Jun 25th, 9:00 AM

New perspectives in fashion sustainability through the use of bacterial cellulose

Patrizia Bolzan
Politecnico di Milano, Department of Design, Italy

Daria Casciani
Politecnico di Milano, Department of Design, Italy

Arianna Regaglia
Politecnico di Milano, School of Design, Italy

Citation

Bolzan, P., Casciani, D., and Regaglia, A. (2022) New perspectives in fashion sustainability through the use of bacterial cellulose, in Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.), *DRS2022: Bilbao*, 25 June - 3 July, Bilbao, Spain. https://doi.org/10.21606/drs.2022.793

New perspectives in fashion sustainability through the use of bacterial cellulose

Patrizia Bolzan*, Daria Casciani, Arianni Regagli
Politecnico di Milano, Italy
*corresponding e-mail: patrizia.bolzan@polimi.it
doi.org/10.21606/drs.2022.793

Abstract: Fashion constitutes a sector with a high environmental impact, particularly because of shorter product life cycles and an exponential increase in the speed of production and in the number of goods created, sold, or unconsumed and thrashed. This paper aims to explore new perspectives of design and production processes toward environmental, social, and cultural sustainability through bio-fabrication. After an analysis of the context of reference and a review of existing literature, the research focuses on experimentation with bacterial cellulose (BC) to investigate the limits and potentials of controlled growth, waste processing and integration, accessories creation and recyclability, and the assembly/disassembly of clothing and/or accessories at the end of life.

Keywords: sustainability; biofabrication; bacterial cellulose, fashion design

1. Introduction

The significant repercussions of Covid-19 on every aspect of life (Saladino et al., 2020, Tisdell, 2020; Maital & Barzani, 2020), are also influencing the fashion system (McKinsey & Company, 2020), revealing more evidently the systemic problem of this sector linked not only to the mismanagement of sustainable aspects but also to the business and consumption models currently induced.

The fashion industry needs a radical change toward sustainability through a holistic approach that considers the ecological, economic, social, and cultural impacts (Ceschin & Gaziulusoy, 2016). Making the fashion industry more sustainable in such complexity, means implementing changes within the supply chain, especially acting on the design and production processes, through new technologies that will impact new textile materials, and the resulting garments and/or accessories.

A possible path in this direction concerns the use of new materials based on living organisms and biotechnology used for the biofabrication of textiles, especially as a replacement for animal skin (Provin et al., 2021). Through a structured synergy between the world of design and biofabrication, it is possible to determine a socio-environmental and cultural impact on the fashion sector (leather goods sector), through the reduction of consumption of raw materials and resources and thanks to the implementation of new production paradigms able to alter the traditional logic without depriving the output of the expressive-sensory, experiential, and cultural value, thus obtaining positive social impacts. As designers, we could influence the necessary positive change thanks to the inner designerly knowledge and material selection skills. If the designer becomes a creator of sustainable and functional materials for the fashion system, then real transformational change can take place. Bacterial cellulose (BC) may be a material with a strategic role in the development of new zero-waste design and production strategies, low-impact physical-sensorial characterization, and programmable dismantling.

This issue will be explored through a preliminary experimental investigation conducted at Politecnico di Milano and aimed at empirically defining possible application pathways for BC in pure form or integrated with other waste materials, as well as the drying, assembly, and disassembly processes surrounding it. Conclusions will reflect critically upon limits and opportunities of BC application in the fashion sector toward environmental, social, and cultural sustainability.

2. Literature review

2.1 Multiperspective sustainability impacts of the fashion industry in the leather goods sector

The socio-environmental impact of animal or synthetic leather is crucial: animal leather is the most demanded in products but, at the same time, the most polluting (Dixit et al., 2015) and ethically discussed due to unfavorable conditions for animal welfare (Jain et al., 2020). The raw material is subjected to processes that include cutting off unwanted parts, with consequent production of waste, and the treatment of leathers with alkaline solutions to remove unwanted substances and increase the permeability of the material. Finally, during tanning, post-tanning, and finishing processes, aimed at conferring physical and aesthetic properties to the material, a large amount of chemically altered water is re-injected as wastewater (Lofrano et al., 2013; Ozgunay et al., 2007; Ritterbusch et al., 2019). Although solid waste from these processes can be recycled into new raw materials such as soap, biodiesel, and fat liquor (Ahmad & Ansari, 2013; Colak et al., 2005; Ravindranath & Gopalakrishnan, 2010), the overall environmental and ethical impact of the traditional tanning industry to date is too high in relation to increasing standards of sustainability.

Alternatively, synthetic or vegan leathers derive from the transformation of polymers such as polyvinyl chloride (PVC) or polyurethane (PU) (PETA, 2021), so from non-renewable resources that in the production phase are harmful to humans and polluting the environment. In addition, during their use, they release non-biodegradable microplastics that are spread into the environment (CHEJ, 2004; Davis, 2020; EPA, 2014).

An issue that involves the entire fashion industry is related to overproduction whereby only 30% of the clothing produced is sold at the set price, another 30% is put on sale and the remaining 40% remains unsold (Danigelis, 2017), resulting in incineration or landfill and the production of about 10% of global carbon emissions (Dhir, 2021). This phenomenon is further amplified by the fast fashion business model which contributes to the shortening of their lifecycle and a consequent increase in textile waste, of which, only less than 1% is used for the production of new clothing (Ellen MacArthur Foundation, 2017).

Outsourcing of production to developing countries is used to relocate environmental impacts (Claudio, 2007) and to exploit underpaid labor in precarious working conditions. This strategy implies additional negative effects from obsolete and inefficient production facilities and infrastructure, with poor controls over resource management and chemical-contaminated effluent that result in greater impacts both on the environment and also to human health (Joseph & Nithya, 2009). In fact, increased risks of developing cancer or other forms of terminal illness have been found in tanning workers (Decouple, 2013; Garai, 2014; Munny et al., 2019). The same conditions have also been found in employees in the vegan leather industry, from fossil-based polymers due to the gasses released during their manufacture and the chemical additives used during the production process (CHEJ, 2004; Davis, 2020; EPA, 2014).

A further consequence of outsourcing is the weakening of local know-how: de-localization implies a loss of the heritage of craftsmanship, technical skills, knowledge of materials, and processes derived from a long succession of inventions and innovations that occurred over generations (Barrère, 2013) and difficult to recover once abandoned.

Finally, the value and cultural impact of the leather goods sector revolves around the quality, good craftsmanship, and aesthetic appeal of the material itself (De Klerk et al., 2019), these fundamental characteristics have also been widely reproduced in artificial leather manufacturing.

Nowadays, the growing awareness regarding sustainability issues has led to a shift in consumer behavior that shows a tendency to give increasingly more value to the ethical implications of what they buy (Manchiraju & Sadachar, 2014; Pagiaslis & Krontalis, 2014); socio-environmental sustainability results today as a new dimension necessary to attribute quality and desirability to the product (De Klerk et al., 2019; Kianpour et al., 2014).

We are therefore witnessing the possibility of a detachment from the traditional conception of leather, the user is increasingly willing to move away from a usual perception of the product in a perspective of sustainability that can combine "green aesthetic" and fashion appeal (Sauerwein et al., 2017). Among this, the use of bio-fabrication as an emerging method for the production of new types of "skins" may offer an answer to the current overproduction, as well as encourage alternative zero-waste strategies and avoid the problems generated by outsourcing.

