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Article

Design and manufacturing of building products based on biomaterials: A systematic literature review and a framework proposal based on the meta-synthesis method

Zehra Gülşah KOÇ*, Gökçe TUNA

Department of Architecture, Yıldız Technical University, Istanbul, Türkiye

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ABSTRACT

The increased usage of resources and waste generation is putting pressure on the natural environment and producing worldwide environmental problems. Different building and manufacturing methods are necessary when the validity of linear production and the discard concept fades. Overconsumption of resources such as energy and raw materials, as well as environmental issues caused by building products throughout their life cycles, are raising environmental awareness in the construction industry and presenting new options such as focusing on biological and natural processes.In this context, there are several design techniques, such as biodesign, in which organisms (algae, bacteria, fungus) are integrated into the design and perform a purpose in the building (energy production, indoor air cleansing, etc.). This situation is generating a new class of materials. Biomaterials are being developed as part of sustainable material and design research, with the objective of implementing biodesign principles. The goal of this study is to develop a framework for designing and manufacturing biomaterial-based building products. In this case, comprehensive literature review and meta-synthesis techniques were used. A thorough literature study provided definitions, terminology, theoretical and practical knowledge on biodesign, and meta-synthesis developed framework stages for biomaterial manufacturing. The framework covers the pre-production, production, and post-production processes, as well as the steps that need to take at each process. Thus, it is believed that the framework, which will be established with a correct description and categorization, will help architects who wish to study in this field and contribute to the acceptance and broad use of biomaterial-based building products.

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***Corresponding author**
*E-mail adres: koc_gulsah@hotmail.com

INTRODUCTION

Uncontrolled expansion in resource consumption and waste creation stresses the economy and the environment, causing global environmental problems. Currently, the construction industry's requirement for raw materials has a negative impact on the environment, accounting for around 38% greenhouse gas emissions, making it one of the causes of environmental problems globally (UNEP, 2020). Given this, the construction industry consumes 40-50% of all primary raw materials (Blok et al., 2019) and contributes 40% of worldwide energy consumption yearly for building life cycle processes such as manufacturing of building products, use, and destruction (Yadav & Agarwal, 2021). The world's population is predicted to reach over 9 billion people by 2050, with 70% of them expected to reside in cities. It is anticipated that this increase would place previously unheard-of pressure on the natural resources and urban infrastructure already in place (Flynn, 2016). However, about 60% of the world's carbon dioxide emissions will come from the manufacture of materials, which is expected to reach 180 billion tons in 2050. Consequently, while lowering the carbon footprint is one of the building industry's primary goals, new approaches are also required to address these issues. Reducing the usage of materials that rely on fossil fuels may be possible by converting waste and by-products into inexpensive biodegradable materials using a low-energy, carbon-sequestering biofabrication process (Lipińska et al., 2022).

In the literature, the sustainable aspect of building products produced with biomaterials is emphasized. In this context, *Fungi-based products* are biodegradable and require minimal energy for production. Local agricultural wastes can be utilized in production (Gavriilidis et al., 2024; Barta et al., 2024; Lekka et al., 2021). *Algae-based products*, wastewater, etc. can be used to grow algae in the production of building products. Algae-based building products appear to increase carbon dioxide absorption, thermal efficiency and energy efficiency (Roudbari, 2025). *Bacteria-based products*, the use of bacterial cellulose, which is biodegradable and renewable, can significantly reduce environmental issues associated with the construction industry (Massoud et al., 2024). Bioconcrete, bacteria repair by converting soluble organic nutrients into insoluble inorganic calcite crystals that heal cracks (Bashir et al., 2016). This provides an environmentally friendly alternative to concrete, reducing maintenance/repair costs and extending the lifespan of concrete. The potential of biomaterials lies in their renewability, carbon sequestration capacity and ability to improve indoor air quality, all of which contribute to the production of a healthy and sustainable built environment (Chen et al., 2024).

Despite all these advantages of biomaterial-based products, the number of applications is limited. As a reason for this, Waszkowiak (2019) states that information on techniques that actively integrate organisms into architecture is scattered, which limits and complicates examples in this field; Zolotovsky (2017) and Imani et al., (2018) state that there is a gap between the use of organisms on an architectural scale and the methods and processes for performing such studies; and Ozkan et al., (2021) state that organisms are capable of sensing and responding to environmental stimuli, so there is an urgent need to develop new production methods and a framework for designing with organisms.

The study aims to define and classify innovative bio-based materials and to create framework on the design and production of biomaterial-based building products for the use of biomaterials in architecture. It is assumed that an accurate definition, classification and a framework to be created in this field will be effective in the adoption and widespread use of innovative biomaterial-based building products and will be a source of research on the potential of biomaterials. In this context, a systematic literature review and meta-synthesis method were utilized. The selected studies were synthesized within the scope of meta-synthesis and the common pattern in the studies was extracted and the steps to be included in the framework were determined. In line with the evaluation of the results of the analysis, this study defines biomaterials, classifies them in terms of conventional and innovative concepts, and proposes framework to produce biomaterial-based building products for architectural applications of biomaterials.

BIOMATERIALS IN ARCHITECTURE

Biodesign defines new behaviors and properties by combining organisms with artificial systems (Hayos et al., 2022). By incorporating organisms into the architecture, it is aimed at meeting the needs of energy production, cleaning the indoor air, etc. in the building. Therefore, design research is shifting from working with inanimate materials (plastic, glass, etc.) to working with organisms such as fungi, bacteria, etc. (Collet, 2020). In this context, biomaterials are being developed within the scope of sustainable materials for biodesign applications.

