for biomimetic products and projects is needed to evaluate their contribution to sustainable development in urban areas. In regard to assessment tools, tools including a life-cycle analysis method has been proposed to help designers and engineers find solutions, using a biomimetic approach [107], and development of relevant indicators is needed to assesss the impacts of biomimetic approaches on biodiversity and ecosystems based on existing indicators [108].

6. Conclusions

Applications of biomimetics, mimicking nature, can be observed in both contexts of historical and contemporary architecture design. At the urban design level, we can observe a trend of mimicking nature at the ecosystem level. It has been said that such applications are expected to lead to not only reduction of environmental impact but also positive effects on social aspects, such as enhancement of well-being. Based on our empirical review here, it was suggested that biomimetics in the field of architecture and urban design can contribute to the holistic sustainability of cities, particularly in the form of the application of the concept of biophilia to planning and managing built structures and urban areas. As shown in Section 2, research topics including Biophilia and Material need more research on biomimetic applications in architectural and urban design. Regarding the scale of the application, urban-scale research is limited and is a promising area of research that can facilitate the social implementation of biomimetics.

In the recent application of biomimetics to urban design, innovative information technologies facilitate understanding of the complex mechanisms of ecosystems and also the mimicry of such systems in urban planning and management. In this light, an ontology to connect different knowledge(s) and terminologies in biology, ecology, and engineering is required. Information technologies can contribute further to the social implementation of biomimetics based on a proper ontological platform.

For further innovations, an additional analysis of organisms, biodiversity and ecosystems in terms of functions and processes based on scientific knowledge from biology and ecology, and also rooted in local and traditional knowledge, can contribute to the development of biomimetic technology [109]. This local and traditional knowledge includes the wisdom of sustainable lifestyles, known before the era of dependence on fossil fuels. A method of extraction of appropriate local and indigenous knowledge that can help develop ideas and tailor technologies based on that knowledge has also been proposed [110]. Social science research on local and traditional knowledge should also continue, and its lessons should be applied in biomimetic design. The results of this research can be combined with those of advanced interdisciplinary research on biomimetics, in order to develop and implement biomimetic technologies for the sustainable management of cities and architecture.

There are works that identified practical application trends in the industry or lay people [111,112]. Still, the research foucing on social implementation of biomimetics is limited. The biomimetic methods for architectural design and urban design further need to be integrated in order to facilitate globally sustainable trajectories, and these two types of knowledge, scientific and traditional, can contribute to the integration of biomimetic methods in the design of structures and spaces at different scales.

Author Contributions: Conceptualization, Y.U. and R.K.; methodology, Y.U. and E.B.; formal analysis, Y.U. and E.B.; investigation, Y.U., E.B. and R.K.; writing—original draft preparation, Y.U.; writing—review and editing, Y.U., E.B. and R.K.; supervision, R.K.; project administration. Y.U. and R.K.; funding acquisition, Y.U. and R.K. All authors have read and agreed to the published version of the manuscript.

Funding: This study is funded by the JSPS KAKENHI Grant Numbers JP20K12398; JP16KK0053; JP17K02105; Kurita Water and Environment Foundation [20C002]; Foundation for Environmental Conservation Measures, Keidanren [2020].

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Topics and Target Scales of the Reviewed Papers

Table A1. Topics and target scales of the reviewed papers which are focusing on specific biomimetic applications.

Architecture/Urban	Author (Year of Publication)	1. Material	2. Structure	3. System	4. Biophillia
Architecture	Edmondson, A. C. (1986).		○		
Architecture	Aldersey-Williams, H. (2004)	○	○		
Architecture	Dollens, D. (2006)		○		
Architecture	Vincent, J. F. V. (2006)	○			
Architecture	Building Research Establishment (BRE). (2007). Naturally innovative :	○	○		
Architecture	Badarnah, L. & Knaack, U., (2008)		○		
Architecture	Turner, J. S., & Soar, R. C. (2008, May)		○	○	
Architecture	Memmott, P., Hyde, R., & O'Rourke, T. (2009)	○	○		
Architecture	Vincent, J. F. V. (2009)	○	○		
Architecture	Royall, E. (2010)		○	○	
Architecture	Eilouti, B. H. (2011)		○	○	
Architecture	French, J.R.J. and Ahmed, B.M. (2011)		○	○	
Architecture	Gamage, A., & Hyde, R. (2011)	○	○	○	
Architecture	Gruber, P. (2011)	○	○	○	
Architecture	Kellert, S. R., Heerwagen, J., & Mador, M. (2011)		○		○
Architecture	Peters, T. (2011)			○	
Architecture	Knippers, J., & Speck, T. (2012)		○		
Architecture	Menges, A. (2012)		○		