2.2 Brief overview of alternative bio and circular leather-like materials

In this panorama, there is a growing need for biodegradable and cruelty-free leather substitute materials. Therefore, circular strategies, accompanied by new production technologies, are developed to increase the ecological and social sustainability of the leather goods industry (Hildebrandt et al., 2021; Milly, 2019; Qua, 2019; Quijano, 2017; Wood, 2019).

Obtaining ethically sustainable and environmentally friendly leather turns out to be a practicable trajectory starting from naturally based materials (Meyer et al., 2021). An example is MuSkin, a fully biodegradable mushroom skin whose production is carried out without the use of toxic substances making it safe for the health of the human being (producer and user) and compatible with the environment (Bustillos et al., 2020; Grado Zero Innovations, 2017). Produced from pineapple leaves combined with polylactic acid (PLA) bioplastic, Pinatex is a leather-like material that is not found to be 100% biodegradable despite adhering to circular economy principles (Ananas Anam Ltd, 2021; Meyer et al., 2021).

Another strategy comes from the use of waste materials from the food industry, such as Atlantic Leather, which recycles skins from fish raised following high standards of sustainability, making use of a by-product that would otherwise be discarded (Palomino & Defeo, 2018). Another interesting opportunity is the integration of living organisms (Ginsberg & Chieza, 2018) as functional components in the creation of new biocompatible and biodegradable materials through biofabrication processes.

2.3 Design of biofabricated organic materials and processes toward sustainability

In the contemporary scenario, the contamination between the world of design and that of biofabrication appears to be an emerging theme, on which many research groups are converging in a widespread way. The term "biofabrication" (Fritz et al., 1994) refers to a technology that aims at the construction of artifacts or semi-finished products using materials or processes derived from biology; it's a process that "deals with science, engineering and technology or production, based on using living matter as raw materials" (Mironov et al., 2009). In particular, it's possible to distinguish two different production strategies: engineering processes such as bioprinting (Yang et al., 2019), and natural processes of bioassembly of the material itself, which will be the topic of discussion in this paper due to the greater potential for reducing the environmental footprint and improve the socio-cultural impact of the products. Given this context, numerous applied studies are developing a design and production methodology capable of incorporating living organisms to create biomaterials through the design hybridization of nature and its growth processes (Myers, 2012; Camere & Karana, 2017). The resulting biomaterials or Growing Materials (GMs) contain biomass, are biodegradable, and are inherently made through biological processes and/or are biologically derived (Lee et al., 2020).

GMs are manufactured from living organisms such as fungi (Karana et al., 2018), algae (Wjffels et al., 2013), and bacteria (Lee, 2011). Their main properties are the possibility of assembly with nanometric precision, differentiated cultivation to influence the intrinsic properties of the material of which they are composed (Wu et al., 2004), the ability to self-assemble through hierarchical structures visible at the macroscopic level (Lehn, 2002; Seeman & Belcher, 2002; Whitesides & Grzybowski, 2002), and the programmability of growth in predetermined shapes with consequent limitation of material waste. Widely used in the medical field, microelectronics sector, and packaging, in this paper, they will be investigated in the fashion design sector, where Bacterial Cellulose (BC) GMs are widely applied in the fashion-tech area, showing themselves as sustainable alternatives to traditional solutions.

BC is created by activator bacteria placed in a sweetened tea base; the bacteria, nourishing on the glucose in the liquid, initiate a fermentation process that leads to the formation of Kombucha, a commercially popular beverage in markets around the world (da Silva et al., 2021). Fermentation also stimulates the growth of additional bacteria that distribute themselves in layers on the surface of the liquid, leading to the formation of macroscopic organic structures that are completely natural and biodegradable (Laavanya et al., 2021).

Compared to synthetic materials and those of animal origin, BC is less impactful from an ethical, social, and environmental point of view precisely because of its production process which has a lower environmental impact, using renewable resources and does not require chemical treatments, and is safer for human health. Moreover, being completely biodegradable, it has sustainable end-of-life. An interesting comparative LCA study of biofabricated and animal-derived leathers (Hildebrandt et al., 2021) showed that the environmental benefit (related to the reduction of CO2 emissions) of BC materials is only achieved if the consumption of the material itself is limited.

On an aesthetic-sensory level, BC appears as a very flexible skin with extremely versatile properties and characteristics that can be altered by making modifications to the starting substrate. In particular, it is possible to realize a wide range of colors, finishes, and textures characterized by strengths and thicknesses also very different from each other, consequently categorizing the qualities of BC in superficial (consistency and flexibility) (Nguyen et al. 2021) and optical (transparency and colors)(Ng & Wang, 2016).

Such aesthetic-sensory information can be interpreted and manipulated by designers to enhance the development of the material, favoring not only its use as a substitute for traditionally marketed leathers but to define its own unique features by dissociating from the concept of a surrogate for traditional fabrics (Rognoli et al., 2015)

It follows that it is important to highlight the role of designers in this context: designers have the task of approaching and devoting themselves to a manufacturing process that is closely related to craftsmanship; there is a change in the role of the designer who from being a passive recipient becomes an active producer of materials (Karana et al., 2018). Through the experimental experience of the material, the designer becomes capable of associating aesthetics and physical and perceptual characteristics of the material directly to the design of the final artifact (Cleries & Rognoli, 2021), through flexible and modular processes oriented towards sustainability.

Facing numerous but fragmented research and small-scale experiments aimed at investigating the properties of BC and the applications of controlled morphogenesis to define a specific form or dynamic function (Collet, 2013; Camere & Karana, 2018; Karana et al., 2020), the purpose of this paper is to investigate the potential of BC with regards to production processes and methodologies related to sustainability of the Fashion sector.

3. Methodology

BC GMs were experimented with the aim of promoting the design and implementation of solutions with a higher degree of sustainability, thanks to the critical observation of the results of empirical evidence obtained through stabilized and replicable production processes.

To date, the many research studies on BC focus either on its structural and biochemical characteristics (Gatenholm & Klemm, 2010; Iguchi et al., 2000), where the focus is on the composition and properties of the material itself, or on prototype applications for limited editions (Chan et al., 2018; Fairs, 2014; Ng, 2017), which do not have the peculiarity of exploring the replicability of both the production process and the final result. The presented experimental study is positioned in this interstitial space meanwhile conducted with the holistic approach typical of the designer, which considers both soft qualities and technical characteristics in each phase of ideative development.

The outcome is an iterative experimental path, to give rise to an expansion of knowledge structured and replicable to support designers and innovators in a conscious use of BC, also responding to consumers environmental, aesthetical and cultural sensitivity.

Reflecting on the actual reaction of consumers towards a material that is still little known, there is also a desire to work from the perspective of waste prevention, creating new semantic value to the design outputs, to reduce future environmental impact. With these premises, the contribution offered by this study with a material designer-oriented approach (Cleries & Rognoli, 2021) is outlining guidelines to promote a conscious and structured use of BC and its by-products in circular design solutions for the fashion field.

3.1 Research question and aim

Given the opportunities and limitations retrieved, this study wants to contribute to answering a series of questions related to the conscious introduction of BC material in fashion, where it is the designer who has the opportunity and responsibility to take concrete actions toward an improvement of processes toward environmental, and cultural sustainability.

