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New Sustainable Fashion Design Scenarios: A Designer Journey in Textile Experimentation with Plants

Nicla Guarino, Stefano Parisi, and Valentina Rognoli

Abstract The complex age we live in, characterised by the Anthropocene era and Industry 4.0, demands a radical paradigm shift in production, consumption, material choices, and, consequently, the relationship between designers and Nature.

In this scenario, the clothing industry is clearly in the spotlight for being one of the most significant contributors to global environmental disasters and resource depletion. Thus, now more than ever, it is time to promote an imperative change in the fashion system towards circularity and regeneration.

This chapter presents an updated and articulated state of art describing the strong bond between designers and Nature in the fashion field. Specifically, the analysis highlights inspiring and promising examples from design research and practice in relation to Biomimesis, particularly focusing on the integration of plants into the process.

To show the potential of Living and Growing Design in the clothing field, a case study of an experimentation journey undertaken by a fashion design practitioner is illustrated, analysing its use of textiles as substrates for seedlings.

Through the MDD method, the DIY-Materials approach and Tinkering activities, the current research employs seeds, plants and bio-based materials as tangible tools to enable an emotional connection between users and their garments. The study produced theoretical and practical outputs: a material library, a speculative fashion collection, and an open-source manual for DIY experimentation and testing. These outcomes aim to inspire designers to care for their artefacts and foster a renewed connection with Nature.

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1 Introduction

In the last decades, every sphere of our life and all market sectors have experienced substantial global changes, represented by the development of a pervasive technological revolution and the delineation of a geological era in which the impact of humans is pivotal—the "Anthropocene" (Crutzen and Stoermer 2000).

Under these circumstances, the current production and consumption model is reaching its limits by exploiting raw materials for a brief lifespan and discarding them prematurely. Following this trend, we will drain the Planet's non-renewable resources, create untenable waste and harm all living organisms, including humans.

In particular, the fashion industry is deemed to be an increasingly volatile contributor to these global issues. This is mainly due to the proliferation of fast fashion, which is responsible for disasters such as pollution, resource depletion, poverty, health issues, and violation of human rights.

According to studies by the Ellen MacArthur Foundation (2017a) on the negative impacts of this system, the clothing industry produces around 40 million tons of textile waste per year. Considering garments as disposable goods implies excessive consumption of resources while disregarding the long and complex supply chains that characterise the textile and fashion industry. In fact, each stage of production has an environmental impact due to the consumption of water, materials, chemicals, and energy (Moretto et al. 2018; Rognoli et al. 2022).

In order to find a way forward within this framework, it is fundamental to acknowledge the age we live in and the potentials and consequences it entails. Indeed, it is clear that Anthropocene factors are converging with the effects of the "Fourth Industrial Revolution" (Schwab 2016), opening up alternative ways of rethinking and reshaping the relationship between design, Nature, and technologies, prompting a radical paradigm shift, especially within the fashion industry, in three key areas.

The first aspect of this shift is the embracement of a circular economy, representing the best solution to use existing or renewable materials and reintegrate them into a "cradle-to-cradle" system (McDonough and Braungart 2002) without drastically impacting the environment and society. The Ellen MacArthur Foundation (2017b) describes circularity as "an economy that is restorative and regenerative by design" as it aims to eliminate waste and pollution, prolong product lifecycles, and regenerate natural systems. Regeneration is a fundamental concept in this framework, as it must be considered as a broader and more dynamic model that "emphasises a co-evolutionary, partnered relationship between humans and the natural environment" (Cole 2012).

The new circular and regenerative mindset requires everyone involved in the supply chain to act and improve their behaviour. Thus, as we are "on the brink of a materials revolution" (Franklin and Till 2018, p. 9), the second area of this undergoing transition is to recognise the power of materials in our lives. Indeed, "materials play a key role in the configuration of our environment and our life" being "visible or invisibly interwoven within our realities" due to their ability to nurture and enrich us (Guasch Sastre 2021, p. 12).

