Prototype of a self-sufficient biofabrication protocol for remote territories

Prototipo de un protocolo de bio-fabricación autosuficiente para territorios remotos

Recieved: July 15, 2019. Accepted: September 24, 2019
DOI: https://doi.org/10.18389//dearq26.2020.12
Investigation paper

Abstract

The exploration of materiality is of fundamental importance for the processes of architecture and design. Due to the rapid development of digital manufacturing, prototyping processes today have made customized systems accessible to all audiences. However, not all parts of the planet have access to these technologies and standardized materials that are required by today's industrial machinery and standards. Therefore, creating bio-manufacturing practices, for which local self-sufficiency and the use of local materials, is essential to create circular models. This fact underlines the importance of experimental materials research that connects exploring territories of all kinds of environments with self-understanding and responsible use of technologies in sensitive territories. In turn, this allows the self-sufficient emerging manufacturers to develop in extreme territories.

This work highlights some important points in the bio & eco-manufacturing approach by investigating the use of materials in one of the most southern place on the planet, Puerto Willams, Chile. The planning procedure was developed as a first approach to the territory as was the development of the samples of biocomposites and potential materials to work with in this area. As a result of our experience, this paper discusses both the technological aspects of bio-manufacturing and the social and ecological considerations involved. It also integrates cooperation within an interdisciplinary group of networked laboratories interested in disseminating and contributing to the bio-fabrication design movement in Chile.

Keywords: Bio-fabrication, biomaterials, self-sufficiency, remote territories, open source

Resumen

La exploración de la materialidad es fundamental para los procesos de arquitectura y diseño. Debido al rápido desarrollo de la fabricación digital, los procesos de creación de prototipos actuales han hecho que los sistemas personalizados sean accesibles a todos los públicos. Sin embargo, no todas las partes del planeta tienen acceso a estas tecnologías y a materiales estandarizados que son requeridos por la maquinaria y los estándares industriales actuales. Por lo tanto, la creación de prácticas de bio-fabricación para la autosuficiencia local y el uso de materiales locales es esencial para crear modelos circulares. Este hecho subraya la importancia de la investigación en materiales experimentales que conecten la exploración de territorios de múltiples entornos con la auto-comprensión y el uso responsable de tecnologías en territorios sensibles. A su vez, esto permite que los fabricantes autosuficientes emergentes se desarrollen en territorios extremos.

Este trabajo destaca algunos puntos importantes en el enfoque de bio y eco-fabricación al investigar el uso de materiales en uno de los lugares más australes del planeta, Puerto Willams, Chile. El procedimiento de planificación se desarrolló como una primera aproximación al territorio, así como el desarrollo de las muestras de bio-compuestos y materiales potenciales para trabajar en esta área. Como resultado de nuestra experiencia, este artículo discute tanto los aspectos tecnológicos de la bio-fabricación como las consideraciones sociales y ecológicas involucradas. También integra la cooperación dentro de un grupo interdisciplinario de laboratorios en red interesados en difundir y contribuir al movimiento de diseño de bio-fabricación en Chile.

Palabras clave: Bio-fabricación, biomateriales, autosuficiencia, territorios remotos, código abierto

Acknowledgements: Thanks to Fab Lab Austral, Pontificia Universidad Católica de Chile, and the support of Computational Design Group MIT organized by Paloma Gonzales for their support in carrying out this exploratory work. Also, thanks to the Rhine-Waal University of Applied Sciences and the Commission of Equal Opportunities for Women for allowing the exchange of knowledge on this expedition. We extend our deep gratitude.