According to the literature, most of the biomaterials research focuses on medical applications. Biomaterials are man-made materials that interact with biological system components in a controlled manner (Biyomedtek, n.d.; Güven, 2014), allowing a non-living substance to replace injured or lost live tissue or organs by exhibiting compatibility with a living tissue or organ (Baydemir, 2022).

Biomaterials used in architecture differ from those used in medical applications. Biomaterials are materials taken from or created by living entities such as plants, animals, bacteria, and fungus. These materials are also known as biologically generated materials (Penn State University, n.d.). Biomaterials used in architecture are categorized as bio-based materials and are thus referred to as bioproducts. Bioproducts include all products obtained from biological sources, such as feed, biofuel, and bio-based materials (Food and Agriculture Organization of the United Nations, 2019). Bio-based materials, including biomaterials, are defined as substances or materials derived from living things. This approach may apply to both natural materials like wood and bamboo, as well as contemporary products (Heil et al., 2023). In this sense, biobased materials are divided into two categories: conventional and innovative (Figure 1).

Conventional bio-based materials are biodegradable and recyclable materials made from animals and plants (e.g., flax, hemp) (Yadav & Agarwal, 2021; Materialdistrict, 2014). These materials can be utilized in construction as raw materials for building elements, but they do not survive inside the structure. *Innovative bio-based materials* are a new type of material that includes organisms like algae, bacteria, and fungi.

- *Algae* are photosynthetic, freely moving aquatic microorganisms that can form colonies and filaments. They are classified into two groups: macroalgae and microalgae (Aktar & Cebe, 2010). Microalgae are the form of algae commonly employed in architectural applications. Environmental elements such as light intensity, temperature, nutrients, pH, water content, CO2 consumption, and O2 availability can all have an impact on algae.
- *Bacteria* are prokaryotic organisms that are almost everywhere (TÜBİTAK, 2023). Temperature, nutrients, pH, and oxygen are environmental parameters to consider for typical species utilized in the creation of bacterial-based building materials.
- *Fungi* are single-celled or multicellular organisms that generate spores and consume organic materials (Jones, 2019). Mycelium is the fungus's vegetative part under the soil, consisting of thin filaments (hyphae) (Heil et al., 2024). In general, light intensity, temperature, nutrients, pH, humidity, and water content all have an impact on mycelium growth.

Innovative bio-based materials are those generated from organisms or that contain manufactured components that enable a structure to interact with its surroundings and adapt to changing situations. Biodesign applications include innovative bio-based materials. Products made from these materials are also referred to as biohybrids or living building products in different studies (Heil et al., 2023), which are derived from organisms, use little energy and produce little waste, are biologically produced and contain at least one biodegradable component (Zolotovsky, 2017; Ghazvinian, 2021), have a structural or non-structural function (BRE Group, 2020), and are developed by integrating organisms into an inanimate building element or building material to fulfill a function (Ataç, 2019). Since these products are created by combining living and man-made components, the new product possesses the characteristics of both (Smith, 2021) and can benefit from many biological system properties such as self-sustainability, self-repair, self-replication, and biosignal responsiveness (Gilbert & Ellis, 2019).

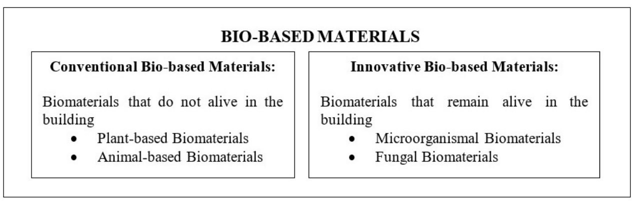


Figure 1. Classification of biomaterials.

This study refers to algae, bacteria, and fungi-based products as *innovative biomaterial-based building products*. Innovative biomaterial-based building products may be created at several levels, including material, piece, and component in the structure. According to their operating mechanisms, these products are classified as *bio-inert, bio-responsive, or bio-active* (Zolotovsky, 2017; Ghazvinian, 2021);

- *Bio-inert products* are those in which organisms are utilized in manufacturing but then killed, resulting in a passive end product. Because of their passive properties, these products can be grouped under conventional bio-based materials; however, because algae, bacteria, and fungal biomaterials represent a new class of materials, bio-inert products are classified as innovative bio-based materials, and an assessment was conducted accordingly. One example of this group is the Hy-Fi pavilion.
- *Bio-responsive* products change their qualities or form in response to environmental inputs. The product responds to environmental signals such as pH, pollutants, pressure, temperature, light etc. Bioconcrete is one example of this category.
- *Bio-active products* respond to biological signals and either interact with or are triggered by them. Such products have the capacity to impact and modify their surroundings through chemical, biological, and mechanical processes. BIQ House is one example of this group.

META-SYNTHESIS METHOD

Among the terms that comprise the notion of meta-synthesis, meta refers to going beyond the research presented, whilst synthesis refers to combining more than one study without compromising the originality of the studies. Meta-synthesis is said to have originated from the requirement to analyze and synthesize qualitative research in a certain subject together (Polat & Ay, 2016; Tekindal & Tonbalak, 2021), and it was initially proposed by Noblit and Hare in 1988. Meta-synthesis does not imply a comprehensive description of the findings from the research or the collection (Nye et al., 2016; Ozcakir Sumen, 2019). Rather, it is a methodological technique to create new knowledge that is based on interpretative analysis of existing qualitative research data. The objective is to use main study findings as data in a third-order interpretation (Aspfors & Fransson, 2015; Nye et al., 2016). The third level aims to give fresh viewpoints by evaluating data from various investigations. Meta-synthesis is used to establish new ideas, conceptual models, study gaps, extend current knowledge, and provide proof for existing information (Chrastina, 2018). Rather than using statistical methods, researchers in meta-synthesis utilize descriptive narratives to describe and interpret study findings. In such investigations, qualitative findings from research (Toker, 2022) or mixed method studies are reviewed and interpreted. Meta-synthesis is a six-step process.