Particularly, BC allows to efficiently tackle the zero-waste horizon and reduce the negative impacts of possible overproduction within the fashion world. This is due to the controlled growth properties of BC, inside preformed containers, which allow obtaining directly material layers already having complex shapes. In the traditionally adopted production system, there are already techniques for obtaining clothing in a zero-waste logic through an optimization of the entire life cycle and waste management, including avoiding, reducing, reusing, redesigning, regenerating, recycling, repairing, remaking, reselling, and redistributing (De Schoenmakere, & Gillabel, 2017). Traditional techniques, in fact, are limited almost exclusively to the use of repeated modules for the creation of paper patterns (Rissanen, 2013), or through draping to build the garment directly on the body. The aesthetics obtainable from these practices are, therefore, partially limited by design constraints, as well as unable to completely avoid the waste generated by cutting fabrics.

Therefore, these issues of the traditional production system, along with the already known characteristics of the GM being examined, offer additional opportunities for the use of BC in the zero-waste paradigm. Given the existing limitations of wide diffusion of zero-waste design and production strategies in the fashion field impacting the life-cycle of the various artifacts, the research aims to answer these two questions:

- What can be the new and different interpretations of the zero-waste theme through BC?
- How can BC be integrated into the current and future textile supply chain to make the textile and apparel life cycle more sustainable, particularly in the design, production, assembly, and disassembly stages?

The exploration of these issues has led to the structuring of a set of experiments with the aim of investigating the possibilities still not fully exploited by BC with regard to the issue of sustainability, starting from its procedural specificities: controlled growth, drying, integration with other materials, assembling/disassembling and recycling.

3.2 Empirical study procedure and set-up

The experimentation, carried out over an 8-month period within Polifactory - interdepartmental laboratory of Politecnico di Milano, was developed in two phases: (1) the learning of the growth process for the optimization in terms of time and resources used; (2) the study of possible manipulations in both the growth and post-production phases through the use and/or integration of other substances and/or semi-finished products. The results are mainly qualitative and reflections are subjective because in this phase of the experimentation it has been chosen to investigate on small swatches all the possible variants; the quantitative investigation of the measurable impacts in relation to the scalability of the method will be the subject of subsequent development of the research.

In the first phase, standard cultures were started, in different substrates and for different periods of time, with the aim of investigating the growth phases and final aesthetic-sensorial qualities of BC. The second phase saw the punctual modification of the traditional process of culture handling, to verify the potential of BC in terms of growth integrations and recycling processes. Each of the experiments was carried out by recording the growth conditions of each cultivation and the types of manipulations performed.

The synthesis of the adopted approach is presented in Figure 1, where it is noticeable how the experiments with BC, starting from the same cultures, led to the production of three types of basic materials (BC layering, integration in BC layer, BC tartare) and touched four process steps (growing, drying, recycling, assembling & disassembling). The different states of BC, downstream of the drying process, can generate very different application potentials, detailed in the following section.

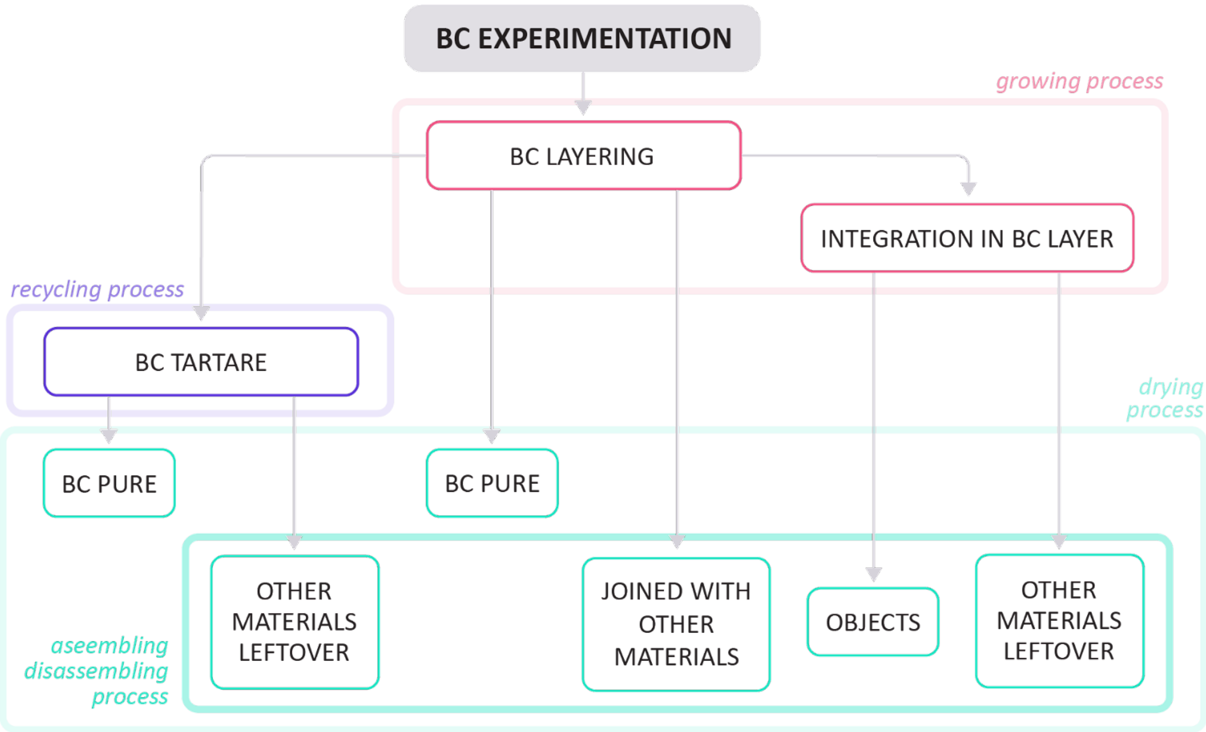

Figure 1. BC Experimentation map

4. Results

In this section we present the experiments carried out to discuss the potential and criticality of BC. In response to the questions previously introduced, it is clear that the issue of controlled growth in preformed containers is of primary importance as the GMs offer the possibility to overcome the traditional logic of production by weaving, rolling, casting, pattern making, and cutting. The creation of excess material, not only would extend the time of overall growth, but would also constitute an inherent contradiction to the nature of the material, impacting various levels of sustainability. BC GMs can grow in the shape of the pattern without the need to cut and have exceeding materials. Even if this is feasible on small scale samples, however, in a real application, it is not possible to imagine a production of shaped container for the realization of every piece of the pattern, because of the high amount of containers necessary to structure a real production of garments and accessories of different sizes and styles.

Therefore, it becomes necessary to think of a methodology to obtain the final product within the concept of sustainability and zero-waste already in the design phases of the process. The proposed strategy starts from the study of the nature of BC itself, which during the drying phase has a significant reduction in volume, becoming dried and compacted. From a BC layer, it is possible to cut and obtain a specific shape and recycle the excess BC by reducing it into smaller parts that can be compacted in the final mould during the drying process. The result is called BC tartare.

The same procedure can also be used for the reuse of pieces of BC that have obvious production defects (i.e. holes or bubbles caused by an abnormal fermentation process), which invalidate their use.

