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Bio-design as a Basis for the Creation of New Architectural Materials: Experience of the Faculty of Architecture of Gazi University

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Abstract The experiences of nature that have been present for billions of years guide scientists and designers in their research, covering different topics such as form, function, aesthetic, production of durable materials, light and practical structures, variety, optimization, conservation of natural systems, bio-diversity, reduction of energy losses, *etc*. From that perspective, nature offers ideas to produce adaptive, highly durable, and smart materials and serves as a raw material source for researchers who learn from nature. This study questioned how bio-inspired designing could be used as an instrument for interdisciplinary research in the triangle of architecture, materials science, and biology, and it discussed the outputs of a workshop held with the students undergoing postgraduate education in architecture. Utilizing "the problem-based process", which is one of the bio-inspired designing processes, this study reviewed the material-related thoughts of architects in line with architects' limited biology knowledge. Furthermore, it examined the gains of the bio-inspired design approach through the pre-post-test and problem-based designing of the self-assessment questionnaire. In conclusion, it is safe to state that nature, as a role model, can present significant information in the search for solutions within interdisciplinary studies in this century when the importance of sustainability is more apparent than ever.

Keywords Architecture, Bio-inspired Design, Biomimicry, Biomimetics, Biology, Material Design, Biomimetic Material

1. Introduction

"Nature does not strive to be meaningful; it already is." [1]

Robert Walser

Bio-informed design has become an increasingly significant and widespread movement in design for environmentally responsible sustainable development [2]. It is a nature-inspired design process to "drive innovation and improve our current product design, manufacturing, and lifecycle methods" [3]. Natural systems, forms, functions, patterns, behaviors, and processes enable ecologically sustainable development of environmentally friendly processes and products [4].

Many models that could be assessed in terms of design and architecture and adapted to these two fields have been presented throughout the evolution of the Earth, lasting 3.8 billion years [5]. Bio-inspired designing indicates the efforts to abstract the natural models, processes, and systems to solve problems defined in any area, and it reflects the method of conveying information. Furthermore, bio-inspired design involves utilizing insights from nature to inspire creative ideas and promote sustainable development.

Among the United Nations 2030 goals are many titles, such as “improving education goals for sustainable development and promoting sustainability” [6]. In this respect, increasing bio-inspired practices in the field of education is significant in the context of sustainable environmental awareness. In addition to the courses in formal education, non-formal activities in the schools will encourage designers who are “beginners” in the “sustainability and biomimicry” approach to design a sustainable future.

While biomimicry is not extensively incorporated into architectural education in Turkey, its application is typically confined to the scale of form and relies predominantly on an analogical approach. This situation is not much different in architecture schools worldwide, except for large-budget research projects [7]. There are few biomimicry-based design education trials in architecture schools [8, 9, 10]. Bio-inspired architectural design has been considered by many researchers at the scale of “structure and form” [11, 12]. From this point of view, it can be claimed that most of the studies in the discipline of architecture cannot go beyond the inspirations for form-finding and cannot be considered in the context of innovative and sustainable design research. The number of studies conducted in universities should be increased to spread the bio-informed approach, make future generations benefit more from this knowledge, and develop sustainable creative thinking.

This study suggests that designers look to nature for a sustainable future. For this purpose, a workshop has been organized to facilitate the participants' access to biological knowledge and transfer it to the design problem by interpreting it. The study asked architects to change their view of nature from form-finding to material design. It aimed to focus on issues from sustainability and energy conservation point of view. A process with a problem-oriented approach was followed to generate innovative ideas and design materials at a conceptual level.

In this respect, this study aimed to discover the innovation bio-inspired designing can present in designing architectural materials, promote the effective use of bio-inspired designing in architectural designing efforts, and examine the results. The research results on “bio-inspired materials” at a workshop held in “the Department of Architecture at Gazi University” during the 2020-2021 Spring Term were shared. The material proposals by the postgraduate students of architecture who utilized the data gained from biological sources such as mammal bones, sea turtles, euplectella aspergillum, cicada, oriental hornet, and bioluminescence were also presented.

2. Bio-material Studies in Architecture

Today, the construction industry causes significant damage to the environment due to the intensive use of materials, energy consumption, and waste generation. These include depletion of natural resources, water and air pollution, habitat loss, and climate change. In this context, using naturally renewable, high-strength, lightweight materials is essential for creating a sustainable built environment in architecture. To achieve this goal, architects constantly research and promote environmentally friendly materials. They also focus on developing new approaches to use resources more efficiently in the design and construction processes. At this point, being inspired by nature offers many solutions for designers and engineers to develop creative and innovative material solutions.

For example, the work developed by Attias et al. [13] presents the results of ongoing research into utilizing “mycelium to provide cleaner architecture and design products with sustainable life cycles”. The architectural case study demonstrates the production of mycelium-based acoustic ceiling tiles and the potential impact of “mycelium-based biocomposites” in architecture and industrial design (Figure 1).

Figure 1. Production of interlocking mycelium-based bricks [13]

Similarly, Vallas & Courard [14] also conducted mycelium research for using recycled materials in architecture. The study investigated using sustainable and recyclable material design mycelium (Figure 2).

Figure 2. Blocks produced with mycelium [14]

In another study, a team of Indian and Italian architects constructed a pavilion called "Shell Mycelium" (Figure 3) in Kerala, southwest India, to create temporary spaces using fungal mycelium. In the project, mycelium spores and organic nutrients were placed in the fiber core, and after a few days of maintenance, they became a white cover [15].

Figure 3. Shell Mycelium Pavillion [15]

In many pavilion designs designed by "ICD (Institute for Computational Design and Construction) /ITKE (Institute of Building Structures and Structural Design)" [16], research on materials with properties such as lightweight, high strength, sustainable, biodegradable, and recyclable is being carried out. In one of these studies, Reichert et al. [17] researched "autonomously responsive architectural systems that adapt to environmental and climatic changes using hygroscopic material properties" (Figure 4).

Figure 4. A larger functional prototype was created to explore the practical possibilities of the material system [17]

In another study, Abdallah & Estévez [18] investigated optimized designs using Barcelona clay bricks and bio-learning to ensure sustainability in material use (Figure 5).

Stoma Brick (Figure 6) is designed as an evaporative cooling system for building shells based on the principles of various natural methods such as "plant stomata, pine cones, hair protecting the eyes in the desert, and human skin". The designed stoma brick is made of porous material to provide thermoregulation. This designed material has many features, such as air filtration, thermoregulation, and closing according to humidity [19].

Figure 5. Biodigital Barcelona Bricks [18]

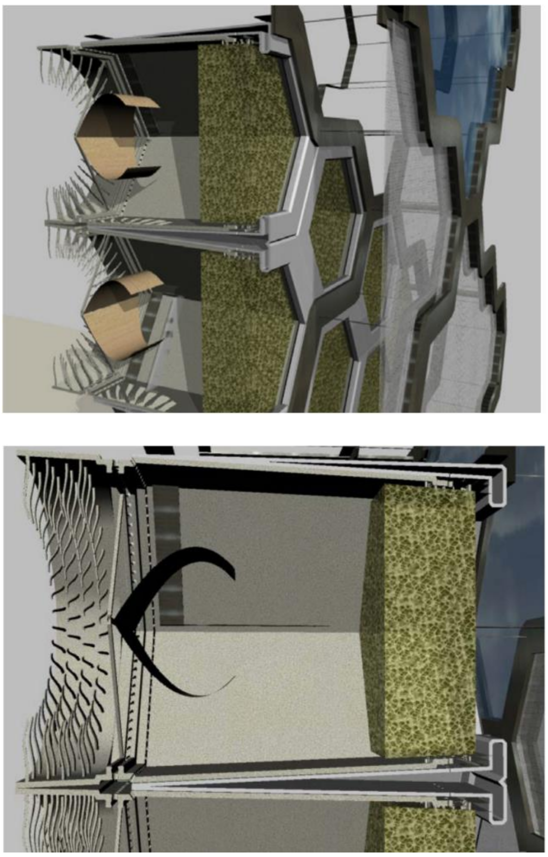


Figure 6. Stoma Brick [19]

The research has shown that architects are increasingly interested in environmentally friendly, biodegradable, recyclable, and environmentally friendly materials.