Step 1: *Identifying research questions*

The research questions are identified first in the study. A carefully chosen research question influences both the study's direction and the quantity of papers included in the synthesis.

Step 2: *Literature review by identifying keywords*

The literature review begins by finding keywords. Databases are searched to find relevant studies. The number of studies included in the synthesis is determined by the researchers' decision-making, the study setting, and the availability of resources (Tekindal & Tonbalak, 2021). In the following stage, a systematic literature review is carried out to identify relevant research. A systematic review requires a well-structured and comprehensive review process. PRISMA standards are often employed in systematic literature reviews.

Step 3: *Identifying the studies to be selected by determining the inclusion/exclusion criteria*

In the systematic review process, inclusion criteria must first be determined. Inclusion criteria are necessary to determine which studies will be included in the research (Toker, 2022). A preliminary decision is made by checking the abstracts of the studies to determine those that meet the inclusion criteria from the studies identified in line with a specific strategy. If the abstract fulfills the inclusion criteria (Toker, 2022), the primary analysis proceeds, with the goal of identifying potential papers for synthesis. Primary analysis entails carefully reading the selected studies. The purpose of this step is to assess whether the studies are appropriate for the scope of the study. Although some suggest the synthesis should only include papers published in academic/refereed journals, others claim that not academic/refereed studies can also provide meaningful results (Noah, 2013). To ensure the currency of scientific discoveries, the publication period might be limited to publications in the last five years for primary research and the last ten years for secondary research (Tekindal & Tonbalak, 2021).

Step 4: *Analyzing and translating the selected studies*

It is the stage at which common themes and sub-concepts within these themes are developed by examining and analyzing the selected studies, as well as revealing and visualizing similarities and differences. The primary goal of this stage is to categorize, arrange, group, and analyze the findings. The topics and concepts in the first study are first summarized throughout the process of translating them into each other (Güneş & Erdem, 2022). Themes should embody the core concept, issue, or solution, or demonstrate a key point. This method is repeated for all papers included in the research, yielding a list of themes (Noah, 2017). The second study is then shown. The second study's themes and concepts are presented, and comments are provided on what is similar to the first study, what may be added to the first study, and where the findings vary. This procedure continues until all of the studies in the synthesis have been examined (Güneş & Erdem, 2022).

Step 5: *Synthesizing study findings*

The findings are synthesized by bringing together translated themes, detecting repeating patterns, and making meaning of them. At this point, the studies are considered as a whole in order to develop a framework. Researchers can use narrative and/or schematic presentation to demonstrate how the investigations are connected (Güneş & Erdem, 2022).

Step 6: *Presenting the process and findings*

This is the final stage of meta-synthesis. It includes a comprehensive report on the process and conclusions. Reporting process (Güneş & Erdem, 2022);

- Conclusions
- Strengths and limitations
- Conclusion and suggestions

Visual tools like graphs, tables, and figures can be utilized to display conclusions with numerical data (Tekindal & Tonbalak, 2021).

REVIEW OF STUDIES ON THE DESIGN AND PRODUCTION OF BIOMATERIAL-BASED BUILDING PRODUCTS USING META-SYNTHESIS METHODS

The steps of selecting studies and reporting the synthesized studies follows the meta-synthesis processes outlined in the third part.

Step 1: *Identify research questions*

- Which steps should a guide for architecture include when designing and producing innovative biomaterial-based building products?

Step 2: *Conduct a literature review by identifying keywords*

Keywords for the study included biomaterials, algae, bacteria, mycelium, architecture, building, construction, and pavilion, which were combined in various ways and searched in databases such as WOS (Web of Science) and Google Scholar.

Step 3: *Selecting research based on inclusion/exclusion criteria.*

Inclusion criteria:
- Studies of architectural scale.
- Projects can be permanent or temporary.
- Biomaterials can be living or non-living.
- Building products can be at the component or element scale
- Studies with at least one species of organism.
- Types of work: bio-inert, bio-responsive, or bio-active.
- Qualitative or mixed methods studies.
- Primary data studies.

Exclusion criteria:
- Projects in the design phase (not built)
- Studies manufacturing for only a single product
- Quantitative research

The review was done in July 2024. To ensure the timeliness of scientific discoveries in the meta-synthesis, and since the first full-scale structure (BIQ House) was erected in 2013, it was deemed suitable to start the time period from 2013. The search was restricted to the years 2013-2024, and 161 results were found using determined keywords. After excluding non-architecture-related fields such as medicine, 25 papers connected to architecture that matched the inclusion criteria were found. Following that, the primary analysis began, and the studies were thoroughly reviewed. The goal of this stage is to establish if the selected studies are appropriate for the study topic. In this case, it was found that 9 of the 25 studies did not fall within the scope of the study. The full text of the remaining 16 studies were examined, and four studies were rejected for reasons such as representing an unbuilt project, using a quantitative research approach, or scale of the biomaterial-based building product. Thus, the systematic literature review determined that 12 studies should be included in the synthesis. To make the included studies simpler to understand, each one was assigned a code (Figure 2).

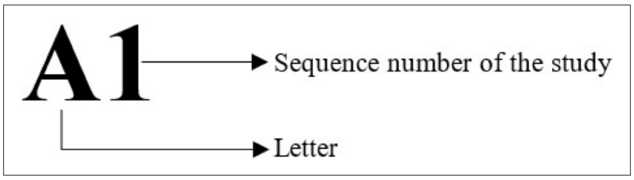


Figure 2. Code representation of included studies.