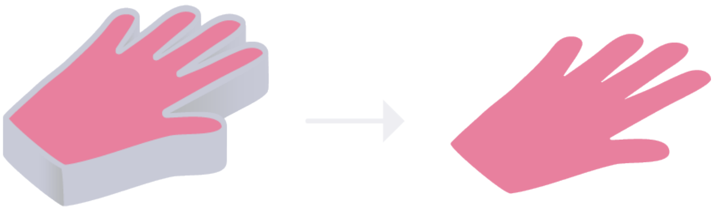

Figure 2. Strategy 1: piece obtained from growth in a pre-formed container.

Figure 3. Strategy 2: piece obtained from growth in a standard container and recycling of BC waste.

Exploiting the same technique, it is also possible to provide an answer to the question of how BC can make the lifecycle of textile products more sustainable: another branch of experimentation has investigated the textile waste integration within BC chopped with the aim of creating a new material completely derived from waste. The same textile leftovers can also be integrated with the GM, generating a resulting material with a completely different aesthetic quality.

The evolution of these experimentations has led to the creation of more structural BC composites, thanks to the integration of waste powders of wood and brick materials, always compactable thanks to the intrinsic properties of this GM, without including other additives.

Another line of experimentation has been identified in the possibility of inserting accessory components in the BC during the growth phase, to avoid the deformation of the additional elements usually anchored to the textile by deforming them. This last intuition has also opened the way to reflections related to the processes of assembly and disassembly that involve the BC, which can also be considered as a material for the union of several parts of fabric. This brings attention to the use of this material also for design for disassembly, since it can be an alternative to the use of stitching and/or button applications, which represent an issue for the recycling of garments when they reach the end-of-life. In fact, when BC is properly rehydrated, it's possible both to split the parts connected and embedded to/in it, allowing a complete recovery without deformation, and therefore potentially reintroducing them in new production cycles.

In the next paragraphs, the results obtained during this experimental exploratory path, already consistently summarized in Figure 1 are presented.

4.1 Zero-waste material from bacterial cellulose leftovers

The first opportunity offered by the reuse of BC waste is the possibility of chopping the parts of the layer that cannot be used to obtain BC tartare. Once grouped, inserted in masks/moulds and dried, the result is a new film with technical and sensorial characteristics dissimilar to the starting material.

Figure 4. Samples obtained from the combination of BC tartare from waste: different colours (A), uncontrolled shading (B), and linear shading (C).

The samples thus obtained have a slight rigidity compared to a simple layer of BC: this feature, however, does not affect the final yield of the material, which is compact, resistant, although aesthetically more opaque if compared to the starting material.

At the chromatic level, the samples show nuances due to the nature of the starting BC scraps. This characteristic is not to be considered as a limitation, but a concrete opportunity to be adopted to create a dynamic visual effect and to obtain materials with different colors and/or shades, as can be seen in the images below. The most difficult aspect to control is the final thickness of the dried material: the samples in the photo have 80 mm diameter and 1.5 mm thickness and were obtained by filling and compacting a mould of the same diameter but 6 mm thick. So, the 75% unidirectional shrinkage of the volume should be considered.

4.2 Integrating textile waste in BC layer and tartare for fashion materials

Textile leftover integration into BC is possible through two directions: insertion during growth in BC layers or during drying in BC tartare.

In the first case, the inserted textile leftovers are incorporated into the BC layer. Once the sample is dried, the textile components are cohesive to the BC, some wholly covered by the material, others only partially, creating an irregular texture to sight and touch. By increasing the growth time beyond 25 days it is also possible to obtain the complete incorporation of the insertions in the layer. The resulting material maintains the same degree of flexibility as the original BC layer but has interesting multi-material aesthetic-sensorial features. The variability of thickness and material combination defines new tactile and optical opportunities.

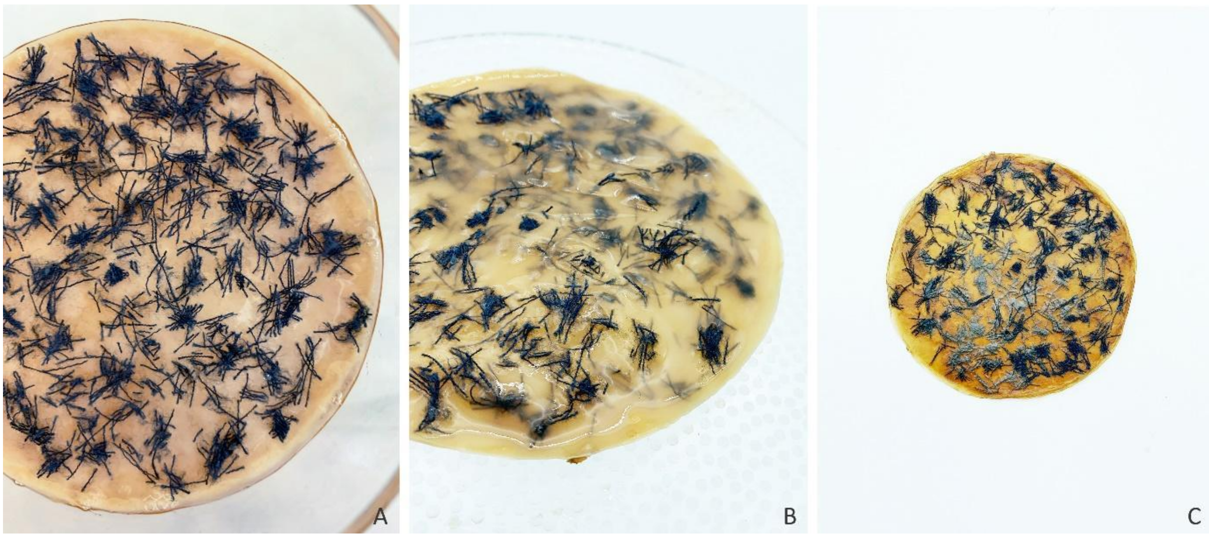

Figure 5. Integration of textile waste in growing BC layer: addition of material to the BC (A), pre-drying sample (B), post-drying sample (C).

On the other hand, if the intention is to integrate the textile leftovers during the drying phase, the best strategy is the integration with BC tartare. In this case, the compound, consisting of chopped organic material and waste of textile fibers, was amalgamated, spread uniformly, and dried. The material thus formed perfectly integrates both textile and organic material waste in a "double" zero-waste perspective. The sample obtained from this process and visible in Figure 6 is resistant, compact, with rough texture, and with a greater rigidity conferred precisely by the presence of waste. Aesthetically, it looks like a rough material but tactile pleasant and with irregular and not replicable aspect.

Both results offer concrete and diverse opportunities, equally functional even if not comparable in terms of aesthetics and structure. It should be noted that the physical and aesthetic properties of the materials created depend both on the production process and on the balance of proportions between the percentage of BC and the percentage of textile leftover. Therefore, the designer has the task of intervening in this productive and procedural choice, to calibrate aesthetic-sensorial results in accordance with the project aims.

Figure 6. Sample obtained from BC tartare and textile waste.

4.3 Integrating other waste in BC tartare for accessories creation

The integration of textile waste in the material has triggered a reflection on the possibilities deriving from the union of waste with a BC base. Broadening the typology of waste to sectors other than fashion can give rise to BC-based composites with greater structure, which can be used for the production of objects and accessories that can be used in the field under analysis. In particular, this further line of zero-waste materials has been tested in the production of buttons.