Aníbal Fuentes Palacios
Laboratorio de Biofabricación FADEU, Pontificia Universidad Católica de Chile
✉ agfuente@uc.cl
Carolina Pacheco Glen
Laboratorio de Biofabricación FADEU, Pontificia Universidad Católica de Chile
✉ cpacheco1@uc.cl
Adriana Cabrera Galindez
Matrix GmbH & Co. KG / Rhine-Waal University of Applied Sciences
✉ cabrera@matrix-gmbh.de
Alejandro Weiss Munchmeyer
Laboratorio de Biomateriales de Valdivia, Chile
✉ alejandroweissm@gmail.com
María José Besoain Narvaez
Laboratorio de Biomateriales de Valdivia. Chile
✉ info@labva.org

Introduction

The materials industry is the human activity that has the second greatest impact on climate change (IPCC UN 2013). In this context, the development of circular economies has aimed to integrate the material production with the ecosystem cycles. As part of the strategies that have been developed, producing materials from living organisms (biomaterials) has been positioned as a feasible alternative to face these problems (Ziegler et al. 2016). This strategy, based on the use of natural polymers highly available in the biosphere (Garmulewicz 2015), enables emerging manufacturing perspectives and practices.

Traditionally, the concept 'biofabrication' has been used in medicine and biotechnology referring to the production of complex biological products such as organs or tissues (Mironov et al. 2009). The reference to 'bio' implies the use of raw materials or process inspired by biology, while the term 'fabrication' means to make or build something from a raw or semi-finished material (Mironov et al. 2009). Nevertheless, in the last decade, artists, designers, and architects have adopted this term to refer to the use of biological organisms for the creation of new materials (Camere and Karana 2017);(Myers 2012). Additionally, in the present framework the term 'biofabrication' will be also used to refer to the cultural practices that surround these emergent technologies.

Developing these technologies becomes particularly relevant in isolated and remote territories where natural resources abound but technological resources are scarce due to the topographic and climatic conditions. In these territories researching biological resources from a biomaterials production perspective becomes necessary in order to establish local and self-sufficient production chains that provide tools for material sovereignty. In this regard, developing open source protocols for biofabrication is crucial to be able to democratize these technologies.

The present research focuses on developing a proposal for a small-scale self-sufficient biofabrication chain of production in remote territories. The case study in which the proposed protocol was applied took place in Puerto Williams, the southernmost town in the planet. This territory is strategic to being able to understand the sub-Antarctic region as it presents enormous restrictions in terms of transporting and in acquiring goods.

Methodological procedure for biofabrication in remote territories

General considerations

Biofabrication practices—understood as the use of biological resources as materials—have always been developed by humans, being wood and wool typical examples. Cultural practices (such as the development of tools, techniques, etc.) have been built around their use; thus, a technological domain has been consolidated that allows matter to be modified in order to be useful for humans. For this reason, it is necessary to declare that the present protocol has been developed from the perspective of foreign researchers temporarily inserted in a previously inhabited territory. Thus, in the present study anthropological tools have been incorporated into how the territory has been approached to understand the preexisting relation between natural resources and local culture.

Moreover, the present protocol focuses on the development of biomaterials composed by a structural filler and a binder agent, which we refer to as 'biocomposites'. Consequently, developing self-generating materials by growing conditions will not be addressed in this research.

Finally, to correctly approach biofabrication practice, five stages have been developed, but only four could be used in this particular research in Puerto Williams. The steps are:

a. Approach the territory: General planning of the visit, considering ecological, biological, geographical, technological, social, and anthropological variables. This includes carrying out previous research of the existing biomes and ecosystems, topography, species, possible anthropogenic resources, native communities and cultures, tools, practices, industries, and relevant actors in the territory, as well as anticipating all the equipment that may be required in the different parts of the fabrication process. In this step, the consequent stages are planned, including the work with the communities or the collection of samples. Once in the territory, it is necessary to corroborate in situ the previously researched information, and, if necessary, to adapt the methodologies, procedures, and goals.
b. Collection of samples: Definition of the biomes relevant to the fabrication process, planning and carrying out the expeditions and collecting raw materials (natural or anthropogenic).
c. Samples processing: Extraction of the relevant compounds or preparation of the ingredients from natural or anthropogenic resources collected.
d. Material experimentation: Development and experimentation of the different mixes of fillers and binders. Design and testing of materials.
e. Objects production: Prototyping of possible uses for a material by developing molding systems and determined fabrication procedures.