It is suggested that the research included in the synthesis be academic/refereed. However, at the building scale, relatively few studies have been conducted using biomaterials, either permanently or temporarily. Most of the studies are on fungi biomaterials. However, because tracking only studies using fungal biomaterials would limit the intended framework, not only the studies are included in the synthesis are based on research papers released by the researchers but also the studies that were not academic/refereed publications but were available on the official websites of product manufacturers or those involved in the technique's development were also included in the synthesis. Thus, the studies included in the synthesis concentrated on algal and fungal biomaterials. Only one study was discovered in which bacteria were employed as a structural component, however due to its quantitative method, it was excluded from the synthesis. The literature shows that experiments using bacteria are focused on healing cracks on the concrete surface. Table 1 shows the selected studies based on the inclusion/exclusion criteria.

Step 4: *Transforming studies into one another*

The NVIVO 14 program was used to analyze and translate the studies. The process starts with uploading the studies to the NVIVO system (Figure 3).

The studies uploaded to the system are carefully analyzed, and the concepts and themes in the studies are identified. According to Noah (2017), themes should embody the core concept, issue or solution, or demonstrate a major point. In NVIVO, the process of developing themes and concepts is known as coding. To begin analyzing the studies uploaded to the system, click the Codes section from the Coding section on the left side of the NVIVO screen and create a new code (Figure 4).

After identifying the themes and concepts in the first study, the themes and concepts in the second study were determined, and the similarities and differences between the two studies were revealed to determine what could be added to the first study and where it differed from the first study. This process was repeated until all studies included in the synthesis had been examined. From the synthesized studies, 7 themes were identified for design and production with biomaterials: *environmental sustainability, economic sustainability, social sustainability, biomaterials, design, production and risks*. In this context, the themes and concepts belonging to the themes and their relationship with the synthesized studies are shown in Table 2.

Table 1. Studies selected for meta-synthesis

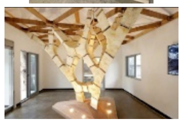
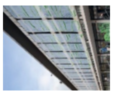
Study Information				Properties of Bio-product							References
				Final Product				Behavior			
Code	Name	Image	Year and Place	Material	Piece	Components	Elements	Bio-inert	Bio-respond	Bio-active	
A1	Monolito Micelio		2018 Georgia Tech School of Architecture				•		•		(Olive, 2019)
A2	Mycelium Mockup Project		2015 AFJD Studio			•				•	(Dahmen, 2016)
A3	Living Room		2023 Farrell Centre, Newcastleupon-Tyne.				•		•		(Scott et al., 2024)
A4	BioKnit Prototype		2022 OME, Newcatle University				•		•		(Agraviador et al., 2022)
A5	Hy-FI Pavilion		2014 Moma PS1		•			•			(Brown, 2017)
A6	Growing Pavilion		2019 Ketelhuisplein				•	•			(The Growing Pavilion, n.d.)
A7	L'orso Fungino		2022 Kansas State University			•			•		(Dessi-Olive, 2022)
A8	MycoTree		2017 Bienal		•			•			(Heisel, 2017)
A9	Air Bubble		2021 Poland			•				•	(ArchDaily, 2024)

Table 1. Studies selected for meta-synthesis

Study Information				Properties of Bio-product							References
				Final Product				Behavior			
Code	Name	Image	Year and Place	Material	Piece	Components	Elements	Bio-inert	Bio-respond	Bio-active	
A10	BIQ House		2013 Hamburg			•				•	(Tallou et al., 2022)
A11	Photo.Synth.Etica		2018 Dublin			•				•	(Pasquero, n.d.)
A12	Urban Algae Canopy		2015 Milano			•				•	(Violano, 2019)

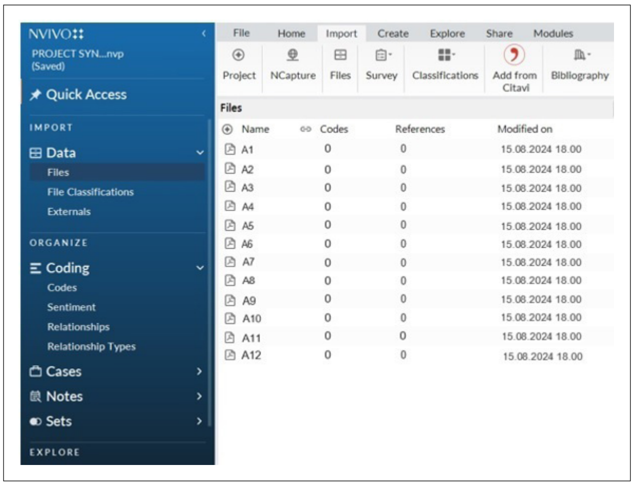


Figure 3. Files uploaded to the NVIVO program.

Step 5: *Synthesizing the findings of the studies*

Analyzing the studies revealed innovative biomaterial-based building products have the potential to achieve the building's sustainability goals. In this context, the environmental sustainability of biomaterials comes to the forefront in the studies. While biomaterials manufacturing can help with resource efficiency and waste reduction, it also allows buildings to produce energy and clean the air. Furthermore, using waste as a resource for producing biomaterial-based building products can help to promote the circular economy. Production using organisms allows for on-site production, which can cut logistics expenses.