Hence BC was chopped and mixed with different types of waste: dust from wood and dust from brick; the resulting composite was placed in shaped containers (Figure 7) until completely dried. The obtained buttons have a non-homogeneous appearance, in which the additional substances inside them have partially absorbed the BC liquids, and have given the final material high stiffness. Also in this case it is possible to notice how the physical and aesthetic properties can be influenced by modifying the percentages of waste and BC in the constitution of the starting compound.

Figure 7. Preparation of the compound (A), pre-formed containers for drying buttons (B), final result (C).

BC combined with waste, therefore, shows suitability for the creation of materials of moderate stiffness, usable in the field of fashion accessories, showing at the same time high potential in a context of sustainability thanks to the absence of further additives. Also in this case, as in any result derived from BC tartare, the shrinkage of the final material is 75% and unidirectional.

4.4 Integration of accessories in BC to extend its lifecycle

The line of accessories can be further expanded by inserting external fashion components into the growing BC; in this case, the result of the integration of eyelets is presented.

The result visible in Figure 8 was obtained by placing the metallic elements on top of a thin layer of BC formed over 5 days; as time passed, these were completely covered by the GM over another 15 days. Once the BC is dried, the functionality of the eyelets integrated with this strategy is the same as that obtainable with traditional processes. However, in the case of disassembling the components, BC simplifies the process of extraction in water so that the eyelet can be reused in subsequent applications.

Figure 8. Integration of metal eyelets in growing BC: pre-drying sample (A and B), post-drying sample (C).

4.5 Seams replacement for textile assembling and disassembling through BC layer

As regards the use of BC for the assembly of textile elements, different possibilities have experimented in order to identify the most suitable methodology to obtain the joining of two layers of fabric. To scout the use of BC as a replacement material for seams - which represent a problem in the management phase of garment recycling when they reach the end-of-life - several tests have been structured. The different samples shown in Figures 9-10 illustrate different options of fabric arrangement, amount of BC layer used, and the creation of specific adhesion points, also through the creation of holes of different diameters on the surface of the fabrics by laser-cutting. Particularly, Figure 9 shows the results of tissue juxtaposition.

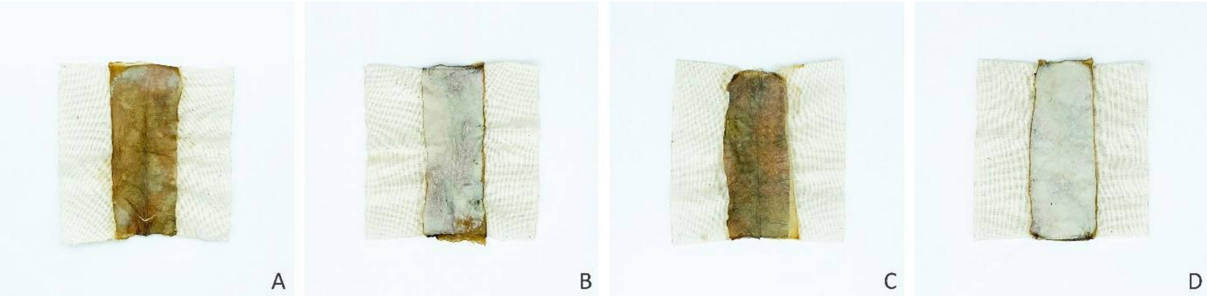

Figure 9. Seams replacement carried out on pulled together fabrics by testing different approaches: one BC layer (A), two BC layers (B), lasered fabrics and one BC layer (C), lasered fabrics and two BC layers (D).

Figure 10, on the other hand, shows the results obtained by overlapping tissues. The variations are given by the insertion of a BC strip between two tissues both unprocessed (E), one unprocessed, and one perforated (F), both perforated (G).

Figure 10. Seams replacement carried out on overlapping fabrics by testing different approaches: one BC layer between two unprocessed fabrics (E), one BC layer between an unprocessed fabric and a lasered fabric (F), one BC layer between two lasered fabrics (G).

Thanks to these tests it was possible to understand the importance of holes in the fabric to obtain a better result both in terms of adhesion and to contrast the shrinkage of the BC during the drying phase: the samples without laser pattern show more folds and higher fragility. Moreover, the samples made of juxtaposed fabrics appear less resistant than the corresponding ones made with overlapping fabrics: if bending them, the BC shows a tendency to detach. In conclusion, the most promising experiment is the one formed by two overlapping fabrics, both with a laser-cut pattern (G): the sample examined is quite flexible and very smooth.

4.6 Disassembling of fashion accessories in BC layer

The last level of experimentation focuses on the disassembly phases of BC integrating other materials, specifically buttons. When placed in a liquid for a prolonged period, the BC has a tendency to rehydrate, increasing in volume and decreasing in firmness, until it returns to a malleable and flexible state.

In Figure 11 the buttons were incorporated into the BC during growth, thus resulting directly integrated into the bacterial tissue, being stable and functional. To proceed with the separation from the BC, after its complete drying, small diagonal incisions were made on its surface, near the button's base.

The sample was then placed in water, where the BC, rehydrating, underwent an increase in volume and a decrease in strength and density. Thanks to the incisions, it was possible to extract the button very easily, which can be reused because it doesn't present damages or deformations.

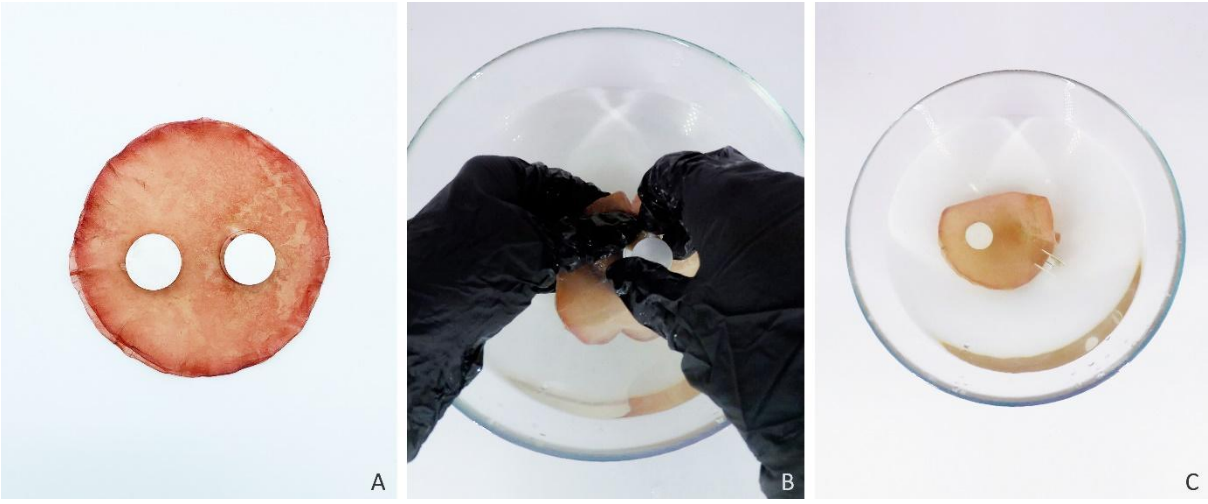

Figure 11. Button disassembly process: starting sample (A), disassembly (B), final result (C).