3. Materials and Methods

Architects' awareness of the problems in the materials they use in their designs and surroundings increases both during the architectural education process and while practicing their profession. However, only a few architects can perform research and development to solve these problems. Accordingly, the primary motivation of this study shaped by the hypothesis that "Architects can transfer and reflect the knowledge of nature through their designs to propose sustainable and innovative solutions to the problems around them" was to search for a solution to the question: "Can architects question the problems of architectural materials around them and perform bio-inspired material designs for solving these problems?"

As a method defining inter-disciplinary information transfer, the bio-inspired design approach enables architects to generate innovative ideas for producing sustainable and ecological material. Helping architects develop an interdisciplinary solution by using the database and vast information of nature was set as the purpose of this study. The method was to conduct problem-solving research with architects based on the bio-inspired design approach and problem-based solution process. The solution to the material problem determined by the six architects participating in the study was sought in nature. During this period, the problem-based approach within the bio-inspired strategy was followed.

Within the scope of the study, the problems and potentials discussed in the context of materials in biology and architecture were revealed, and it was aimed to generate ideas for architectural material design. As a result, it has been tried to indicate how and for what purpose the techniques learned from nature are made through the studies of bio-informed materials developed at the conceptual level. From this point of view, this study aims to create a critical perspective on the bio-informed design approach in architecture and to contribute to the innovative and sustainable material designs that will be developed prospectively.

The problem-based design process followed in this study was briefly explained in Figure 7.

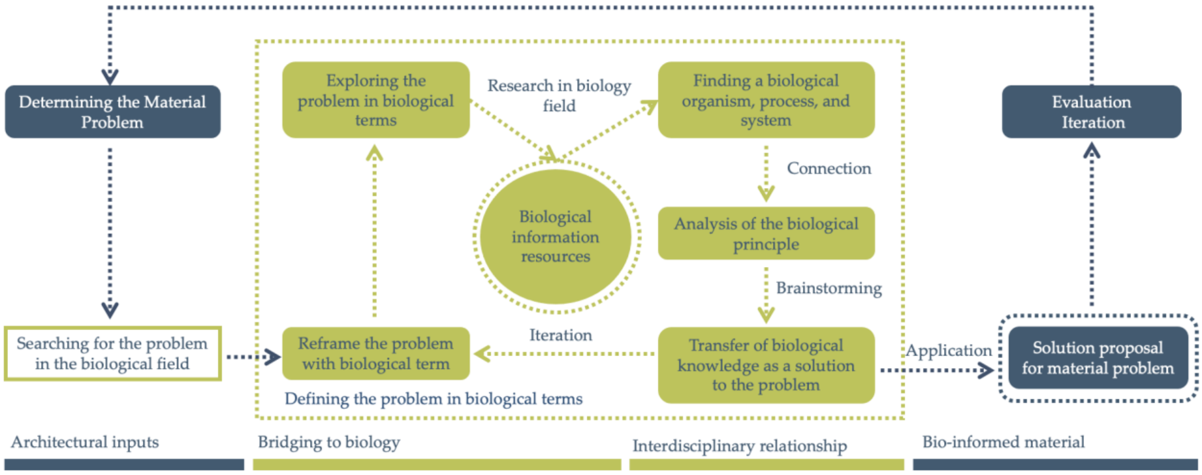


Figure 7. The problem-based design process followed for the material

4. Bio-Inspired Design Processes

The bio-inspired processes in the literature indicate that the relevant procedures have been problem-based and solution-based. The problem-based and solution-based approaches diverge in their initial points of departure and the methodologies employed in the design process [20]. Accordingly, this bio-inspired design process is completed using one of the following two models: the solution-based one progressing with the solution or the problem-based one going with the problem.

4.1. The Bio-inspired Design Process— From Biology to an Application

The researchers from the relevant literature use different terms to reflect the expression "from biology to an application process," such as solution-based [21, 22], solution-driven [2, 23], biology to design [5], biology push [24] bottom-up [25, 26], biology-driven [27] or biomimetics by induction [28]. In this process, a designer starts to work after observing an exciting trait of an ecosystem or organism, conducting a potential procedure for an invention, and creating (or developing) a process or product based on the previously mentioned feature [29].

The solution-based approach outlines the progression of bio-inspired design development, initiating with pertinent information about a biological system serving as the foundation for technical design. In this phase, a natural system that effectively functions in a specific domain becomes the model for technological emulation. Moreover, in-depth analysis of the biological system is crucial for uncovering the fundamental principles of the process and establishing the basis for identifying design issues that can be addressed using these principles. The primary source of information concerning these principles is derived from original research. Subsequent to extracting this knowledge, it is applied to address problems within the relevant field [30]. The process with different models is collectively presented in Figure 8.

As evident in the process models proposed by various researchers and illustrated in Figure 2, the "solution-based approach" commences by identifying a biological solution and subsequently deriving a principle from it. A connection is established between this noteworthy natural principle and the problem within the relevant field. Acting as a bridge between two distinct domains, this connection proceeds through the analysis and abstraction stages, facilitating a deeper understanding of the biological solution. Subsequently, the process unfolds to unveil how the deduced principle can be applied or adapted to address a specific problem. The practitioner in this process aligns the biological characteristics with a given problem, endeavoring to explore solutions and generate design solutions for human challenges.

4.2. The Bio-inspired Design Process— "From a Problem to Biology"

As the second phase of the bio-inspired design methodology, the expression "from a problem to biology" is reflected by different researchers with the following terms: "design looking to biology" [30] "problem-driven" [2, 21, 23], biomimetics by analogy [28], top-down [25], "Problem-Driven Biologically Inspired Design Process" [23], "problem-based" [22], "challenge to biology" [5], "technology pull" [24].

"The problem-driven approach" in bio-inspired design is geared towards addressing a tangible issue, with the starting point of the process firmly established within the context of the specific problem [20, 24]. The process with different models is collectively presented in Figure 9.

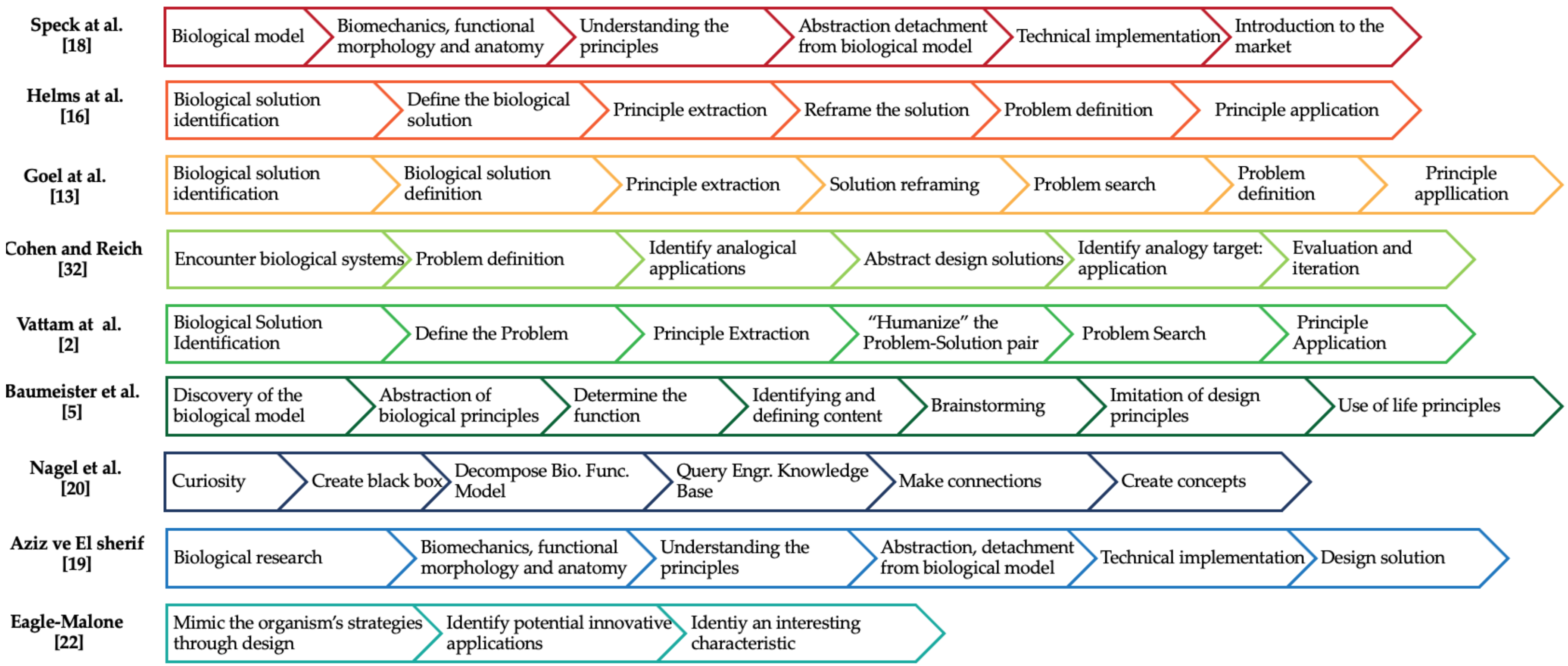


Figure 8. From Biology to an Application process described by different researchers