Biomaterials are not simply materials, but also collaborators, as they are the living components of constructions. With organisms as part of the architectural product, the idea of vitality becomes a design consideration. In this context, the living/non-living condition of organisms in a building product influences how the end product interacts with its surroundings. In a state of sustained vitality, the product evolves into a living system that interacts with its surroundings. The living/non-living condition of organisms influences design and manufacturing processes. Conditions that ensure the organism's vitality must be provided in order for it to persist in the end product. In this context, the product's form can be beneficial in both sustaining the organism's life circumstances and assuring its structural integrity, as well as the aesthetics of the final product. Form in conventional building products is determined by manufacture, but form in biomaterials is determined by organismal growth and development. As a result, form is no longer something that is created, but rather something that the product finds its own form. This indicates that designing with organisms involves not just generating form but also regulating life processes and forecasting organismal behavior. Another thing to consider is that a behavior is being created (healing, producing energy etc.). As a result, the behavior of the product to be created should

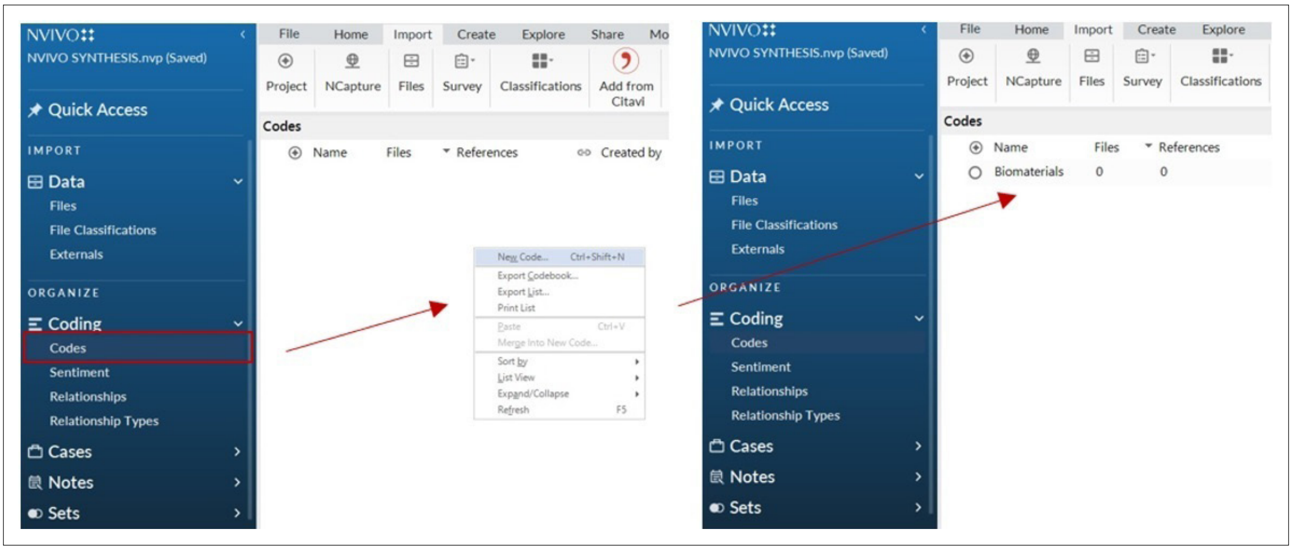


Figure 4. Creating a code in NVIVO.

Table 2. Themes and concepts created

Themes	Concepts	Studies	(f)
Environmental Sustainability	Acoustic comfort	A10, A3, A6, A9	4
	Bio-degradable	A1, A2	2
	CO_2 reduction	A8, A11, A12	3
	Energy efficiency and energy production	A1, A2, A5, A10, A12	5
	Material efficiency	A1, A2, A3	3
	Thermal comfort	A10, A12, A6	3
	Visual comfort	A10, A12	2
Economic Sustainability	Circular economy	A1, A11, A5, A8	4
Social Sustainability	Public participation	A10, A12, A2, A3, A6, A7, A8, A9	8
Biomaterials	Algae	A9, A10, A11, A12	4
	Bacteria	A4	1
	Mycelium	A1, A2, A3, A4, A5, A8	6
	Living/not-living	A11, A2, A9, A1, A3, A4, A7	7
Design	Geometry	A1, A3, A4, A7, A8	5
	Parametric design / digital technology	A1, A3, A4, A7, A8, A11, A12	7
Manufacture	Scale		
	- Monolithic	- A1, A2, A3, A7	4
	- Discrete elements - blocks	- A1, A7	
	Digital manufacturing	A11, A3, A7, A8	4
Risks	Biological risks	A1, A3, A4, A7	4
	Material risks	A1, A3	2

be predicted from the start of the process, and decisions should be made appropriately. The usage of parametric tools in design can be useful for organizing the process and conducting appropriate analyses. In general, studies focus on the influence of form on product performance and which forms are the most efficient. The scale of production is one aspect to consider during the manufacturing process. The scale of production also influences the organism used, the manufacturing process, and the tools utilized in production. Therefore, material, design, and production are all intimately connected. Production with organisms introduces novel micro-macro-scale design techniques and can help to establish new architectural production models. Because the manufacturing of building products is dependent on the growth of organisms, this situation alters the idea of production. In other words, unlike conventional building products, the product is grown rather than manufactured. This kind of manufacturing process alters architecture, taking it beyond design and into the realm of biological system production. Working with an organism involves a multitude of biological and material *risks*. The selected organisms must not be dangerous to people or other living things. Another concern is that products made with organisms may fail to achieve the desired performance parameters.

Step 6: *Reporting of the process and finding*

The synthesized studies highlight the environmental sustainability of innovative biomaterial-based building products (Figure 5). This supports the need to limit the negative environmental effect of building products.