This significant role of materials is the premise introducing the last aspect of this paradigm shift, i.e. the relationship between humanity and the environment and, particularly, between designers and Nature. Not surprisingly, one of the main trends in today's society is reflected in a modern connection between humans and their natural origins. The biologist Wilson (1984) names this concept "Biophilia", defining it as "the innately emotional affiliation of human beings to other living organisms". This bond is thought to be the driver "to product and material innovation" with the "rising concerns around biodiversity and sustainability" (WGSN 2021). However, this extends beyond fashion to encompass art, design and architecture, since science and technology will become the instruments to enable different forms of bonding between people and the Planet.

In summary, regenerative development in the fashion industry requires the realignment of design processes with circular natural behaviours. To make this happen, we should change our perspective on materials and encourage designers and innovators to "realise there is no separation" between organisms and humans (Conners 2020).

The main objective of this chapter is to present how this intention can be translated into practical outcomes. The first section will therefore provide an overview of the existing literature regarding the hybridisation of science and design, with an emphasis on the opportunities presented by Biodesign and Growing Design in reconnecting designers with artefacts. The review explicitly focuses on the application of plants in textile design and showcases inspiring examples of garments designed by fashion designers.

The following section focuses on the central intention of the study, which is to introduce the experimental journey into the world of bio-based and growing materials in the fashion field. The goals and tools of the investigation are presented by describing the research methodology rooted in the Material Driven Design (MDD) method, Tinkering approaches, and Do-It-Yourself (DIY) practices. Then, the design journey will be narrated through diary activities with comments and images on the main steps of materials selection and development. After presenting the three main research results—an extensive material library, a speculative collection and an open-source book—we will discuss the findings of the analysis and the new scenarios for future exploration. Finally, the conclusions will provide a complete summary of all the points covered, defining the study as an ode to the embrace of Nature in fashion design.

2 State of the Art

Numerous approaches have surfaced to rethink the existing design system and support the possibility of integrating Nature's roles for its purposes (Camere and Karana 2017). In the following exploration through literature and practice review, two distinct areas, Biomimicry and Biodesign, with a particular attention on Growing Design, are examined. Indeed, these notions, rooted in biotechnology and biological knowledge, represent a potential path for material design to replace reliance on fossil-based resources. The review then focuses on the application of plants in textile design practices.

2.1 Biomimicry: Starting from Nature

The Biomimicry Institute (n.d.) identifies the term "Biomimicry" as the "practice that learns from and mimics the strategies found in Nature to solve human design challenges in a regenerative way". The term was first coined by Janine Benyus (Conners 2020), stating that "Biomimicry is innovation inspired by Nature and it is a new way of inventing by looking to the natural world for our inspiration".

As inferred through these definitions, Biomimesis is a principle that can be applied in science, technology, design and many other fields in order to reproduce some effective characteristics inspired by the natural sphere. Therefore, Biomimicry could redirect the fashion industry's future by regenerating materials and textiles.

In this context, the Biomimicry Institute (2020) paves the way and presents an outline of the potential fibres of the next-generation fashion system, going beyond the biomimetic application and including natural resources (such as wool, cotton, or silk produced from regenerative farms or certified eco-friendly processes), bio- and cellulosic-based fibres (obtained from agricultural waste and sustainable rayon production) and fabrics made from microbes (such as bacteria- or yeast-based materials).