Approach to the territory

Puerto Williams is the capital of the Chilean Antarctic province. This town has a population of approximately 2,200 citizens. Because of its geographic location, it is an entry platform for studies developed in Antarctica, and its extensive territory contains a diversity of landscapes and biological resources (Arenas et al. 2005). The Magellan ecoregion hosts, within its shorelines, a diversity of macroalgae and mollusks (Ojeda et al. 2018). This allows an active productive system of artisanal shellfish fishing such as *Lithodes santolla*, *Paralomis granulosa*, *Loxechinus albus*, and algae collection such as *Gigartina skottsbergii*.

Figure 1. Recording the stages developed for the biofabrication protocol: a. Approach to the territory; b. Collection of samples; c. Samples processing; d. Material Experimentation. Source: Compiled by authors.

Figure 2. First visit to the Ukika community. Source: By authors.

Aware of this diversity, indigenous Yaghan communities are also relevant actors as they grant important values to mollusks, specifically *Mytilus edulis*, not only as a source of food, but they are also used as tools, ornaments, decorations, and for building shelters (Emperaire 2002). Another species of interest for Yaghan people is the *Macrocystis pyrifera* algae. This was crucial for survival in the austral region as it was used as a fishing line due to its strength, elasticity, and easy winding (Gusinde 1986; Ojeda et al. 2018). Nowadays, despite the lack of communication and the imposition of a new culture, a few members of the Yaghan community inhabit a small settlement called Ukika. This community has integrated with the Puerto Williams community at large and takes part in local activities. Unfortunately, over the years, their work with local materials has been lost, even though, there is also a desire to conserve their roots and also promote their traditions. That is the case with algae: when we asked about how they use it, the answer was that nobody has come to teach them how to work with it. Considering this and seeing the opportunities for design intervention, the possibility of using this abundant raw material not only means that new techniques will be implemented but also that ancient traditions will be reactivated in the territory. All this information provides us with the possibility of working mainly with marine organisms such as algae and mollusks for biocomposite fabrication. Nevertheless, materials and equipment are also required for the evaluation of other ecosystems such as the forest, mountain, and peat bog areas.

Biomaterials design is considered to be a DIY (Do it yourself) practice, mainly because it is developed under a self-sustained system by an individual or a group of people (Rognoli et al. 2015). It relies on accessible manufacturing tools and machinery in domestic or fabrication facilities were there is a convenient workspace and gear instruments to work with handcrafted or local materials. When working in remote territories, access to these types of instruments may be restricted by local and available resources. Therefore, the evaluation process involves determining specific tools and devices that need to be taken into the research area. These are classified under two main categories and are mostly based on their purpose regarding the bio-manufacturing process: (1) instruments needed to collect samples, and (2) tools for the biocomposite fabrication. Consequently, supplies must be considered for the field work and for the laboratory or workspace. In the first scenario, all types of tools that allow the extraction of biological matter must be considered: from cutting tools to tweezers. Different types of storage elements are also needed. Recording and documentation devices are essential to keep track of identified organisms and describe areas as well as climate conditions. Measuring instruments, processing tools, or molds for shaping materials are required for the material or biocomposite manufacturing. Furthermore, cooking utensils are also required such as heating or grinding instruments. Finally, some chemical compounds could be needed as ingredients for the biocomposite production.

Collection of samples

The characterization of relevant matter for biofabrication relies on how the territory is approached in two categories: the valuable natural resources that can be found in situ and the anthropic organic products of the area. As such, the field trips took a sea level to mountain approach while discussions with the community allowed flows of industrial, domestic and landfill wastes in the area to be recognized. Regarding the short length of the investigation and the limited utensils and workspace, no organisms were collected to grow materials. Instead, the biofabrication approach was directed towards finding natural polymers and local compostable fillers by including organic and inorganic ingredients to be incorporated in biomaterials.

Field researches were undertaken mainly to look for marine residual matter on the shoreline. Seashells and algae biomass were the two main elements used for biofabrication in the marine context. Seaweed contains polysaccharides in its structure, which can be used as a polymeric matrix for binding, while mollusc shells are primarily composed of the mineral calcium carbonate and can be recycled as a filler for creating biomaterials. The biological materials recognized in this context were mainly seashells from mussels (*Mytilus edulis* and *Choromytilus chorus*), clams (*Venus antiqua* and *Chlamys vitrea*), barnacles (*Austromegabalanus psittacus*), and also brown seaweeds such as giant kelp (*Macrocystis pyrifera*).