Economic and social sustainability continue to be overlooked. One explanation for this might be that the selected studies have no direct bearing on the economic and social sustainability of innovative biomaterial-based building products. However, the synthesized studies can still provide insight into the economic and social sustainability of these products. The examined studies appear to focus on fungal biomaterials. One explanation for this might be that fungal biomaterials are simple to get and grow, requiring no expensive tools. The reason for the scarcity of research on bacterial biomaterials is because most of them are focused on manufacturing materials like bioconcrete, and it is outside the scope of the study. Another issue is that there has been few research on biomaterials used in facade applications, such as bacterial cellulose, and the available studies cannot be included in the meta-synthesis since they were conducted quantitatively.

The studies provided information on form and design tools. In general, studies focus on the impact of shape on product performance and which forms are the most efficient. In terms of manufacturing, the most crucial information collected is

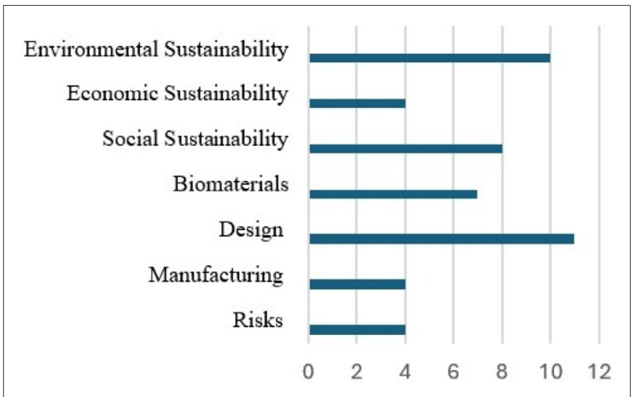


Figure 5. Themes obtained from meta-synthesis.

the product's scale. The scale of the product is crucial since it influences the design and manufacturing processes. In this context, it is clear that studies in literature concentrate on the production of discrete elements (bricks, panels, etc.). This might be because production is easier and more controllable. Although monolithic manufacturing reduces costs owing to on-site production and transportation, it brings several challenges in process management. The studies revealed broad information about the tools used in the design and production processes.

When organisms are used to produce building products, viability criteria are included in the process. As a result, laboratory tests are required to understand the factors influencing viability and the organism-environment relationship. Laboratory tests are also required to establish the qualities of the material conditions in which the organism will be transferred, as well as the end product's performance. Because biomaterial-based building products are manufactured by merging biological and man-made components, the end product possesses properties of both. As a result, during the pre-production phase, it is vital to establish which biological system characteristics, such as self-repair and self-sustainability etc., will be included into the end product and to make decisions appropriately. However, decisions should be made not just about the product, but also about its relationship with the ecosystem, the organism, the material context in which the organism will be transferred, design, and user needs. In general, the literature focuses on making specific items (bricks, panels, etc.) and assessing their performance. However, it does not specify what decisions must be made in the run-up to production. Similarly, there is little information available on the steps that must be taken during the post-production process. Pre-production process shapes the production and post-production processes. As a result, the pre-production process is critical for planning the entire process. There are only a few studies in the literature that have built a model for building products using algae, bacteria, and fungal biomaterials. One possible explanation is because biomaterials are not standardized, therefore a single model with definite decisions cannot be used in every study. Although dealing with biomaterials necessitates different production stages depending on the demands and organism, there are certain common steps that may be taken. In this context, developing a framework consisting of general stages might serve as a guide for architects interested to engage in this subject. The synthesized studies give significant information on organismal production (e.g., mycelium composite production), but little guidance on how the process should be organized and what decisions should be made at each stage with the exception of some ideas for identifying related steps (Figure 6).