2.2 Defining Biodesign and Growing Design

The notion of "Biodesign" represents an extensive area that embeds concepts such as "cradle-to-cradle" (McDonough and Braungart 2002), "Biophilia" (Wilson 1984) and "Biomimicry" (Biomimicry Institute n.d.). William Myers (2012) identifies Biodesign as "the emerging and often radical approach to design that draws on biological tenets and even incorporates the use of living materials into structures, objects and tools" (p. 8). Echoing these terms, Keune (2021) adds that Biodesign integrates living organisms as crucial components that could improve the function of the final product. Nevertheless, it can be inferred that this field encompasses vast manufacturing possibilities if one considers, for example, the definition by Mironov et al. (2009) of "Biofabrication"—that is "the production of complex living and non-living biological products from raw materials such as living cells, molecules, extracellular matrices, and biomaterials". In support of this, Biofabricate and Fashion for Good (2020) argue that Biodesign "leaps ahead of imitation and mimicry to integration and use, dissolving boundaries and synthesising new hybrid objects and architecture" (p. 10).

This new field results from the intersection of design and biology and has become one of the most studied approaches by numerous scholars (Camere and Karana 2017, 2018; Collet 2013). In detail, Growing Design describes a process focusing on the development of novel materials from living organisms for product design, going under Collet's (2013) definition of "Nature as a co-worker" in the material process (Camere and Karana 2017). Hence, Camere and Karana (2017) describe Growing Design as a material design practice altering the designers' workspace into biological laboratories and mixing their creative attitude with a scientific point of view. This practice grows innovative materials from organisms such as fungi, bacteria, yeast, algae, mycelium and plants, and can provide novel expressive, functional, and interactive possibilities by prolonging their "livingness" over use-time (Karana et al. 2020).

Applying these notions to the field of the textile and clothing industry, Rognoli et al. (2022) assert that, in fact, "the potential for the fashion sector derives from the possibility that different organisms can self-grow into fibres, tissues, or dyes, using life-friendly chemistry and processes typical of biological growth" (p. 756).

2.3 Fabricating Textiles with Plants

The presence of plants in humans' surroundings is highly influential, as it has been demonstrated with biophilic tendencies. Indeed, there is a significant connection between the history of humanity and its existence within a natural reality. The anthropologist Natasha Myers (2021) coined the term "Planthroposcene" to describe a vision of the world in which humans collaborate with plants so that materials can contribute to reducing anthropogenic emissions. In this way, the plants could be the ideal instrument to demonstrate the importance of the circular system and encourage people to dispose of their garments appropriately.

Carole Collet's work shows the possibility of "exploring the intersection of biomimicry, living technologies, and biomanufacturing" (Criado 2016). In her project *Biolace,* she reprograms plants as "living machines" (Collet n.d.) projected into 2050 to discover the potential of emerging technologies and reduce the impacts of the textile industry. The series comprises four fictional hyper-engineered plants woven into the growing roots to produce an alternative textile (see Fig. 1a). Collet's work inspires the use of plants in the design process, based on the collaboration between living organisms and the designer, demonstrating the feasibility of obtaining food and clothing from seeds (Collet n.d.).

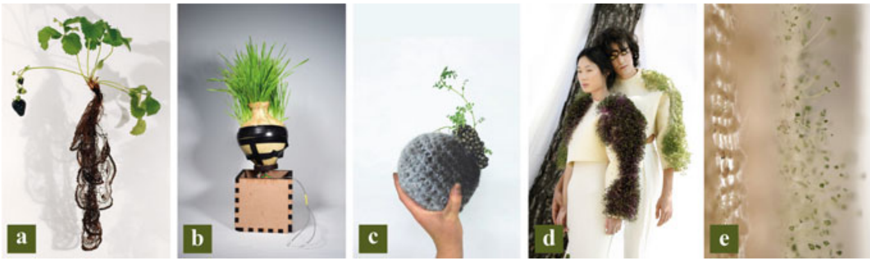

Fig. 1 (**a**) *Strawberry Noir*, part of the *Biolace* series by C. Collet, 2012. Photo by Carole Collet; (**b**) Centrifugal force experiment set-up by J. Zhou et al., 2020. Photo by Jiwei Zhou; (**c**) Soil-filled freeform crochet with a rim of chickpea-yarn by S. Keune, 2018. Photo by Svenja Keune; (**d**) *Symbiotic Nature* by P. Ulargui Escalona, 2020. Photo by Paula Ulargui Escalona; (**e**) Growing woven piece with integrated chia seeds in wool yarns, from *beGrounded* by Lara Campos. Photo by Manuela Reyes