Figure 9. From a Problem to Biology process described by different researchers, Developed from [30]

Figure 3 illustrates that Lindemann and Gramann [31] condensed the problem-based process into four stages: formulating the target, establishing a connection with the biological system, analyzing the associated system, and achieving the technical solution. And these stages may iterate. Bogatyrev and Vincent [32] outlined a six-step process centered on extracting essential traits from biological models and applying them to technology. Chakrabarti et al. [33], Shu [34], and Cheong et al. [35] summarized a process model based on natural language processing, commencing with defining an original functional keyword to articulate a problem and concluding with the significance of a biologically relevant keyword. Lastly, Cohen and Reich [36] initiated the process by defining the problem and elucidating the step of incorporating a biological perspective into the problem. Following the study of biological systems, emphasis is placed on the phase where the natural approach is abstracted, and information is transferred for problem-solving. The process model incorporates six steps, culminating in an assessment phase where relevant evaluations take place.

As gleaned from the aforementioned points, the initiation of the problem-based design process, as examined by various researchers, involves defining and scrutinizing the problem. Following an in-depth analysis of the problem and the identification of the required function, the problem is contextualized within the realm of biology, and a solution is sought within this discipline. During this phase, investigations are conducted to understand how nature addresses this problem, exploring the relevant biological principles, processes, and phenomena. Additionally, endeavors are undertaken to unveil how these biological elements solve the pertinent problem, and the principles derived from this exploration are delineated. Subsequently, these principles are transferred to the applicable field.

4.3. The Design Process for Bio-Inspired Problem Solving Implemented in the Study

The workshop program took place from December 10th to December 13th., and only graduate students participated. On the first day of the workshop, the "Bio-Inspired Design Approach Questionnaire" was administered to the students to obtain their personal information. This form is about being aware of identity information, gender, and bio-inspired design. Within this context, the students' understanding is evident in Table 1.

During a workshop, architecture students were first asked to define a problem around them and describe what they saw/experienced regarding a material used in architecture. While determining the problem, the questions “What is the problem with the materials?”, “What do you want to explore?” and “How will you contribute to architectural design and sustainability if you solve that problem in the material?” were directed to the students. The purpose here was to clarify the function expected from that material. On the other hand, the design purpose was to develop a system that would include the sustainability of architectural materials.

After defining the problem, architects were asked to “biologize” the problem they found and to generate ecological, sustainable, and innovative solutions after investigating this problem in biology. The steps of this investigation are presented in table 2.

Table 1. Information about the students who attended the workshop

The Total Number of Students (n)	Gender		Awareness of Bio-inspired Design Approach	
	Girl	Boy	Yes	No
6	4	2	-	6

Table 2. Steps followed with the Problem-Driven Design Process

Steps	Explanation	General Process
Definition	Definition of the problem	Description of the architectural material problem
Analyze/ Clarify	Examination of the problem	The detailed analysis of architectural material problem; environmental, functional, and structural necessities and restrictions
Biologization	Biologization of the problem	Re-definition of the problem with the biological terminology Definition of the keywords defining the design problem
Searching	Exploration of the biological information	Researching the natural models, processes, and information through keywords
Association	Biology-architecture association	Questioning the relationship between the biological information obtained at the end of the studies and establishing the relevant connection
Brainstorming	Presence of relationship	Brainstorming about how the information selected to be implemented and detailed analysis of the biological creature and process
Generating	Transferring biological information / Design	Implementing the biological information to the architectural problem and generating a solution

5. Workshop Experience and Architect's Proposals

This study can contribute to the field of architectural design education with the inter-disciplinary areas by suggesting approaches for architectural education. Re-positioning the informational gains achieved through a different discipline in design education may help gain significant perspectives for design education literature and both practical and theoretical backgrounds.

Accordingly, this study was limited to integrating “a bio-inspired approach to the design process” within a workshop, an informal teaching methodology. The bio-inspired design process related to this workshop was observed and assessed. The workshop program is presented in Figure 10.

Students’ gains were designed in line with the revised Bloom’s taxonomy within the workshop. The authors conducted this workshop to fulfill the targets in Table 1 with the timeline created in Figure 10.

After using the taxonomy table in planning the education program, the steps of learning, teaching, and assessing are collectively designed. Taxonomy (classification of educational purposes/gains) is defined as a schema structured within a gradual hierarchy that enables the category of cognitive, affective, and psychomotor learning expected from students at the end of education [37]. Revised Bloom’s Taxonomy covers the informational and cognitive dimensions; therefore, it was combined with a matrix/table defining the relationship between the two dimensions [38]. The column of this table consists of the “information dimension” and four sub-categories: “factual, conceptual, procedural, and metacognitive”. The table line includes “remembering, understanding, applying, analyzing, evaluating, and creating”, which are the “Cognitive Process” steps. The learning target is presented in the cell, where the column, including the cognitive process dimension, intersects with the line, including the information dimension [38, 39]. The targets were defined as nouns and verbs to determine which cell on the Revised Bloom’s Taxonomy the targets should be positioned on. After this step, based on these nouns and verbs, the sub-dimensions of the informational and cognitive process dimensions where the targets were to be included were set, and the targets were placed in the taxonomy table (Table 3).