In other ecosystems relevant resources were found, such as abundant lignin in decomposing trunks in forests or *Sphagnum magellanicum* in peat bogs. However, the use of these resources was discarded for either technical or ecological reasons. Regarding the materials available for making things from anthropic waste, abundant wood ashes were found because firewood is the main source of heating in the area.

Samples processing

The understanding of biological materials and their compositions is a source of inspiration for designing with natural resources. In this way, is important to consider three critical factors such as their chemical composition, microstructure, and architecture (Wegst, Bai, Saiz, Tomsia, and Ritchie 2014). Many of the materials that exist in nature have mechanical properties that overcome those that are synthetic and man-made (VIncent 1982). This is relevant if we consider that their structural consolidation involves low energetic use and no environmental impact. Also,

MATERIALS	CATEGORY	CONDITION OF THE SAMPLE	AFTER PROCESSING
Carbon	Filler	Chunks	Sieved Ø 1Mm - Ø 3Mm
Mussel Seashell	Filler	Fragmented / Intact	Sieved Ø 1Mm - Ø 3Mm
Lignin	Binder	Dry - Powder	Sieved Ø 1Mm - Ø 3Mm
Lignin	Binder	Moist - Plaster Like	Dried
Wood Ashes	Filler	Dry - Powder	Sieved Ø 1Mm - Ø 3Mm
Wood Cellulose	Filler	Tree Fibers	Sieved Ø 1Mm - Ø 3Mm
Calafate Husk + Seed	Filler	Humid Paste	Dried
Sphagnum Moss	Filler	Humid	Dried
Green Algae	Binder	Humid	Dried - Agar Extracted
Brown Algae	Binder	Humid	Dried

Table 1. Characterization of samples collected in Puerto Williams. Source: Compiled by authors.

Figure 3. Sample E-04, Agar Bioplástic. (LABVA). Source: Elaborated by authors.

the chemical reactions in which they are consolidated are aqueous solutions, under atmospheric pressure and ambient temperature (Marc André Meyers et al. 2008) (Marc A Meyers et al. 2006); Wegst et al. 2014). In addition, most materials found in nature are composites, which means that there are two principal components in their structure: an organic part (polymeric and proteic composed by polysaccharides or polypeptides) and an inorganic part (ceramic minerals like calcium salts or silica) ((Marc A Meyers et al. 2006); Meyers 2008; (Sanchez, Arribart, and Guille 2005) (U. G K Wegst and Ashby 2004);(Ulrike G.K. Wegst et al. 2014). The correct balance and distribution between these components is what gives biomaterials their specific properties. Consequently, a key stage in the biocomposites production process is the extraction of the required components. Due to the diversity of the collected samples, it is necessary to foresee all the equipment necessary to: 1) avoid the decomposition of the organic matter and determine the procedures to stabilize the ingredients (cleaning, washing, cooling, cooking, dehydrating, grinding and / or sieving); and 2) adequately store each of the samples for the preservation and reserve the new ingredients to be used in biomaterial recipes. Access to water and a proper sink is essential to clean the samples. To process the samples, a kitchen-like laboratory was mounted in the FabLab Austral facilities; it includes a kitchen, pots, blender, grinders, and strainers.

In our case, anthropic waste, marine resources as well as biological materials collected from the forest were selected (Table 1). Because of timing, not all the materials were able to be fabricated into biomaterials samples.

Material experimentation

For the experimental approach, materials are classified using biomimicry principles regarding how biological composites perform. This involved the division of those that behave as binding agents because of gelifying properties under certain conditions while others are sorted for their structural performance and filler behavior. The material experimentation involved two case studies in simultaneous conditions. The first one is related to the viability of self-autonomy biofabrication in extreme conditions while the other explores the creation of a biocomposite based on collected samples.