Table A1. *Cont.*

Architecture/Urban	Author (Year of Publication)	1. Material	2. Structure	3. System	4. Biophillia
Architecture	Fernández, M. L., Rubio, R., & González, S. M. (2013)	○	○		
Architecture	Taghizade, K., & Taraz, M. (2013)		○		
Architecture	Van Renterghem, T., Hornikx, M., Forssen, J., & Botteldooren, D. (2013)		○		
Architecture	Webb, M., Aye, L., & Green, R. (2013)	○			
Architecture	Zare, M., & Falahat, M. (2013)		○	○	
Architecture	Chen, D. A., Ross, B. E., & Klotz, L. E. (2014)		○		
Architecture	Raoa, R. (2014)		○	○	
Architecture	Browning, W.D., Ryan, C.O., & Clancy, J.O. (2014).				○
Architecture	Garcia-Holguera, M., Clark, G., Sprecher, A., & Gaskin, S. (2015)			○	
Architecture	Gil, P., Rossi, C., & Coral, W. (2015, July)				○
Architecture	Han, Y., Taylor, J. E., & Pisello, A. L. (2015)		○		
Architecture	Ramzy, N. (2015)		○		
Architecture	Sara, K., & Noureddine, Z. (2015, May)			○	
Architecture	Shimomura, M. (2015)	○	○	○	
Architecture	Madre, F., Clergeau, P., Machon, N., & Vergnes, A. (2015).		○		
Architecture	Menges, A., & Reichert, S. (2015).	○	○		
Architecture	Achal, V., Mukherjee, A., & Zhang, Q. (2016)	○	○		
Architecture	Elmeligy, D. A. (2016)	○	○	○	
Architecture	Fujii, S., et al. (2016)	○			
Architecture	Tsujino, M. (2016)	○			
Architecture	Vuja, A., Lečić, M., & Čolić-Damjanović, V. M. (2016, November)		○		
Architecture	Garcia-Holguera, M., Clark, O. G., Sprecher, A., & Gaskin, S. (2016).			○	
Architecture	López, M., Rubio, R., Martín, S., & Croxford, B. (2017)		○	○	
Architecture	Al-Obaidi, K. M., Ismail, M. A., Hussein, H., & Rahman, A. M. A. (2017).		○		
Architecture	Bechthold, M., & Weaver, J. C. (2017).	○	○		
Architecture	Chayaamor-Heil, N., & Hannachi-Belkadi, N. (2017).			○	
Architecture	Fecheyr-Lippens, D., & Bhiwapurkar, P. (2017).		○		
Architecture	Gruber, P., & Imhof, B. (2017).		○		
Architecture	Speck, O., Speck, D., Horn, R., Gantner, J., & Sedlbauer, K. P. (2017)		○		
Architecture	Yuan, Y., Yu, X., Yang, X., Xiao, Y., Xiang, B., & Wang, Y. (2017).	○	○		
Architecture	Gao, R., Liu, K., Li, A., Fang, Z., Yang, Z., & Cong, B. (2018).			○	
Architecture	Webb, M., Aye, L., & Green, R. (2018).		○		
Architecture	Xing, Y., Jones, P., Bosch, M., Donnison, I., Spear, M., & Ormondroyd, G. (2018)	○	○		
Architecture	Cuce, E., Nachan, Z., Cuce, P. M., Sher, F., & Neighbour, G. B. (2019).		○		
Architecture	Khelil, S., & Zemmouri, N. (2019).			○	
Architecture	Sheikh, W. T., & Asghar, Q. (2019).		○		
Architecture	Terrier, P., Glaus, M., & Raufflet, E. (2019).	○			
Urban	Todd, N. J., & Todd, J. (1994)			○	

Table A1. *Cont.*

Architecture/Urban	Author (Year of Publication)	1. Material	2. Structure	3. System	4. Biophillia
Urban	McLennan, J. F. (2004)			○	
Urban	Pedersen Zari, M. and Storey J. B. (2007)			○	
Urban	Pedersen Zari, M. (2010)			○	
Urban	Tero, A. et al. (2010)			○	
Urban	Kenny, J., Desha, C., Kumar, A., & Hargroves, C. (2012)		○	○	
Urban	Gruber, P., & Benti, D. (2013)		○	○	
Urban	Goel, S., Bush, S. F., & Ravindranathan, K. (2014, November)			○	
Urban	Hidalgo, A.K. (2014)				○
Urban	Buck, N. T. (2015).		○	○	
Urban	Pacheco-Torgal, F. (2015)	○	○	○	○
Urban	Pedersen Zari, M. (2015)			○	
Urban	Fink, H. S. (2016)				○
Urban	Pedersen Zari, M. (2016)			○	
Urban	Pedersen Zari, M. (2017).			○	
Urban	Pedersen Zari, M. (2018).			○	
Urban	Ferwati, M. S., Al Suwaidi, M., Shafaghat, A., & Keyvanfar, A. (2019).		○	○	○

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