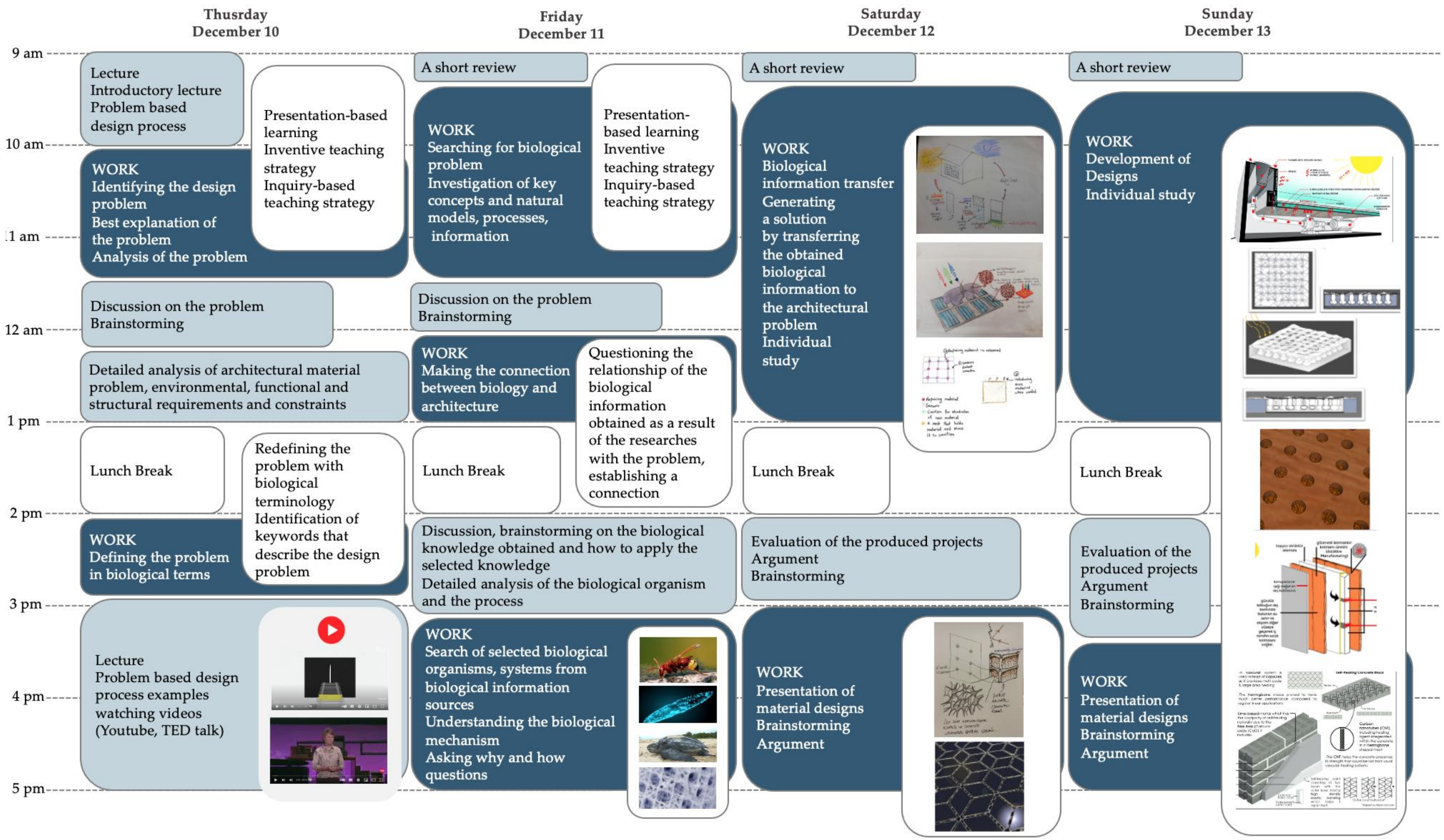


Figure 10. The problem-based design process conducted during the workshop lasting four days

Table 3. Determining the workshop targets using the informational and cognitive dimension of "Revised Bloom's Taxonomy"

BIO-INSPIRED DESIGN COURSE OBJECTIVES	INFORMATIONAL STEP	COGNITIVE FIELD STEP					
	COGNITIVE / INFORMATION	Remember	Understand	Apply	Analyze	Evaluate	Create
The students start to learn the concepts of bio-inspired/ biomimetics/ biomimicry/ bionic/ bioinspiration/ bionics and a problem-based process approach.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students start to learn "the problem-based process and steps" in biomimetic design.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students will discover and accurately describe design problems. They will find and define the most appropriate words related to the design problem. They will explore and explain the related vocabulary of the design problem.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students will learn to define the design problem they have identified in biology terms.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students will correctly scan the solution of the design problem in biology resources. They will determine associated systems, organisms, and processes.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students will correctly analyze associated systems, organisms, and processes. And they will explore the underlying mechanism of biological function. The students will start to identify the relationships between systems and problems.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students will learn to relate biological knowledge to architecture. As a result of the analysis they perform, they select the appropriate information for the problem. They correlate with biology and architecture.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students will carry out a feedback process in the design process. In this process, they will explore and define the relationships between the variables correctly.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students will organize the bio-inspired design process. They will follow the necessary steps to solve the problem.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						
The students will develop a dynamic process to establish a biology-architecture relationship from the first to the last stage in the biomimetics design process.	Factual						
	Conceptual						
	Procedural						
	Metacognitive						

After the workshop was initiated, students' knowledge of the topic was measured through the pre-test. Moreover, "the level of students' knowledge and skills" was measured through "the post-test" on the last day of the workshop program, and students assessed "the problem-based design process" with a five-item questionnaire administered to them.

5.1. Problem Definition

A crucial phase in "the problem-based process" involves clearly and transparently articulating the definition of the problem. Instructors specified specific titles such as "material, natural material, architectural material" to define the problem clearly and planned a series of preliminary investigations to ensure the understandability of the topic. The definitions and searches for examples were necessary to clarify the issue, determine the deficiencies, and reveal the problem. While defining the problem, the brainstorming sessions helped the participants describe their problems. The students who participated in the workshop were asked how the potential solution to their problems could contribute to architecture and nature, and they were requested to approach the problem from that perspective.

5.2. The Definition and Biologization of the Problem

After setting the problem, designers also focused on the functional investigation regarding the material. Specifying the function of the material contributed to the efforts to make the situation more understandable. Furthermore, the terms defining the role of the material facilitated the relationship established with biology while being searched in the biological references. This step contributed to establishing functional relationships in the natural field and conveying this relationship as "the solution to the problem".

"The transformation of the problem" into a biological problem indicates that the problem exceeds the borders of architectural design and becomes biological. The "biologized" issue begins with investigating and determining the natural sources and web addresses that will guide the design solutions. Asking, "How does nature perform this function?" is essential for progress.

Participants who specified the material-related problems utilized the keywords and defined their problems to make these problems biological issues (Table 4). The material problems described also include the function expected from that material. The physical equivalent of this function was matched through the keywords defining the function. By doing so, the architectural material problem was simplified, and the natural equivalent of the function that the material will have can be set.

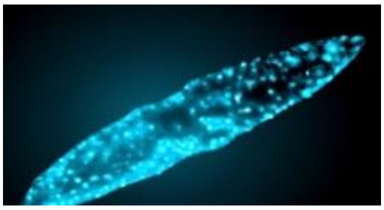
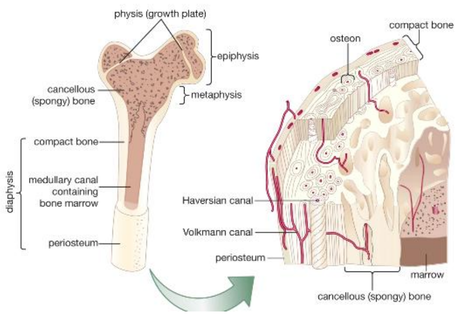
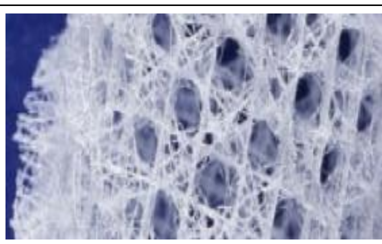
5.3. Discovery of Biological Information

After biologizing their problems, the researchers started to search for a biological solution in biological sources and websites. The searches performed using the keywords contributed to the efforts to conduct the process systematically. The designers focused on the functional keyword and stayed within the limits of the problem, which helped them not get lost within the broad database of nature. In this period conducted by the designers, the examples that were not functionally suitable were eliminated, and the biological examples where only the principal transfer was possible were selected. Table 5 presents the natural creatures chosen by the designers at the end of the process.

Table 4. Designers' material problems and the keywords through which the issue was biologized.

	Description of the Problem	Bridging to Biology
A1	To illuminate buildings, they built a natural environment at night using biomaterials in an energy-efficient manner	Communication in Biological organisms
A2	A material design that will increase the efficiency of the energy obtained from solar cells	Absorb solar energy
A3	Self-healing of an architectural coating material to extend its economic life	Self-healing
A4	Responsive, adaptive, and thermoregulatory material design in architecture	Adaptive Thermoregulation
A5	Acoustic sound absorbing material design to provide noise control and acoustic comfort	Pore, Porosity
A6	Coating of architectural surfaces with antimicrobial material	Antimicrobial

Table 5. The biological creatures selected by the designers at the end of the process

<table>
<tr><th></th><th colspan="2">Biological Systems</th><th>Biological Principles</th></tr>
<tr><td>A1</td><td></td><td>Dinoflagellate Pyrocystis Fusiformis
photo-plankton</td><td>It emits lights through the luciferase enzyme after perceiving a threat. Use of the creature as a bio-material.</td></tr>
<tr><td>A2</td><td></td><td>Oriental hornet</td><td>It was discovered that the shell covering the body of the oriental hornet acted like a photo-voltaic cell. The pigments in the culture of the oriental hornet absorb the solar energy transformed into electricity.</td></tr>
<tr><td>A3</td><td>
</td><td>Mammal bones</td><td>When a microscopic crack occurs, the osteocyte cells release an acid that creates a cavity called BMU, which heals the damage.</td></tr>
<tr><td>A4</td><td></td><td>Dermochelys coriacea</td><td>The solid tracheal circles within the structure of the trachea have a compressible form, and these tracheae can maintain the temperature of the blood circulation through reverse flow over the tissues on their surface.</td></tr>
<tr><td>A5</td><td></td><td>Euplectella Aspergillum</td><td>It has a spongy characteristic like all sponges. Moreover, this porous characteristic represents a mathematical expression that can be defined in the literature.</td></tr>
<tr><td>A6</td><td></td><td>Cicada</td><td>It shreds and kills the bacteria through its nanopillars.</td></tr>
</table>