For the first scenario, experiments have been developed in order to obtain agar or alginate from Puerto Williams algae using low-cost extraction methods. Both are polysaccharides used as binders in the fabrication of biofilms, bioplastics, and biocomposites. For these purposes, we collected samples of *Macrocystis pyrifera*, the most abundant seaweed on the Puerto Williams coastline. To validate the methodology and to compare the

CODE	SCIENTIFIC NAME	TYPE OF SEAWEED	COLLECTION SITE	WEIGHT (gr)	PROCESS	TIME (PRESSURE COOKER)	RESULT / OBSERVATIONS
E-01	Gracilaria chilensis	Red Algae	Chiloé	50 gr.	1.Washing Samples (clear water) 2.Pressure Cooker 3. Sieve	2 Hours (80 ml H_2O)	No separation between cellulose and water
E-02	Macrocystis pyrifera	Brown Algae	Puerto Williams	400 gr. (Wet)	1.Washing Samples (clear water) 2.Pressure Cooker 3. Sieve	2 Hours (25 ml H_2O)	Water and cellulose are separated Presents sediment stratification
E-03	Ulva Lactuca	Green Algae	Chiloé	20 gr	1.Washing Samples (clear water) 2.Pressure Cooker 3. Sieve	2 Hours (80 ml H_2O)	No separation between cellulose and water
E-04	Ulva rigida	Green Algae	Valdivia	120 gr.	1.Washing Samples (clear water) 2.Pressure Cooker 3. Sieve	3 Hours (80 ml H_2O)	Water and cellulose are separated. The liquid presents viscosity like agar

Table 2. Agar Extraction Comparison Chart. Source: Compiled by authors.

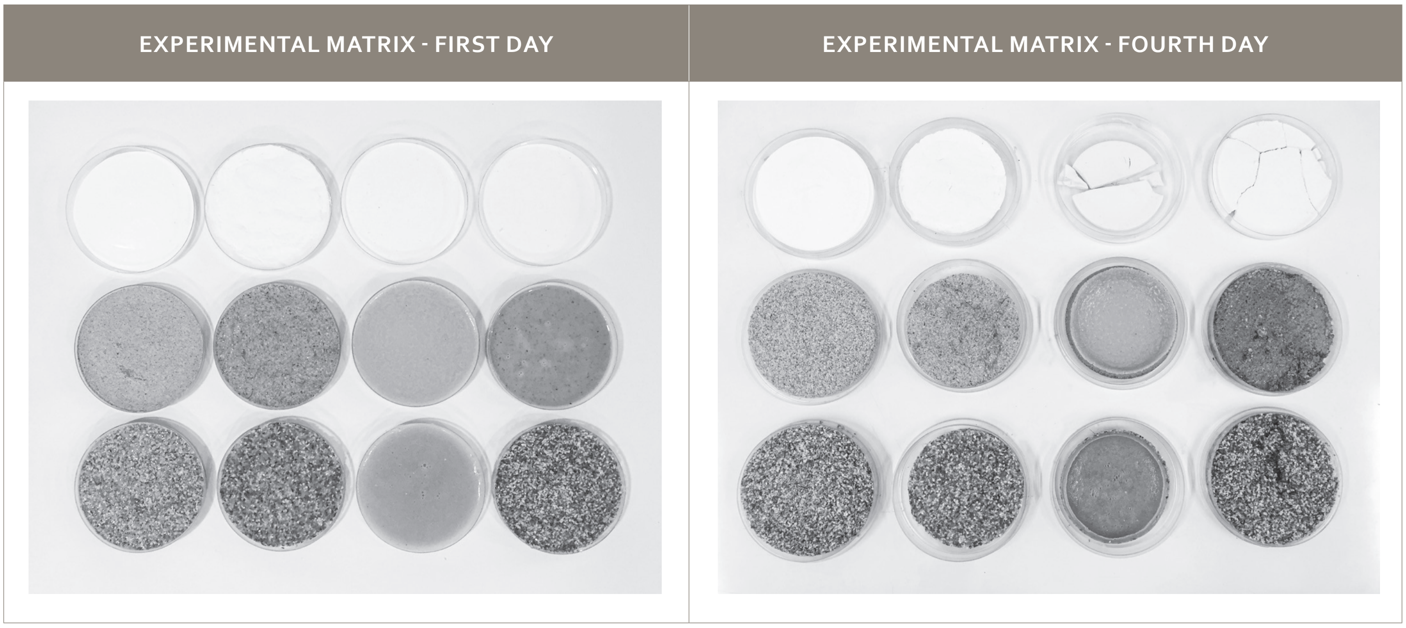

Figure 4. Comparison of experimental matrixes
(RECIPE CODES: A-MSAl2, B-MSAl1, C-BC-CEN-04, D-MSSU1, by Materiom and LABVA) Source: Elaborated by authors.