Another case study that represents a stimulating combination of science and textile design is *InterWoven*, the most famous creation of the German artist Diana Scherer. Thanks to her multidisciplinary approach, in 2015, she developed a series of tapestry-like textiles in collaboration with biologists and engineers (Scherer n.d.) by manipulating roots in the soil according to artistic patterns. This co-working process with the plants was also reported in *Rootbound*, an innovative dress presented in the *Fashioned from Nature* exhibition at the Victoria and Albert Museum (n.d.) between 2018 and 2019.

InterWoven's root system was further explored by Jiwei Zhou's study (2019) to develop the project into "a durable and applicable material for product design" (p. 6). Through her analysis, she first gathered all the essential information on Scherer's art piece. Then she experimented with new root structures and clustered data on plants' properties, such as resistance to gravity and centrifugal force. She also displayed her final concept in which roots were grown through porous discrete beads to create 3D volume and emulate the mass-produced IKEA ALSEDA puff (Zhou 2019). In particular, Zhou et al. (2020) identified key design parameters and improved the ability of plants' roots to bind discrete porous structures through the use of the Material Driven Design approach and Tinkering activities (Fig. 1b). In addition, *InterWoven* has been carried forward by Carrete et al. (2022) exploring and analysing Engineered Plant Root Materials (EPRM) in relation to their mechanical properties. In particular, the use of agar-agar as a biopolymer matrix has been confirmed as a medium that allows the improvement of load distribution and tensile properties (Carrete et al. 2022).

Lastly, the investigation by Svenja Keune highly influenced the design process presented in this chapter. Her research is based on exploring textile design techniques through the integration of plants and analysing their application in interior design depending on the structural variables of construction (Keune 2018). Her work of co-designing textile fibres with seeds and sprouts—in different materials, surfaces, shapes, weaving techniques, patterns and interiors (Fig. 1c)—is defined by the author as “Textile Farming” (Keune 2018). One of the most interesting points of Keune’s work is the attention given to the designer’s role in the process of plant growth. She emphasises that Biodesign opens up “alternative ways of connecting with and caring about plants”, creating “forms of interaction and symbiosis” (Keune 2018, p. 28). Furthermore, the biological analysis of the seeds’ components, their life cycles and the experimental tests on the potential combinations between fabrics and plants explored by Keune represent inspiring aspects for the work presented in this chapter.

Considering the novelty of this field of research based on a limited number of studies and publications, the following practice review aims to provide a complete overview of fashion design practices combined with Growing Design by analysing particular garments integrating seeds and plants.

An example to mention is the collection *And the World will be as One* by Jacob Olmedo, who graduated from Parsons School of Design (New York) in 2017 with this project. The graduation project is set in a future that combats “mass species extinction” and climate change (Parsons School of Design n.d.), strengthening the bond between users and Nature. As part of his experimentation, he layered organic cotton, rock wool and felt to sow grass seeds. More recently, the artist has been working on textile design and innovative techniques, combining knitted textiles with bio-based and 3D-modelled beads containing dirt and seeds (Olmedo n.d.).

Fashion designer Paula Ulargui Escalona is the author of numerous stimulating works on sustainability and Biodesign. The most interesting is *Symbiotic Nature*, in which she tested the growth of seeds by playing with Nature through colours and patterns of living sprouts (see Fig. 1d). Her “second skin” garments enable the consolidation of “a direct connection between two organic bodies of different species” (Ulargui Escalona n.d.). The symbiotic feeling is the common thread with *beGrounded*, a project by the designer Lara Campos. She explores “a new habitable space in the form of a woven garment with growing sprouts, as a sensorial and interactive experience” (Campos n.d.). Her work also includes an eco-friendly kit that allows customers to grow chia seeds on textiles and promote taking care of garments (Fig. 1e). Along similar lines, *Growing Garments* by Anouk Christel Schaedler (n.d.) follows the trends of living textiles and is composed of different green clothes that invite to bring Nature closer to humans and their environments.