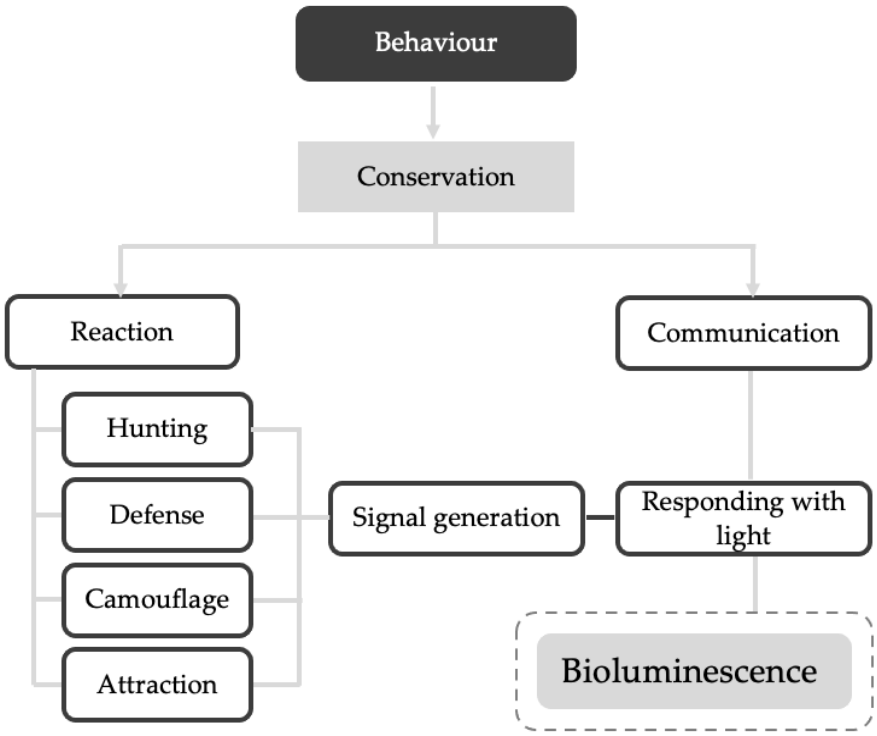


Figure 11. Selection and analysis of the relevant biological model (models) (method of transfer, inference) (A1)

After deciding on the biological phenomenon, participants started examining the natural phenomenon's function and determining the principle to be transferred. Figure 11 represents the analysis conducted by designer A1 to investigate why "Dinoflagellate Pyrocystis Fusiformis" displayed attitudes and communicated. The mechanism the creature used to fulfill this function was specified. This mechanism was established as the principle to be transferred to the architectural design in the following step.

Efforts were made to understand the structure of the model, components of the material, system, mechanism, and form, and how these components were organized at different scales to learn about the biological model. How the model organized attitudes under certain conditions, which these conditions were, and how the model acted were also discovered. This information was deemed necessary to understand the correct principle of the biological model.

5.4. Solution Generation

Designers started to transform the biological systems or phenomena selected for the solution of their problems into solutions suiting their problems. The natural system or phenomenon was deeply analyzed, and the mechanism within the creatures was examined. Therefore, the principle/strategy regarding the biological system and phenomenon was deduced. Understanding why and how the function occurred in the natural system/phenomenon helped participants comprehend the transfer of the natural principle into the architectural design problem (Figure 6).

While deducing a principle from the biological phenomenon and implementing this principle to the architectural design problem, participants need to transform the principle into the architectural design (Figure 12). This transfer covers abstraction/interpretation from one discipline (e.g., biology) to another (e.g., Architectural design). Therefore, as can be deduced from Figure 12, understanding and interpreting which function occurred in the biological field and why and how this happened helped gain suitable implementation ideas to reflect the process of the architectural design problem.

Student A1 used "Dinoflagellate pyrocystis fusiform" with a direct luminescence characteristic as part of the process and developed a design concept through which illumination could be achieved from water (Figure 13). The mineral water obtained after filtering and cleaning the rainwater first reaches the pump within the lower layer in this concept product. The adjustable hydrophore channels the water into the double-glass section coated with ethylene tetrafluoroethylene (ETFE). Therefore, the greenhouse effect due to overheating is prevented, and natural illumination is achieved in the desired dimensions and at the expected time. In addition, brainstorming was performed at the transfer/abstraction step where the study was conducted so that the designers could transfer the biological principles correctly.