gelling properties, we also had to also incorporate other types of seaweed from south of Chile such as: *Gracilaria chilensis*, *Ulva Lactuca* and *Ulva rigida* (Table 2). The first step to be able to obtain agar from the cellular wall and cellulose fibers of algae was through temperature variations. The output of the experiments showed that procedure E-04 is useful for a correct agar domestic extraction.

The second material experimentation involved developing a biomaterial composed mainly of calcium carbonate from mussel shells that were collected on the Puerto Williams seaside. The purpose of the exercise is to characterize open source biocomposites recipes based on $CaCO_3$ and organic binders in a remote territory. The objective of the experiment was to determine whether open source recipes can be used for these types of environments and using local matter. The research also explores the relationship between compounds, binders, their granulometry, their volumetric reduction, and their behavior as biocomposite. The mussel shells were cleaned, dried, grounded, and sieved. For this experimental matrix the binding and plasticizers agents were obtained from an industrial chemical facility. These include agar, alginate, glycerol, sugar, and calcium propionate for antifungal purposes.

Results

The experience of Puerto Williams, as a case study for the protocol implementation, allowed for an approach to biofabrication that was supported by territorial cultural aspects. The execution of this protocol highlighted the opportunities that arise—for the biofabrication process and development—when we grasp the availability and abundance of resources concealed in natural structures. Correspondingly this also proves that an adequate equipment and infrastructure is determinant for the production of specific biomaterials.

Whilst analyzing the resources for the ingredient extraction, it became clear that despite the abundance of a given resource—whether it comes from a natural or anthropic source—sometimes, because of the timeframe, infrastructure or seasonality, we would not be able to use that resource for biocomposite elaboration.

The development of the last stage is still pending for this protocol, that is to say, the production of objects, wherein the stability and behavior of materials are put to the test.

Conclusion and Future Work

Implementing a self-sufficient protocol for biofabrication in Puerto Williams, revealed certain requirements and possibilities in terms of using these technologies in the near future. The first point relates to the access to knowledge and information resources for the natural environment to be correctly evaluated from a design biofabrication perspective. For creative disciplines, the understanding of biopolymers and bioelements seems to require more in depth knowledge (chemistry for example) than the necessary tools to understand traditional biomaterials such as vegetable or animal fibers.

In second place, there are still many fabrication processes that are not accessible for domestic or local procedures without depending on industrial production (eg. alginate). Regarding this type of proceedings, a minimum requirement of a kitchen-like infrastructure must be considered to develop this protocol in a remote location. Although the protocol is developed for isolated areas, it always involves a relative anthropization of the territory.

Finally, one of the most relevant points, that this investigation did not address, relates to the performance and usability of developed biomateriales in this context. This aspect is fundamental to be able to think about an eventual massification of these technologies. All of these questions have allowed us to recognize the opportunities to establish self-sufficient biofabrication systems. Indeed, they are still in need of more development and are a long way from becoming a feasible reality. For this reason, we understand the present proposal as a first approach to the systematization of open source protocols for the implementation of sustainable and self-sustaining production systems to be distributed throughout the territory. A future protocol methodology should include, in addition to the stages described in this research, more recipes to develop biomaterials, tools for transferring knowledge, design fabrication tools, and anthropological methodologies in order to aspire to its universal application in any location. For now, work in remote territories, allows methodological approaches to be developed on a local scale and with efficient use of resources for biofabrication practices.