5. Discussion and conclusion

This paper offers an overview of the potential of BC manufacturing, production, and transformation processes applied to fashion and focuses on the impact of this material and processes from an environmental, social, and cultural perspective.

The production process of BC requires a large amount of water that, compared to animal leather, has the advantage of not having to undergo purification processes. Although in the experimental processes of this paper we used pure and strictly controlled liquids, we could hypothesize to reuse the water resources both during (i.e. rainwater or liquids derived from food waste) and at the end of the growth phase. This resulting liquid can be disposed of in the environment as a completely natural compound, be reused as an activator in new cultures, or be used at a larger scale as a by-product for fertilization in the agricultural sector. In this sense, BC materials facilitate the transition to a sustainable non-linear intersectoral bioeconomy model through materials obtained from renewable sources or by reusing waste (Collet, 2018).

Based on the results of the experiments, BC has a positive impact at the environmental level in a zero-waste logic with an important cultural impact. The obtained samples from waste or that integrated waste show to have crucial potential in terms of new applications and aesthetic/sensorial characteristics both of leather-like or completely new materials. This new landscape of materials could respond to the consumer interest for ethical, aesthetic, and sustainable solutions, also increasing the emotional attachment of users, thereby prolonging their use against a use-dispose attitude (Haines-Gadd et al., 2018).

The addition of metal and plastic accessories in BC materials allows for their disassembling, thus impacting also on the simplification of the manual disassembling operations of the components by the workforce. Similarly, the use of BC as seams replacement has a positive environmental impact, also by decreasing the manual work on disposal and recycling processes. From this perspective, it is also possible to highlight a positive impact on society, by limiting the exploitation of workers. At the same time, biomaterials can give rise to new virtuous methods of sustainable and local production by creating resilient socio-technical systems (Manzini, 2011). BC GMs could become a solution against overproduction and outsourcing allowing, locally grown biomaterials with a KM-0 approach and made-to-order customized waste-free biofabrication.

At the end of this experimental research, some issues arise to be explored with further phases of experimental and application development:

- is there a possibility of making marketable garments completely sustainable by taking advantage of the products and processes described here?
- considering BC's relationship with water, what methodologies can be used to sanitize such created fashion products?
- what aesthetics and narratives could encourage ethical and sustainable consumption of BC-made clothing and accessories?

These questions could be considered future challenges in which the creative thinking highlighted in design research and explored in experimental actions is translated into design activities aware and responsible about the complexity of the topic and its impacts on various levels of sustainability. Even if, at present most research studies are still limited to laboratory experimentation, the paper aims to lay the foundations to allow a further systemic knowledge of the BC potential for designers and researchers in relation to the scale-up in the same or other contexts of application.

Acknowledgements: Experimentation was conducted as part of the DE_FORMA project (Design Explorations on bio-Fabricated Organic Materials) through the funding program for fundamental research, by the Department of Design of Politecnico di Milano. We are thankful to all the colleagues of the project DE_FORMA who did not participate in the activity and the writing of the paper but supported us in the initial discussion: Erminia D’Itria, Flavia Papile, Stefano Parisi, Barbara Pollini, and Carlo Emilio Standoli.

6. References

Ahmad, J., & Ansari, T. A. (2013). Alkaline protease production using proteinaceous tannery solid waste. *J Pet Environ Biotechnol*, 4(136), 2. https://doi.org/10.4172/2157-7463.1000136

Amed, I., Balchandani, A., Berg, A., Hedrich, S., Jensen, J. E., & Rölkens, F. (2020). The State of Fashion 2021. *McKinsey & Company.* https://www.mckinsey.com/~/media/mckinsey/industries/retail/our%20insights/state%20of%20fashion/2021/the-state-of-fashion-2021-vf.pdf

Ananas Anam Ltd. *About Us - Piñatex.* https://www.ananas-anam.com/about-us/

Barrère, C. (2013). Heritage as a basis for creativity in creative industries: the case of taste industries. *Mind & Society*, 12(1), 167-176. https://www.africanscholarpublications.com/wp-content/uploads/2020/07/AJAAT_Vol17_No1-8.pdf

Bustillos, J., Loganathan, A., Agrawal, R., Gonzalez, B. A., Perez, M. G., Ramaswamy, S., Boesl, B. & Agarwal, A. (2020). Uncovering the mechanical, thermal, and chemical characteristics of biodegradable mushroom leather with intrinsic antifungal and antibacterial properties. *ACS Applied Bio Materials*, *3*(5), 3145-3156. https://doi.org/10.1021/acsabm.0c00164

Camere, S, & Karana, E. (2018). Fabricating materials from living organisms: An emerging design practice. *Journal of Cleaner Production*, 186, 570–584. https://doi.org/10.1016/j.jclepro.2018.03.081

Camere, S., & Karana, E. (2017). Growing materials for product design. *In Alive. Active. Adaptive: Proceedings of International Conference on Experiential Knowledge and Emerging Materials (EKSIG 2017)* (pp. 101-115). https://www.researchgate.net/profile/Serena-Camere/publication/319355171_Growing_materials_for_product_design/links/59a6c6fea6fdcc61fcfbbae7/Growing-materials-for-product-design.pdf

Ceschin, F., & Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design studies*, *47*, 118-163. https://doi.org/10.1016/j.destud.2016.09.002

Chan, C. K., Shin, J., & Jiang, S. X. K. (2018). Development of tailor-shaped bacterial cellulose textile cultivation techniques for zero-waste design. *Clothing and Textiles Research Journal*, 36(1), 33-44. https://doi.org/10.1177/0887302X17737177

CHEJ. (2004). *Executive Summary.* https://chej.org/wp-content/uploads/Bad-News-Executive-Summary.pdf

Claudio, L. (2007). Waste couture: Environmental impact of the clothing industry. *Environmental Health Perspectives*, 115(9). https://doi.org/10.1289/ehp.115-a449

Cleries, L., & Rognoli, V. (2021). Materials Designers: A New Design Discipline. http://hdl.handle.net/11311/1164651

Colak, S. E. L. I. M. E., Zengin, G. Ö. K. H. A. N., Ozgunay, H. A. S. A. N., Sarikahya, H., Sari, O., & Yuceer, L. (2005). Utilization of leather industry prefleshings in biodiesel production. *Journal of the American Leather Chemists Association*, 100(4), 137-141. https://www.researchgate.net/profile/Gokhan-Zengin/publication/285692021_Utilization_of_leather_industry_pre-fleshings_in_biodiesel_production/links/5bd9b24292851c6b279c70be/Utilization-of-leather-industry-pre-fleshings-in-biodiesel-production.pdf

Collet C. (2018). Biotextiles: Evolving Textile Design Practices for the Bioeconomy and the Emerging Organism Industry. In: *Soft Landing* (pp. 87-99). https://ualresearchonline.arts.ac.uk/id/eprint/12602/

da Silva, C. J. G., de Medeiros, A. D. L. M., de Amorim, J. D. P., do Nascimento, H. A., Converti, A., Costa, A. F. S., & Sarubbo, L. A. (2021). Bacterial cellulose biotextiles for the future of sustainable fashion: a review. *Environmental Chemistry Letters*, 1-14. https://doi.org/10.1007/s10311-021-01214-x