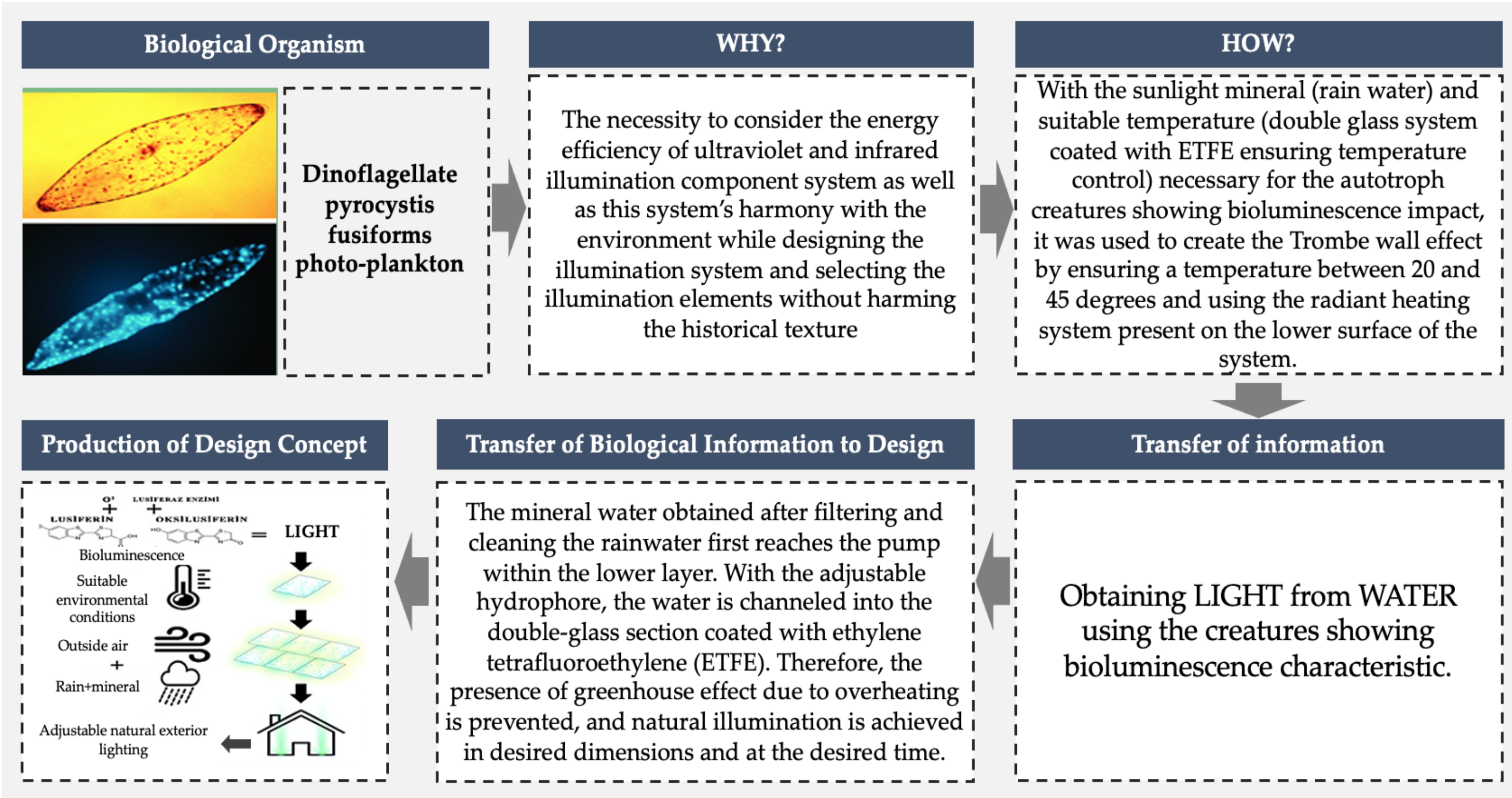


Figure 12. Analysis of the biological organism and information transfer

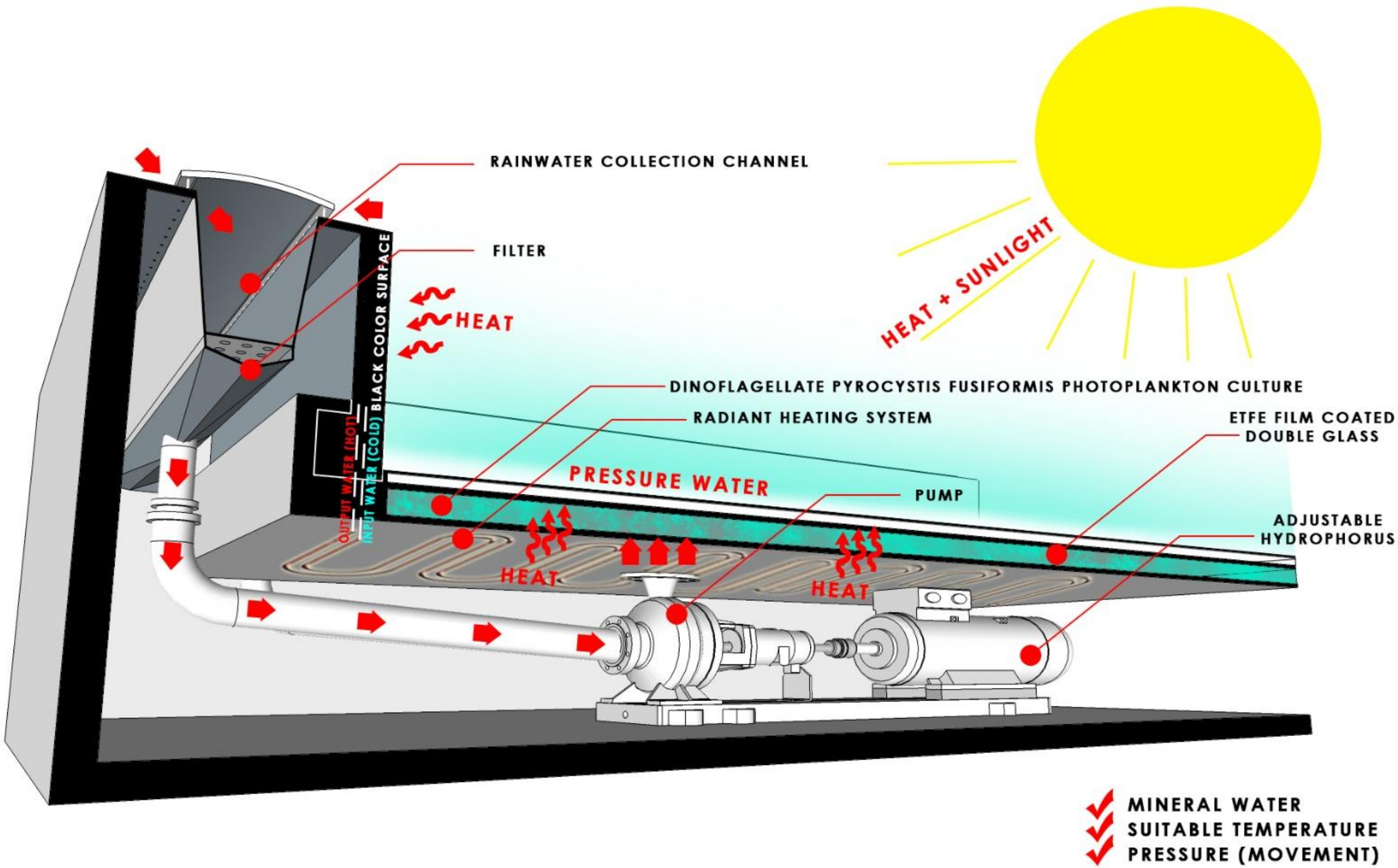


Figure 13. The design of the system containing dinoflagellate pyrocystis fusiform

Designer A5, who was another student, analyzed the geometry of Venus' flower basket (Euplectella aspergillum) for spongy acoustic material design. Studies were performed to examine the geometrical characteristics of the octagon pores within 0.25 cm squares on "Euplectella Aspergillum - Venus' Flower Basket Sponge," a hexactinellid within the filum Porifera living in the deep ocean (Figure 14).

The sound-absorbing coefficients of the acoustic sound-absorbing materials were searched among the responses to the question, "Which material should it be implemented on?" As a result of the analyses performed for this question, "fiberglass" with a density of 32 kg/m3 and a thickness of 50mm was selected to be processed and used with this geometry as a material that could serve the broad octave band ranges within the frequencies of material lightness and sound-absorption (Figure 15).

The question "How should the material stratification happen?" was investigated not to cause deformation on a porous material like fiberglass, which was open to the external environment. Therefore, the studies continued to examine the impact of acoustic panels on the materials and geometry of coating surfaces and the absorption of panels. The results showed that using the "Spongy Wooden Panel" with an axis space of 13 mm, a diameter of 3 mm, and a thickness of 5 mm on the external surface was suitable. As the bottom layer, using 3 mm adhesive was convenient to specify and mount the material (Figure 16).

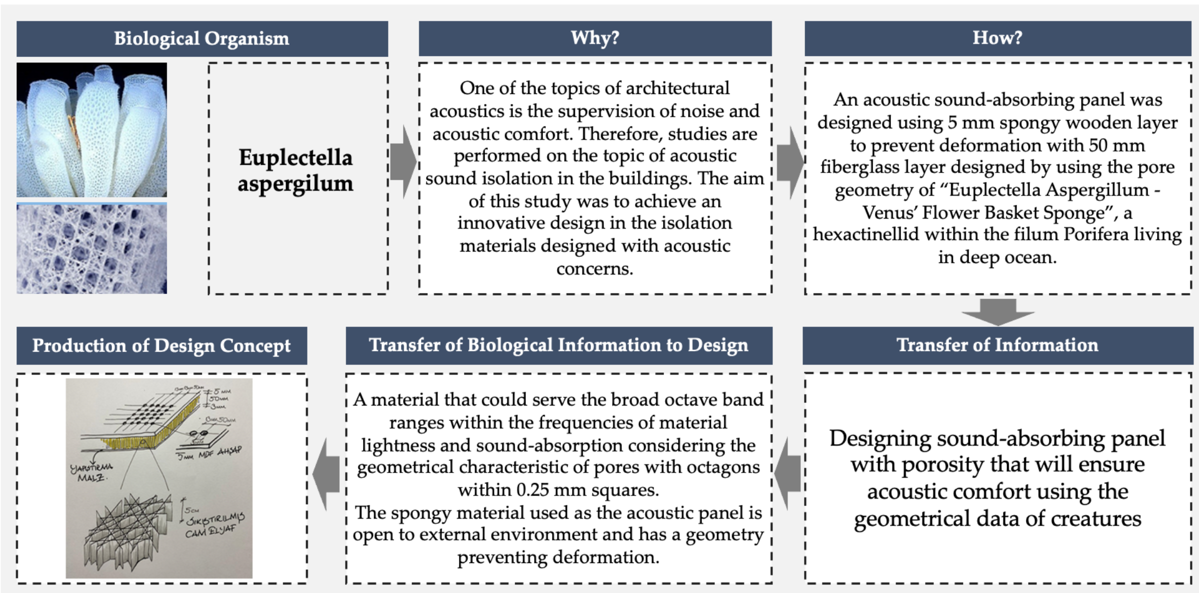


Figure 14. Analysis of the biological model (A5)

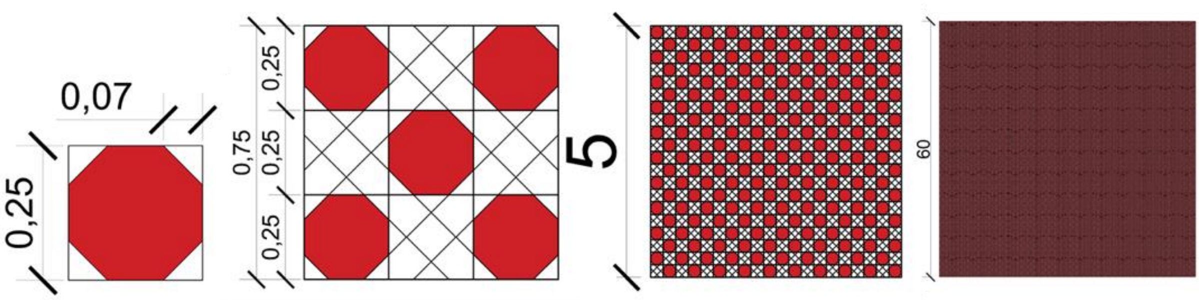


Figure 15. Implementation of the geometry to the material (A5)