2.4 Opportunities and Gaps

The analysis carried out through the current state of the art made it possible to understand the general picture of the situations and potentials that the field of Biodesign and Growing Design can open up to the world of fashion. It is particularly stimulating to observe that the structure of plants’ roots is resistant and easily controllable, allowing the creation of templates and patterns directly in the soil or applied to other matrices. Furthermore, the MDD methodology employed by Zhou (2019) and others (Carrete et al. 2022; Zhou et al. 2020) in their research has been identified as a proper method to be applied in the study we present in the chapter. Another useful insight from that research could also be found in using an agar-based solution as a substrate for improving the strength of growing sprouts. Likewise, another useful technique is recognised in Svenja Keune (2018) and Jiwei Zhou's tests (2019), who proposed helpful monitoring tools and tinkering diaries to follow the life cycle of plants.

Similarly, the analysis of fashion design practices revealed numerous exciting opportunities. For instance, some designers have utilised fabrics as a medium for seeds' growth, while others, like Jacob Olmedo (n.d.), have integrated seeds into bio-based materials. Another fascinating reflection that can be derived from all these examples is the potential for symbiotic relationships between designers and their living creations. In this context, there is the possibility of using this new relationship as a tangible tool to reintegrate fashion products into closed loops, promoting circularity.

However, a gap observed in these examples is the absence of a comprehensive production guide that allows for the replication of these processes through DIY practices. This research addresses this gap by creating an open-source manual for home investigation. By providing guidance and encouraging experimentation, people are empowered to cultivate their unique and personal bond with their growing garments, thus contributing to sustainable fashion practices.

3 Experimentation Journey: Designing Fashion with Plants

This study mainly targets materials designers and fashion creators who can merge biology and design, implement the knowledge and insights gained from the research conducted so far, and challenge the *status quo*. After introducing the intents of the experimental journey, it is pivotal to propose the aforementioned material-centred and experiential methodologies that could favour the shift towards a non-harmful textile industry and the creation of disruptive designs.

3.1 Project Objectives and Motivations

Set in a future scenario, this project is inspired by the natural world with the purpose of introducing to the market an emergent typology of circular apparel. To this end, a capsule collection was conceived to be biodegradable and dispersed in the soil, allowing the garments to rebirth at their end of life. The concept takes advantage of the integration of living artefacts to reinforce the relationship between object and designers and perpetuate it with the final users through acts of nurturing and caring (Pinto et al. 2013). Consequently, the main objective of this experimental journey is to make this concept attainable, bringing tomorrow's fashion firms to offer their customers garments with a second life.

Aiming to design this speculative collection, the fashion items were enriched with living seeds and growing sprouts to be taken care of and planted in the ground at their disposal. Hereby, different materials have been the object of accurate analysis and investigation, representing a significant stage of the process. Among them, bio-based plastics and resins—namely polymers "derived in whole or in part of biological products" (Vert et al. 2012)—are resources suitable for encapsulating dormant seeds. Additionally, growing sprouts were inserted into organic textiles (such as wool and cotton) as tangible means to exemplify their "plantability" at the end of their life and enable the emotional connection between users and their garments.

3.2 Research Methodology

3.2.1 Material Driven Design

Material Driven Design (MDD) is a novel methodology anchored in the notion of "Materials Experience" and, therefore, based on understanding and enhancing the unique experience materials can enable in the design and use time (Karana 2009).