Danigelis, A. (2017). *Retailers bank on environmentally friendly clothing for increased sales. Environmental Leader.* Environment + Energy Leader. https://www.environmentalleader.com/2017/07/retailers-bank-environmentally-friendly-clothing-increased-sales/

Davis, J. (2020). *Is vegan leather worse for the environment than real leather?*. Harper's Bazaar. https://www.harpersbazaar.com/uk/fashion/fashion-news/a30640996/vegan-leather-sustainability/

De Klerk, H. M., Kearns, M., & Redwood, M. (2019). Controversial fashion, ethical concerns and environmentally significant behaviour: The case of the leather industry. International Journal of Retail & Distribution Management, 47(1), 19-38. https://doi.org/10.1108/IJRDM-05-2017-0106

Decouple, P. (2013). Cancer risks associated with employment in the leather and leather products industry. *Archives of Environmental Health: An International Journal*, 34(1), 33-37. https://doi.org/10.1080/00039896.1979.10667364

De Schoenmakere, M., & Gillabel, J. (2017). Circular by Design. Products in the Circular Economy. European Environment Agency, 6.

Dhir, Y. J. (2021). Hazards of fashion and textile waste: Approaches for effective waste management. In *Waste Management in the Fashion and Textile Industries* (pp. 31-58). https://doi.org/10.1016/B978-0-12-818758-6.00002-8

Dixit, S., Yadav, A., Dwivedi, P. D., & Das, M. (2015). Toxic hazards of leather industry and technologies to combat threat: a review. *Journal of Cleaner Production*, 87, 39-49. https://doi.org/10.1016/j.jclepro.2014.10.017

Ellen MacArthur Foundation. (2017) *A new textiles economy: Redesigning fashion's future.* http://www.ellenmacarthurfoundation.org

EPA. (2014). *Final amendments to the air toxics standards for flexible polyurethane foam production, fact sheet.* https://www.epa.gov/sites/default/files/2015-12/documents/20140730factsheet.pdf

Fairs, M. (2014). *Microbes are "the factories of the future".* Dezeen and MINI frontiers. https://www.dezeen.com/2014/02/12/movie-biocouture-microbes-clothing-wearable-futures/

Fritz, M., Belcher, A. M., Radmacher, M., Walters, D. A., Hansma, P. K., Stucky, G. D., Morse, D. E., & Mann, S. (1994). Flat pearls from biofabrication of organized composites on inorganic substrates. *Nature*, 371, 49-51. https://doi.org/10.1038/371049a0

Garai, J. (2014). Environmental aspects and health risks of leather tanning industry: a study in the Hazaribag area. *Chinese Journal of Population Resources and Environment*, 12(3), 278-282. https://doi.org/10.1080/10042857.2014.910875

Gatenholm, P., & Klemm, D. (2010). Bacterial nanocellulose as a renewable material for biomedical applications. *MRS bulletin*, 35(3), 208-213. https://doi.org/10.1557/mrs2010.653

Ginsberg, A. D., & Chieza, N. (2018). Other biological futures. *Journal of Design and Science*. https://doi.org/10.21428/566868b5

Grado Zero Innovations. (2017). *MuSkin*. Life Materials. https://lifematerials.eu/MuSkin-en.pdf

Haines-Gadd, M., Chapman, J., Lloyd, P., Mason, J., & Aliakseyeu, D. (2018). Emotional durability design nine—A tool for product longevity. *Sustainability*, 10(6), 1948. https://doi.org/10.3390/su10061948

Hildebrandt, J., Thrän, D., & Bezama, A. (2021). The circularity of potential bio-textile production routes: Comparing life cycle impacts of bio-based materials used within the manufacturing of selected leather substitutes. *Journal of Cleaner Production*, 287. https://doi.org/10.1016/j.jclepro.2020.125470

Iguchi, M., Yamanaka, S., & Budhiono, A. (2000). Bacterial cellulose—a masterpiece of nature's arts. *Journal of materials science*, 35(2), 261-270. https://doi.org/10.1023/A:1004775229149

Jain, N., & Jain, M. (2020). Animal Cruelty and Rights: Review and Recommendations. *International Journal of Policy Sciences and Law*, 1(2). https://ijpsl.in/wp-content/uploads/2020/12/Animal-Cruelty-and-Rights-Review-and-Recommendations_Navya-Jain-Muskan-Jain-.pdf

Joseph, K., & Nithya, N. (2009). Material flows in the life cycle of leather. *Journal of Cleaner Production*, *17*(7), 676-682. https://doi.org/10.1016/j.jclepro.2008.11.018

Karana E., Barati B., Giaccardi E. (2020). Living artefacts: Conceptualizing livingness as a material quality in everyday artefacts. *International Journal of Design*, 14(3), 37-53. https://doi.org/10.1162/artl.2009.16.1.16103

Karana, E., Blauwhoff, D., Hultink, E. J., & Camere, S. (2018). When the material grows: A case study on designing (with) mycelium-based materials. *International Journal of Design*, 12(2). http://ijdesign.org/index.php/IJDesign/article/viewFile/2918/817

Kianpour, K., Jusoh, A., & Asghari, M. (2014). Environmentally friendly as a new dimension of product quality. *International Journal of Quality & Reliability Management*, 31(5), 547-565. http://doi.org/10.1108/IJQRM-06-2012-0079

Laavanya, D., Shirkole, S., & Balasubramanian, P. (2021). Current challenges, applications and future perspectives of SCOBY cellulose of Kombucha fermentation. *Journal of Cleaner Production,* 126454. https://doi.org/10.1016/j.jclepro.2021.126454

Lee, S. (2011). *Grow your own clothes*. https://www.ted.com/talks/suzanne_lee_grow_your_own_clothes?language=en

Lee, S., Congdon, A., Parker, G, Borst, C. (2020). Understanding 'Bio' Material Innovations. A primer for the Fashion industry. *Biofabricate & Fashion for Good*. https://fashionforgood.com/wp-content/uploads/2020/12/Understanding-Bio-Material-Innovations-Report.pdf

Lehn, J. M. (2002). Toward self-organization and complex matter. *Science*, *295*(5564), 2400-2403. https://doi.org/10.1126/science.1071063

Lofrano, G., Meriç, S., Zengin, G. E., & Orhon, D. (2013). Chemical and biological treatment technologies for leather tannery chemicals and wastewaters: A review. *Science of the Total Environment*, 461, 265-281. http://dx.doi.org/10.1016/j.scitotenv.2013.05.004

Maital, S., & Barzani, E. (2020). The global economic impact of COVID-19: A summary of research. *Samuel Neaman Institute for National Policy Research*, 2020, 1-12. https://www.neaman.org.il/EN/Files/Global%20Economic%20Impact%20of%20COVID-19_20200322163553.399.pdf

Manchiraju, S., & Sadachar, A. (2014). Personal values and ethical fashion consumption. *Journal of Fashion Marketing and Management.* 18(3), 357-374. https://doi.org/10.1108/JFMM-02-2013-0013

Manzini, E. (2011), SLOC, The Emerging Scenario of Small, Local, Open and Connected, in Stephan Harding, ed., Grow Small Think Beautiful (Edinburgh, Floris Books)