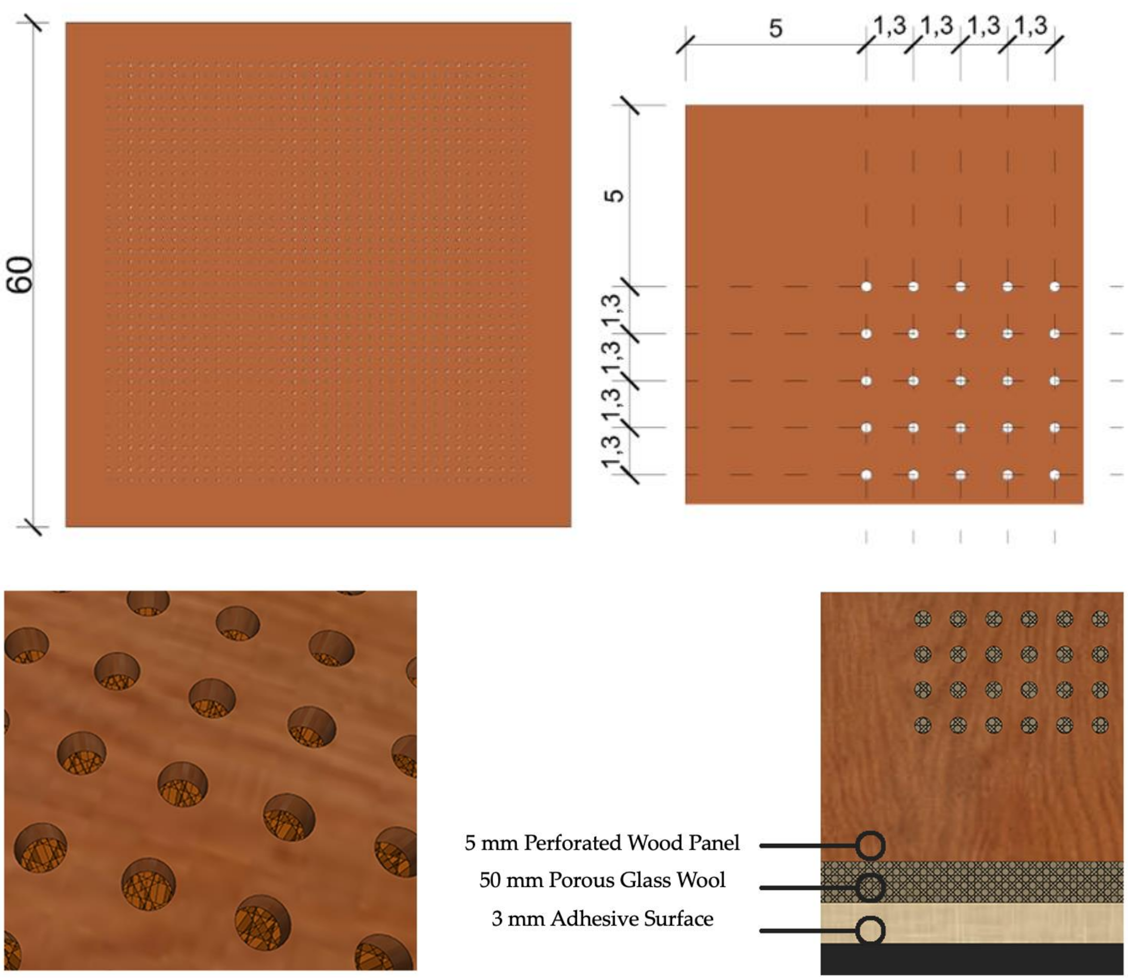


Figure 16. Spongy Wooden Panel (A5)

Based on the data found and implemented in this study, it is safe to say that a sound-absorbing acoustic panel design can be generated. However, experimental activities and applications should be utilized to test the materials. This test can be performed in Acoustic-Silent rooms, which can be practically produced and considered as the laboratory environment, and in ODEON applications, which are volume acoustic applications. Therefore, the changes that can occur through the dimensional changes of a geometrical entity can be quickly determined.

Table 6 presents the bio-inspired materials students created during the four-day workshop. The results show that all design proposals were prepared using sustainable materials, reflecting environmentally friendly concepts.

Table 6. Bio-inspired materials were designed at the workshop.

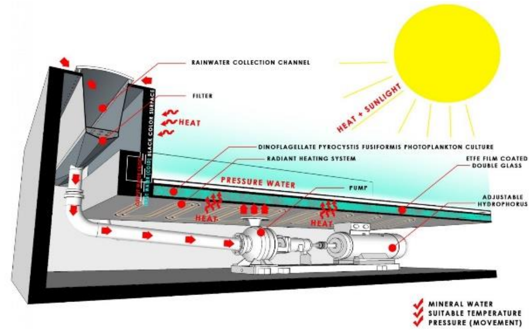
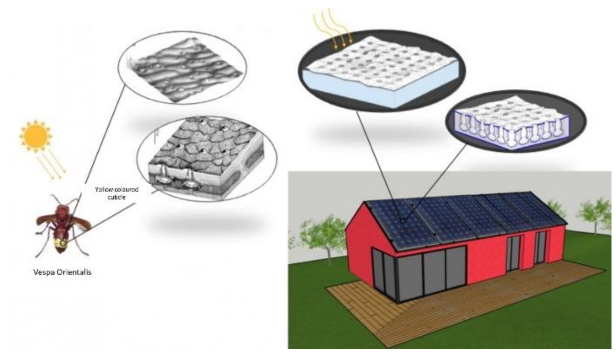
Student	"Definition of the problem"	"Biological system"	"Biological principle"	"Output"
A1	Illuminating buildings as well as built and natural environments using bio-materials in an energy-efficient form		It emits lights through the luciferase enzyme after perceiving a threat. Use of the creature as a bio-material.	
		Dinoflagellate Pyrocysts Fusiformis	Communication among creatures	Biotechnological material
A2	A material design that will increase the efficiency of the energy obtained from solar batteries		It was discovered that the shell covering the body of the oriental hornet acted like a photo-voltaic cell. The pigments in the culture of the oriental hornet absorb the solar energy transformed into electricity.	
		Oriental hornet	Absorb solar energy	Solar cell system

Table 6. Continued

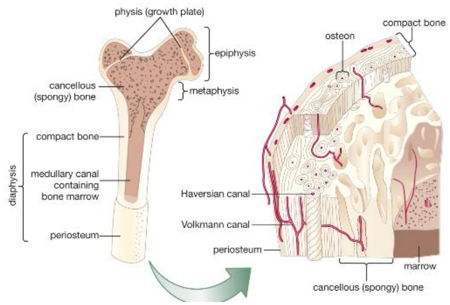
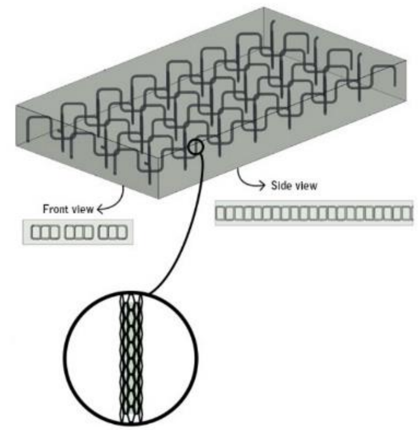
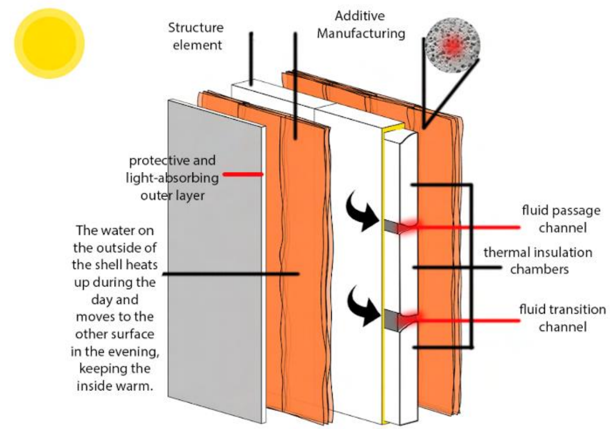
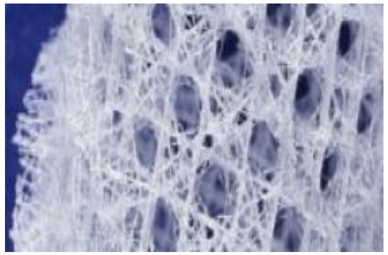
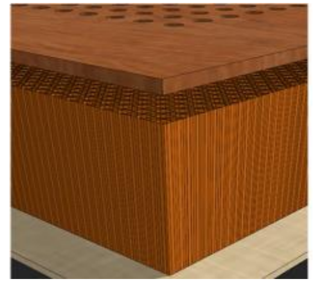
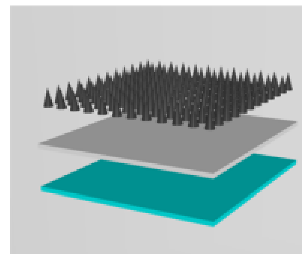
A3	Self-improvement of an architectural coating material to increase its economic lifespan		When a microscopic crack occurs, the osteocyte cells release an acid that creates a cavity called BMU, which heals the crack	
		Mammal bones	Self-healing	Self-healing material
A4	Adaptive and thermo-regulative material design in architecture		The solid tracheal circles within the structure of the trachea have a compressible form, and these tracheae can maintain the temperature of the blood circulation through reverse flow over the tissues on their surface.	
		Dermochelys coriacea	Adaptive Thermoregulation	Thermoregulatory material