MDD is a "journey" that facilitates design when the material is the starting point as it is "established from material properties and experiential qualities to materials experience vision" and vice versa (Giaccardi and Karana 2015; Karana et al. 2015, p. 37; Zhou 2019). In particular, four main stages are at the basis of this approach: (1) Understanding the Materials, including tinkering and characterization; (2) Creating Materials Experience Vision to envision the materials' role in contributing to superior performances and unique user experience; (3) Manifesting Materials Experience Patterns, to identify attributes to translate the vision into the material, based on user studies; (4) Designing Material/Product Concepts, namely the actual design phase (Giaccardi and Karana 2015). Moreover, this experience can be carried out through four levels of interaction between materials and people, i.e. sensorial, interpretive, affective and performative levels (Giaccardi and Karana 2015). Thus, the use of this methodology made it possible to evaluate the materials from the outset, acknowledging their objective and subjective characteristics and being able to define the designer and user experience.

3.2.2 Material Tinkering

The research deals with a specific phase of the MDD exploration process: Material Tinkering. Indeed, the design of circular and emerging materials implies a disruptive transition in their compositions and processes and in the designer's learning attitude.

Material Tinkering is defined in broad terms as a hands-on and creative experimentation process aiming to discover the material and improve it through an iterative approach (Parisi et al. 2017). It is a learning approach grounded on the interaction between designers and matter, taking inspiration from the Bauhaus didactic notion of "Learning by doing" and from the scientific pillar of "trial-and-error" (Clèries et al. 2021; Rognoli and Parisi 2021).

This method was applied to the present study at three possible levels, i.e. tinkering with the formula, processes or samples (Parisi et al. 2017; Rognoli and Parisi 2021). In this research, the use of plants and seeds also favoured “BioTinkering”, which is the act of “tinkering with biology” leading to insight in order to reach innovation (DIYbio 2011). Finally, the outcomes obtained during this experimentation journey can be described as “materials drafts and demonstrators” and documentation of many kinds, as “cookbooks” reporting the results of all the Tinkering activities (Rognoli and Parisi 2021).

3.2.3 DIY Practices

As seen, the role of material designers requires great responsibility since their challenge is to tackle alternative resources through sustainable “recipes” (Rognoli et al. 2021) without compromising the aesthetical attributes of a product.

Consequently, innovative materials are produced not only in research laboratories (Manzini 1986) but rather the habit of developing material artefacts with full autonomy is increasingly widespread (Rognoli et al. 2021). Four emerging patterns can be identified in these activities: the examination of the material context; the exploration through tinkering; the experimentation with DIY processes and the development of material drafts; the evaluation and selection of material drafts to turn them into material demonstrators (Rognoli et al. 2021). The result of material self-production, named “DIY-Materials” by Ayala-Garcia et al. (2017), represents speculative solutions that help to envision alternative futures. Following these steps, the experimentation journey presented in this chapter begins autonomously with the analysis of bio-based and living plants, arriving at the creation of DIY-Materials demonstrators for feasible application in a circular fashion.

3.3 Investigation Activity Diary

To effectively implement the emerging materials discussed earlier, three main DIY investigation activities were carried out enabling to experiment on samples. The first two practices involved bio-based materials tinkering, conducted between September and November 2021, and growing materials tinkering, conducted between October and December 2021. The third activity focused on testing the biomaterials’ biodegradability and was run in December 2021. At the end of each of these stages, the most suitable materials for fashion applications were selected, based on their properties.

The overall process spanned eight months and culminated in the creation of material demonstrators between March and April 2022, along with other speculative outcomes to support the project.

3.3.1 Tinkering with Bio-Based Materials

The first experimental activity concerned the tinkering process with DIY bio-based plastics and resins.

The investigation started with the combination of all the components, accompanied by the drafting of a cookbook in which all the required ingredients and household utensils—such as stove, scale, glasses, pots, bowls, silicone moulds, plates, spoons, spatula, whisk and baking paper—were reported. In this step, tutorials on tinkering and online open-source platforms, such as those offered by Fab Textiles (Davis 2017; Dunne 2018), Materiom (n.d.), and Ribeaux (n.d.), were consulted as guidelines for self-production. In particular, the work of Bogers (2020) was fundamental in providing guidance on the categorisation structure and the collection of information necessary for the final documentation.