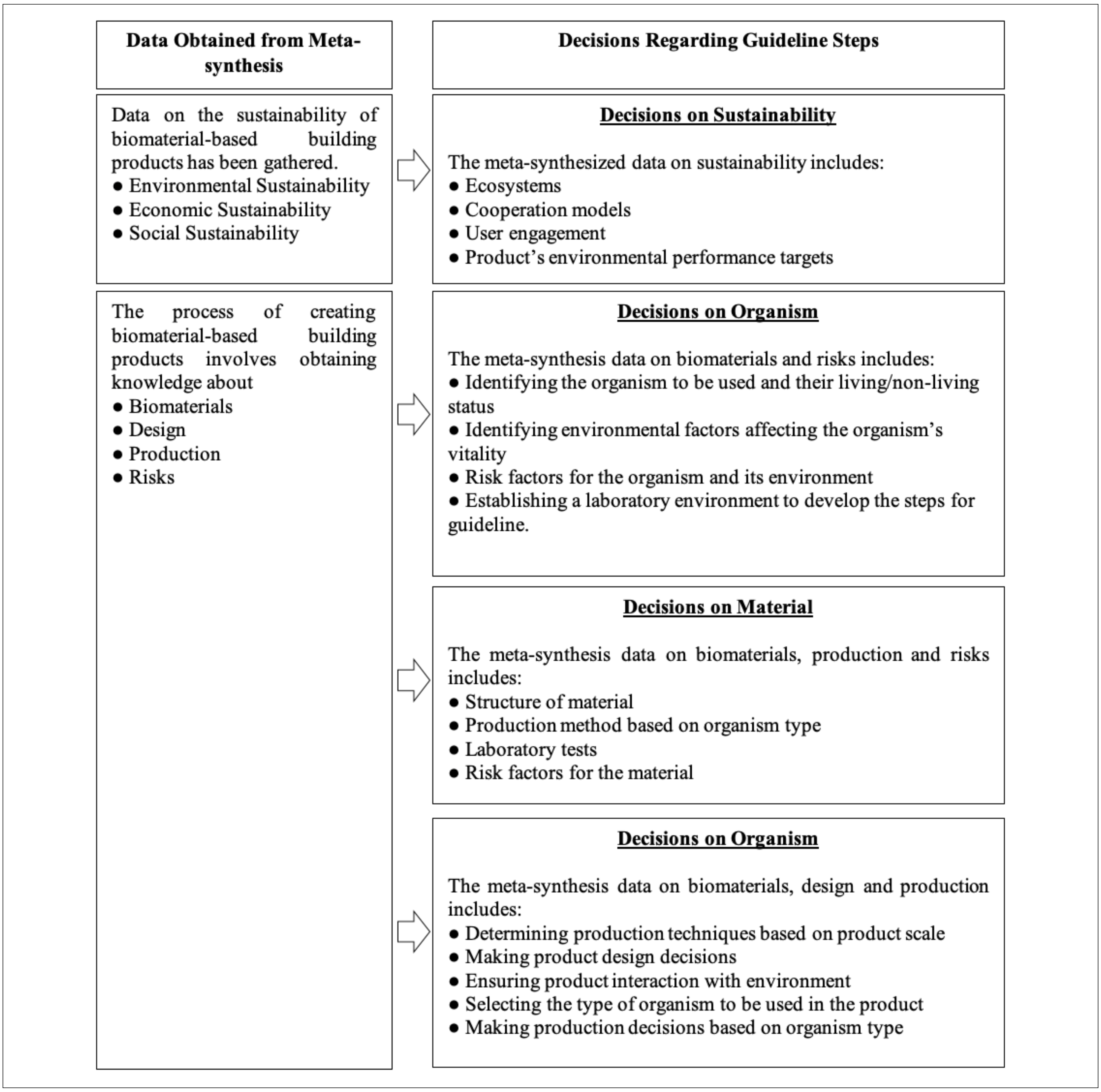


Figure 6. The themes derived from the meta-synthesis and the outline for the framework steps.

CONCLUSION AND RECOMMENDATIONS

The growth in resource use and waste output stresses the ecosystem and contributes to worldwide environmental problems. The construction industry is one of the industries where building products have an impact on the environment throughout their life cycle. It is expected that increased global material production in 2050 would result in higher carbon dioxide emissions. As a result, one of the construction industry's key goals is to reduce its carbon impact. Biofabrication technologies may be used to turn byproducts and waste into low-cost biodegradable materials, reducing the need for fossil fuel-based resources. In this context, there are numerous design strategies available, such as biodesign, which includes embedding organisms into architectural products to address user problems. Biodesign applications aim to include organisms into the design to provide services such as energy production, air cleaning etc. As a result biomaterials are being developed in biodesign. Biomaterials used in architecture are biobased materials that are generated or produced by living organisms.

There are two types of biobased materials: conventional and innovative. Biodesign applications include innovative bio-based materials. Innovative bio-based materials are a new type of material composed of algae, bacteria, and fungi. These materials enable the production of sustainable, living, and dynamic structures by allowing the building to interact with its surroundings and become a part of the ecosystem. The new class of materials necessitates new design and manufacturing procedures. A meta-synthesis study was conducted to investigate innovative biomaterial-based construction products, revealing their effects on sustainability, design, and production. While the cases analyzed demonstrate how organisms are incorporated into both sustainability and design and manufacturing processes in the production of architectural products, they also highlight the obstacles and risks encountered in this field.

From a design perspective, the utilization of innovative bio-based materials represents a fresh approach to architecture. However, further research and laboratory tests are required to ensure that these materials fulfill architectural flexibility, structural stability, and utility. Since the organism is required to perform a role in the finished product, it is critical to understand the parameters impacting the organism's vitality and how to preserve it. However, the focus should not be only on the organism's resilience. The aim here is not just to produce a product using organisms. Other aspects, such as ecosystem compatibility, building products' environmental performance, user needs etc. should be considered and included in the design process as well.

Although working on biomaterials needs different production processes depending on the requirements and organism used, there are certain common steps that may be followed. In this context, the steps to be taken in the pre-production, production, and post-production processes using biomaterials, as well as the relationships between these processes, have been addressed holistically by producing a framework consisting of general steps. Thus, the process is intended to be controllable, straightforward, and comprehensible. Each step in the framework was developed using data gathered from the meta-synthesis of the studies examined (Figure 7).

Pre-Production Process

Step 1: *Ecosystem decisions; in this step, the goal is not only* to create innovative biomaterial-based building products, but also to ensure that these products interact with the environment on a larger scale. In this context, the region's energy and water cycles should be examined to establish the function of the biomaterial-based product that will be produced within the system. In this stage, a large-scale and sustainable manufacturing model may be planned by developing collaboration models that use waste as a resource.

Step 2: *Product decisions; the process begins by examining* the previous step's outputs and considering the decisions taken. The selections made for the ecosystem can help choose the most appropriate organism type based on the ecosystem cycles and the type of waste created in the following stage. In this step, a precise definition of the product to be produced helps to choose the organism, design, and production methods. In addition, the product's scale, design decisions, and environmental performance standards that the end product will fulfill should also be determined. The environmental performance goals that the product has to meet will also help to determine the final product's behavior (producing energy, healing cracks, etc.). As a result, determining the product's behavior will be beneficial when making the initial decision on which organism to select.

Step 3: *Organism decisions; the process begins by examining* the previous step's outputs and considering the decisions taken. The integration of organisms in architectural products transforms the material from a passive to an active component of the architectural system. Determining the environmental factors that impact the organism is critical in terms of constructing the organism's habitat. Laboratory tests are necessary to establish which environmental conditions influence the organism and how.

Step 4: *Material decisions; the process begins by examining* the previous step's outputs and considering the decisions taken. At this step, the organism must be able to exist in the material's habitat to which it will be relocated. As a result, material testing must take place during this stage.