Table 6. Continued

A5	Design of sound-absorbing acoustic material to ensure noise control and acoustic comfort		It has a spongy characteristic like all sponges. Moreover, this absorbent characteristic represents a mathematical expression that can be defined in the literature.	
		Euplectella Aspergillum	Pore, Porosity	Acoustic material
A6	Coating architectural surfaces with antimicrobial materials		It shreds and kills the bacteria through its nanopillars.	
		Cicada	Antimicrobial	Antimicrobial material

6. Assessment

The pre-test and post-test procedures were performed to assess achievements aimed at the students while the workshop was being initiated. This test examined whether the procedure performed during the workshop lasting four days had a significant impact on students' perceptions of nature. Students' mean pre-test score was 15, and their mean post-test score was 85. A t-test was conducted to determine the significance of the difference between the two mean scores. Subsequent to this test comparing students' pre-tests and post-tests, there was a variation in the mean scores. The significance threshold was established at 0.05, considering a substantial dependence and relationship to exist when $p<0.05$. [40]. According to the findings, there was a statistically significant difference between the mean scores of the experimental and control groups ($t(6) = -70.000$; $p < 0.05$) as indicated in Table 7.

Table 7. The t-test outcomes concerning the students' scores on the pre-test, post-test, and the "assessment test comprising 10 open-ended items"

	N	X	8	Sd	t	p
pre-test	6	15.00	5,47723	9	-70.000	.000
post-test	6	85.00	5,47723			

Table 8. Answers to the Self-Assessment Form for the Problem-Based Design

SELF-ASSESSMENT FORM FOR THE PROBLEM-BASED DESIGN	
1	**What did you learn while performing the problem-based bio-inspired design?**
	"I learned how to be inspired by nature, search for a solution for our problem, and generate a solution for our problem by abstracting my system." "I discovered that bio-inspired design did not only represent form similarity and that a solution could be brought to architectural problems using creatures' physical, morphological, and behavioral traits." "With this procedure, I learned how to use the characteristics of biological process/organism/relevant processes for the solution of the problem and that this biological transfer could result in economical, sustainable, and environmentally sensitive solutions."
2	**How did you find the creature you examined for the solution?**
	"After deciding the design problem, I asked myself what the equivalent of this problem was in nature." "I found the bio-luminescence creatures named Dinoflagellate Pyrocystis Fusiformis through communication among creatures." "I found relevant biological data by typing ask, nature, and the biological concept of thermo-regulation as the term related to my biological problem on the search engine." "I found an article related to my problem while investigating creatures' characteristics on Google."
3	**What do you think you did the best while performing the practices? Please explain the reason.**
	"I believe I sufficiently reflected the concept of alive raw material providing natural illumination, which has yet to be architecturally examined adequately and which was unique research to my belief." By doing so, I believe I provided a natural solution to the renewable energy resources." "I think the material I will form will be important in ensuring simplicity in use, durableness, and thermo-regulation."
4	**Please clarify in which topic and step you had difficulty performing a problem-based bio-inspired design and explain why.**
	"I had difficulty understanding how to use the SEM images of the system I discovered in line with the problem I found and how to abstract and resolve them." "While performing a problem-based bio-inspired design, I had difficulty finding a unique idea for integrating the biological functions that can be associated with the architectural process because imitating nature-inspired designs previously tried and practiced can create a stereotypical product." "After determining the problem, I had difficulty evaluating what, where, and with which keywords I should look, and whether the data I found can be a part of the solution (whether it is practicable or not). " "I had difficulty performing a unique design because I had never considered the living creatures to produce materials. Therefore, I needed to learn to proceed with what I was unfamiliar with and to achieve adaptation. I had difficulty in examining the dimension of material details because I did not have to think about the point detail this much in my previous studies."
5	**What did you gain while performing the problem-based bio-inspired design? What changes did you observe in your perspective? Please explain.**
	"The education I received has changed my perspective toward "nature."" "I have gained new perspectives due to the education I received." "The content provided at the workshop can be useful in my future career." "I can connect my profession and what I have learned." "This design approach can offer alternative solutions to architectural problems (fronts, structure, furniture, materials, etc.) and be used in all areas. "First of all, it helped me answer that need such a design. Besides, it made me discover different characteristics of living creatures and enriched my world of ideas regarding how I can benefit from them." "The question "Is it possible to produce a material, structure or any architectural item based on this attitude/characteristic?" became effective in my life when looking at the creatures or investigating their attitudes."

Students were asked to assess the problem-based process with a five-item self-assessment form in the bio-inspired design generated during the four-day workshop. The general responses regarding the assessment are presented in Table 8.

7. Conclusions and Future Remarks

The bio-inspired design approach is utilized to produce innovative and sustainable solutions by learning from the experiences of nature and making inferences from the adaptations developed by living things in nature. It should be considered that this approach, whose sporadic trials we see in architectural education, should be systematically addressed and placed in the curriculum.

This paper presents and discusses the results of a 4-day workshop with graduate students in "the Department of Architecture, Gazi University, Ankara, Turkey". There are some limitations in the study. Firstly, in this study with architects, it has been determined that architects have difficulties communicating with a different field.

Architects have had difficulties searching for biological solutions, deriving a biological principle, and adapting this principle to architectural materials. The most important reason is that architecture and biology are epistemologically, linguistically, and methodologically different.

Secondly, the "biology knowledge" of the students and lecturers participating in this workshop was limited. In this context, integrating a biologist in such a workshop may increase the quality of the research results. Furthermore, better results may be obtained when this study, carried out in as little as four days, is spread over a one-semester course.

Lastly, another limitation of this research is that the workshop was carried out as a process that proceeds with the traditional education approach using the "tell-apply" technique. It would have provided different experiences for the participants to see and examine the world of biology in laboratory conditions and to search for discoveries for their problems. However, the environment and tools used by the participants did not have enough opportunities for this. In this context, this research can be interpreted as a view of the biological world and the beginning of discovering biological solutions.

On the other hand, the "problem-oriented process model" allowed the participants to progress systematically. Starting from the architectural problem and analyzing the characteristics of the biological organism, such as structure, function, and behavior, abstraction was realized by establishing analogical similarity/relationship. The designers focused on the structural and behavioral characteristics of the biological organism and carried out the transfer of principles.

This study aimed to show that architects can go beyond imitating the formal features of nature and develop a more sensitive and deeper understanding of nature while designing. Using "the bio-informed design approach" in the problem-solving process will help to discover and produce sustainable, ecological, practical, and innovative designs. From this point of view, it is thought that the study will contribute to developing design pedagogy and arousing interest in bio-informed design thinking and education. Contributing to a comprehensive understanding of the problem-solving process in bio-informed design, this research shows that teaching architects bio-informed design improves nature literacy.

This research has shown that the subject of bio-inspired design has high potential and is very comprehensive. In this context, identifying and developing the tools and methods in bio-inspired design can be considered and developed as a curriculum and training opportunity that can be applied to general architectural education within the scope of a doctoral thesis. Thus, this study can help more architects to know and use the bio-inspired design approach. The spread of this approach, which can be applied with different techniques at every stage of education, will also accelerate the realization of a biomimetic revolution.

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Conflicts of Interest

The authors declare no conflict of interest.

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