After combining the components, the biomaterials mixture was generally brought to a boil. Meanwhile, the casting surface was prepared, and when the compound reached the right thickness, it was poured into it for moulding. Then, during the curing phase, any changes were monitored daily to transcribe the materials' technical and experiential characteristics (such as, respectively, their thickness or hand feel). At the end of the drying process, the bioplastics were also analysed in terms of sustainability by checking the origins and compostability of the ingredients, as well as the reprocessability of the samples. All the collected data and pictures collected were sorted into a cookbook (see Fig. 2).

The glycerine was the common ingredient, mixed with various polymerisation agents: agar-agar, pork gelatine, sodium alginate and calcium chloride, activated carbon, corn starch, potato starch and pectin. Other components included in the matrix were seeds, natural dyes, leaves, flowers and buds, and fabric scraps. The curing process and the moulds used resulted in different textures and shapes resembling eco-leather, PVC or coated fabrics. Some experiments produced knittable yarns, while others incorporated handmade embroidery to redesign the biomaterial surface.

Out of fifty bio-based resulting samples, thirteen were selected according to their suitable variables for the fashion industry—i.e. elasticity, flexibility, lightness, thickness, breathability, waterproofing, aesthetics and versatility. Among these, five samples were chosen for the final project application.

A significant result of this research is represented by an agar-agar sample with encapsulated chia seeds. This particular biopolymer showed seeds' resistance to high temperatures and successfully germinated during the curing process, proving a feasible opportunity to be explored further in the product concept ideation.

3.3.2 Tinkering with Growing Materials

Tinkering with growing materials involved an initial phase dedicated to study the seeds' anatomy—inspired by the work of Keune (2018). The objective of this phase was to gain a comprehensive understanding of the fundamental technical terminology used to describe the seed's growth.

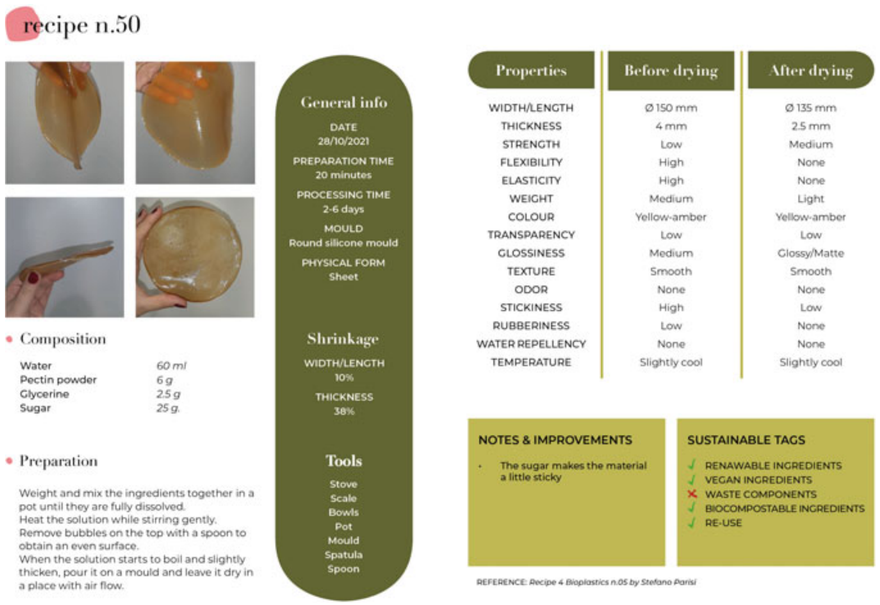

Fig. 2. Example view of a recipe with all the instructive and descriptive information about the sample produced by tinkering with bio-based materials. Image by Nicla Guarino.