References

1. Arenas, Federico, Gastón Aliaga, Carla Marchant, and Rafael Sanchez. 2005. *El Espacio Geográfico Magallanico: Antecedentes Acerca de Su Estructura y Funcionamiento*. http://www.ubiobio.cl/miweb/webfile/media/222/Espacio/2005/Articulo Arenas_et_al Tiempoyespacio.pdf.
2. Camere, Serena, and Elvin Karana. 2017. *Growing Materials for Product Design. EKSIG 2017: Alive. Active. Adaptive*, no. 1: 101–15. https://static1.squarespace.com/static/576953f3bebafb5359bfb528/t/5975e891cd39c316492d0e9c/1500899550482/EKSIG2017_Alive+Active+Adaptive_Proceedings_low+resolution2.pdf.
3. Emperaire, Joseph. 2002. *Los Nómades del Mar*. Santiago: LOM.
4. Garmulewicz, Alysia. 2015. *3D printing in the commons: knowledge and the nature of digital and physical resources*. University of Oxford, UK.
5. Gusinde, Martín. 1986. *Los indios de Tierra del Fuego*. (Vol 2). Buenos Aires: CAEA
6. IPCC. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.
7. Meyers, Marc A, Albert Y M Lin, Yasuaki Seki, Po-yu Chen, Bimal K Kad, and Sara Bodde. 2006. *Structural Biological Composites*, 35–41.
8. Meyers, Marc André, Po Yu Chen, Albert Yu Min Lin, and Yasuaki Seki. 2008. *Biological Materials: Structure and Mechanical Properties. Progress in Materials Science 53* (1): 1–206. https://doi.org/10.1016/j.pmatsci.2007.05.002.
9. Mironov, V., T. Trusk, V. Kasyanov, S. Little, R. Swaja, and R. Markwald. 2009. *Biofabrication: A 21st Century Manufacturing Paradigm. Biofabrication* 1 (2). https://doi.org/10.1088/1758-5082/1/2/022001.
10. Myers, William. 2012. BIO DESIGN, *Nature, Science, Creativity*. https://www.moma.org/momaorg/shared//pdfs/docs/publication_pdf/3167/BioDesign_PREVIEW.pdf?1349967238.
11. Ojeda, Jaime, Ricardo Rozzi, Sebastián Rosenfeld, Tamara Contadora, Francisca Massardo, Javiera Malebrán, Julia González-Calderón, and Andrés Mansilla. 2018. *Interacciones Bioculturales Del Pueblo Yagán Con Las Macroalgas y Moluscos: Una Aproximación Desde La Filosofía Ambiental de Campo. Magallania (Punta Arenas)* 46 (1): 155–81. https://doi.org/10.4067/S0718-22442018000100155.
12. Rognoli, Valentina, Massimo Bianchini, Stefano Maffei, and Elvin Karana. 2015. *DIY Materials. Materials & Design 86* (December): 692–702. https://doi.org/10.1016/j.matdes.2015.07.020.
13. Sanchez, Clément, Hervé Arribart, and Marie Madeleine Giraud Guille. 2005. *Biomimetism and Bioinspiration as Tools for the Design of Innovative Materials and Systems. Nature Materials* 4 (4): 277–88. https://doi.org/10.1038/nmat1339.
14. Vincent, Julian F.V. 1982. *Structural Biomaterials. Mathematical Biosciences.* Vol. 68. https://doi.org/10.1016/0025-5564(84)90080-4.
15. Wegst, U. G K, and M. F. Ashby. 2004. *The Mechanical Efficiency of Natural Materials. Philosophical Magazine* 84 (21): 2167–81. https://doi.org/10.1080/14786430410001680935.
16. Wegst, Ulrike G.K., Hao Bai, Eduardo Saiz, Antoni P. Tomsia, and Robert O. Ritchie. 2014. *Bioinspired Structural Materials. Nature Materials* 14 (1): 23–36. https://doi.org/10.1038/nmat4089.
17. Ziegler, A. R., S. G. Bajwa, G. A. Holt, G. McIntyre, and D. S. Bajwa. 2016. *Evaluation of Physico-Mechanical Properties of Mycelium Reinforced Green Biocomposites Made from Cellulosic Fibers. Applied Engineering in Agriculture* 32 (6): 931–38. https://doi.org/10.13031/aea.32.11830.