Meyer, M., Dietrich, S., Schulz, H., & Mondschein, A. (2021). Comparison of the technical performance of leather, artificial leather, and trendy alternatives. *Coatings*, 11(2), 226. https://doi.org/10.3390/coatings11020226

Milly, M. (2019). *Framing leather. Fostering DIY-materials exploration in Berlin.* http://hdl.handle.net/10589/146905

Mironov, V., Trusk, T., Kasyanov, V., Little, S., Swaja, R., & Markwald, R. (2009). Biofabrication: a 21st century manufacturing paradigm. *Biofabrication*, 1(2), 022001. https://doi.org/10.1088/1758-5082/1/2/022001

Munny, A. A., Ali, S. M., Kabir, G., Moktadir, M. A., Rahman, T., & Mahtab, Z. (2019). Enablers of social sustainability in the supply chain: An example of footwear industry from an emerging economy. *Sustainable Production and Consumption,* 20, 230-242. https://doi.org/10.1016/j.spc.2019.07.003

Ng, A. (2017). Grown microbial 3D fiber art, Ava: fusion of traditional art with technology. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (pp. 209-214). https://doi.org/10.1145/3123021.3123069

Ng, M. C. F., & Wang, P. W. (2016). Natural Self-grown Fashion From Bacterial Cellulose: A Paradigm Shift Design Approach In Fashion Creation. Design Journal, 19(6), 837-855. https://doi.org/10.1080/14606925.2016.1208388

Ozgunay, H., Çolak, S. E. L. İ. M. E., Mutlu, M. M., & Akyuz, F. (2007). Characterization of Leather Industry Wastes. *Polish Journal of Environmental Studies*, 16(6). http://www.pjoes.com/Characterization-of-Leather-Industry-Wastes,88060,0,2.html

Pagiaslis, A., & Krontalis, A. K. (2014). Green consumption behavior antecedents: Environmental concern, knowledge, and beliefs. *Psychology & Marketing*, 31(5), 335-348. https://doi.org/10.1002/mar.20698

Palomino, E., & Defeo, G. (2018). *Material Design Innovation: Fish Leather, a new environmentally friendly material.* https://ualresearchonline.arts.ac.uk/id/eprint/16035/6/Material%20Design%20Innovation%20Fish%20leather%20a%20new%20environmental%20friendly%20material%20%20.pdf

PETA. *Vegan Leather: What It Is and Why It Belongs in Your Closet* https://www.peta.org/living/personal-care-fashion/what-is-vegan-leather/

Provin, A. P., de Aguiar Dutra, A. R., Machado, M. M., & Cubas, A. L. V. (2021). New materials for clothing: Rethinking possibilities through a sustainability approach-A review. *Journal of Cleaner Production*, *282*, 124444. https://doi.org/10.1016/j.jclepro.2020.124444

Qua, F. J. S. (2019). *(Im) Material: a qualitative study on sustainable materials for design through a comparative review of leather and its modern alternatives* [Doctoral dissertation, Massachusetts Institute of Technology]. https://dspace.mit.edu/handle/1721.1/122335

Quijano, L. (2017). *Embracing Bacterial Cellulose as a Catalyst for Sustainable Fashion.* https://digitalcommons.liberty.edu/cgi/viewcontent.cgi?article=1779&context=honors

Ravindranath, E., & Gopalakrishnan, A. N. (2010). Enhancement of biomethanization by pretreatment of limed fleshings from tanneries. *J. Sci. Ind. Res*, 69, 711-716. https://www.researchgate.net/profile/A-Gopalakrishnan-3/publication/266479070_Enhancement_of_biomethanization_by_pretreatment_of_limed_fleshings_from_tanneries/links/55ed3e2408ae3e121847fc6c/Enhancement-of-biomethanization-by-pretreatment-of-limed-fleshings-from-tanneries.pdf

Rissanen, T. I. (2013). *Zero-waste fashion design: a study at the intersection of cloth, fashion design and pattern cutting* [Doctoral dissertation]. http://hdl.handle.net/10453/23384

Ritterbusch, D. F., Hansen, E., Morisso, F. D. P., & Aquim, P. M. (2019). Tanning Process Study Using Chestnut and Acacia Tannin Associated with Acrylic Resin. *Journal of the American Leather Chemists Association*, 114(9). https://journals.uc.edu/index.php/JALCA/article/view/1621

Rognoli, V., Bianchini, M., Maffei, S., & Karana, E. (2015). DIY materials. *Materials & Design*, *86*, 692-702. https://doi.org/10.1016/j.matdes.2015.07.020

Saladino, V., Algeri, D., & Auriemma, V. (2020). The psychological and social impact of Covid-19: new perspectives of well-being. Frontiers in psychology, 11, 2550. https://doi.org/10.3389/fpsyg.2020.577684

Sauerwein, M., Karana, E., & Rognoli, V. (2017). Revived beauty: research into aesthetic appreciation of materials to valorise materials from waste. Sustainability, 9(4), 529. https://doi.org/10.3390/su9040529

Seeman, N. C., & Belcher, A. M. (2002). Emulating biology: building nanostructures from the bottom up. *Proceedings of the National Academy of Sciences*, *99*(suppl 2), 6451-6455. https://doi.org/10.1073/pnas.221458298

Tisdell, C. A. (2020). Economic, social and political issues raised by the COVID-19 pandemic. Economic analysis and policy, 68, 17-28. https://doi.org/10.1016/j.eap.2020.08.002

Whitesides, G. M., & Grzybowski, B. (2002). Self-assembly at all scales. *Science*, *295*(5564), 2418-2421. https://doi.org/10.1126/science.1070821

Wijffels, R. H., Kruse, O., & Hellingwerf, K. J. (2013). Potential of industrial biotechnology with cyanobacteria and eukaryotic microalgae. *Current opinion in biotechnology*, 24(3), 405-413. https://doi.org/10.1016/j.copbio.2013.04.004

Wood, J. (2019). Bioinspiration in fashion—a review. *Biomimetics*, *4*(1), 16. https://doi.org/10.3390/biomimetics4010016

Wu, L. Q., & Payne, G. F. (2004). Biofabrication: using biological materials and biocatalysts to construct nanostructured assemblies. Trends in biotechnology, 22(11), 593-599. https://doi.org/10.1016/j.tibtech.2004.09.008

Yang, G. H., Yeo, M., Koo, Y. W., & Kim, G. H. (2019). 4D bioprinting: technological advances in biofabrication. *Macromolecular bioscience*, *19*(5), 1800441. https://doi.org/10.1002/mabi.201800441

About the Authors:

Patrizia Bolzan, PhD in Design, Assistant Professor at Politecnico di Milano, Design Department, she investigates the ratio between digital fabrication (in particular additive manufacturing technologies) and Design in its practices and processes. She deals with product design system, DIY materials, functional prototypes.

Daria Casciani PhD in Design, Assistant Professor at Politecnico di Milano, Design Department, within Fashion In Process laboratory. Her research interests concern the influence of technological innovation of advanced manufacturing and smart integration to imagine scenarios, systems and innovative solutions.

Arianna Regaglia graduated in Fashion Design at Politecnico di Milano, she is interested in the field of innovative materials for the fashion and clothing industry. She developed a master thesis on the integration of bacterial cellulose in Zero Waste production systems.