Production Process

Step 5: *Production with biomaterials;* the process begins by examining the pre-production process's outputs and then proceeds to suitable production. Although production methods vary depending on the selected organism, production should take into account the organism's biotic and abiotic components. The tools utilized may vary depending on the scale of production. If a problem emerges during this stage, the decisions taken by returning to the previous stage should be reviewed, and production should be repeated. At this point, performance tests should be performed to assess whether the finished product fulfills the performance goals.

Post-Production Process

Step 6: *Monitoring and inspection;* at this step, the product that was produced undergoes testing to determine if it corresponds to the specified performance criteria. A product that does not match the specified performance criteria or is produced wrongly must be reproduced.

Step 7: *Operation;* products that fulfill the desired requirements are tested on-site through installation/assembly.

Step 8: *Maintenance:* During this step, the product is maintained at periodically. Product maintenance can be done by the user or, if necessary, by the producer.

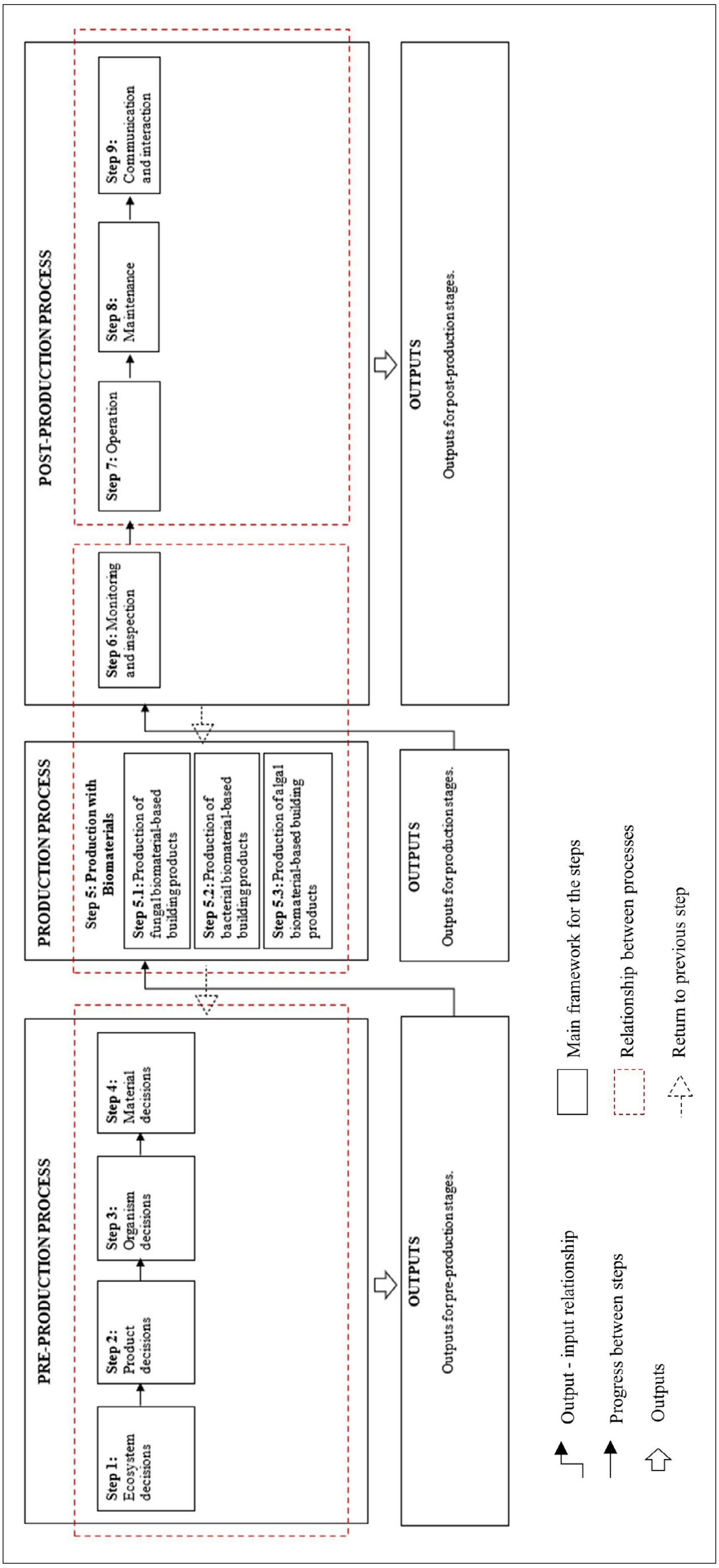


Figure 7. Proposed framework for biomaterial-based building product design.

Step 9: *Communication and interaction;* this is the stage at which the end product is introduced and engagement with the end user is ensured. Various ways, such as art, DIY and GIY kits, or direct technical knowledge on the product, can be used to provide this interaction.

If a problem arises during this step, the product should be maintained first, and if this does not fix the problem, it should be returned to the monitoring and inspection stage, and the process examined. If the problem continues, re-production should be carried out. The study divided the process into stages with the framework developed, and each step was detailed in depth. Since pre-production decisions will have an impact on production and post-production processes, it is recommended that the process be carried out with as much detail and clarity as possible, that every decision be made meticulously.

Products made using innovative bio-based materials are expected to contribute to environmental and economic sustainability by making better use of resources and materials, being biodegradable and waste-free, and reusing waste. However, because there has been a lack of research on the design and manufacture of innovative biomaterial-based building products, this study might serve as a basis for future studies and research.

For future research:

- Studies should be conducted to standardize the use of innovative bio-based materials in architecture,
- Experimental studies should be encouraged to explore their impact on various architectural forms and functions,
- Increasing the durability and manufacture efficiency of innovative biomaterial-based products.
- Cost assessment throughout the production stage

are recommended.

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