This was followed by the sowing processes of five fast-growing plants: catnip, chia, lavender, lemon and sunflower. Diverse substrates were used for those experiments, encompassing textiles such as cotton canvas, cotton pads, cotton wool, paper towels, cotton yarn, wool felt, and knit wool, as well as non-textile options such as agar-agar matrix. Additionally, each experiment involved the comparison of the same seeds inserted on different substrates and different seeds inserted on the same substrates. Each planting process required water and common household utensils, such as containers, glasses, tweezers and spoons. Comprehensive documentation was performed throughout the experimentation, capturing all tools used and tracking the setup and operational steps of the various attempts undertaken to allow replication (see Fig. 3).

For documenting this BioTinkering activity, attention was paid to the germination process from day zero of dormancy to the plant deactivation. Each day, representative photographs were taken, accompanied by a concise description highlighting the key characteristics and differences observed during each phase. Finally, the collected data encompassing the various growth processes were filed and analysed.

Out of the sixteen combinations of different substrates and seeds, chia seedlings in wool felt emerged as the most promising outcome for fashion applications. Indeed, this typology of seeds germinated easily and in large quantities, rooting in the textile sockets and proving a high resistance against movement and gravity.

While tinkering with these growing materials, the observation of all the growth stages was particularly interesting as they effectively demonstrated the potential for

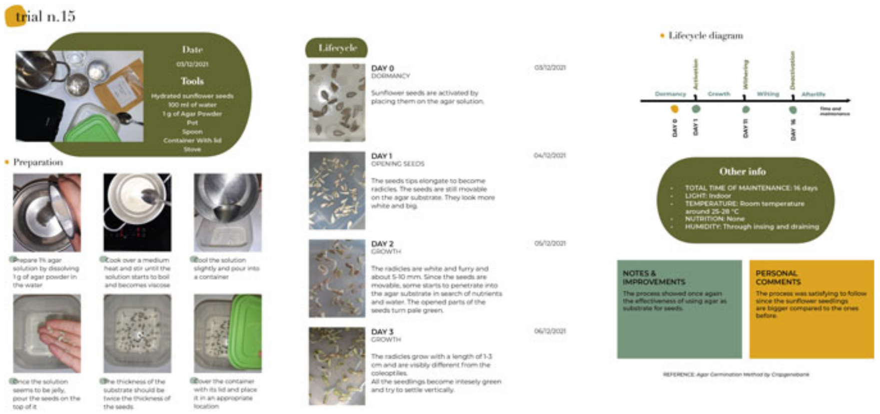

Fig. 3. Example view of documentation on the tinkering process with growing materials, including preparation guide, daily tracking and diagram of plant's lifecycle, additional notes and personal comments. Image by Nicla Guarino.

developing a profound bond with the sprouts. It is worth noting that, in some cases, achieving successful germination was unattainable due to seed dormancy.

3.3.3 Biodegradability Testing

The final stage of the investigation encompassed three tests conducted to understand the biodegradability of biomaterials combined with chia seeds. Bio-based materials recipes were selected from the outcomes of the previous Tinkering activities to produce the most feasible substrates for the seeds. In particular, the investigation regarded a total of ten samples made from agar, gelatine, sodium alginate, potato starch and corn starch, which were further subdivided for each of the three tests. To assess the germination capability of the encapsulated seeds, chia seeds were placed either on the surface or within the biopolymers.

The first test consisted of dissolving the samples in hot water for twenty-four hours to test their water resistance and the ability of the seeds to withstand high temperatures. After an average of two days of drying, the agar-based sample showed greater resistance to shrinkage. Among other findings, the results revealed that, when exposed to water, seeds positioned on the surface of the materials detached earlier than those embedded within the samples. Furthermore, some seeds initiated the germination process, overcoming their dormancy phase, but the boiling water hindered their further germination.

Two experiments were conducted to examine the compostability of the biomaterials in potting and garden soil, along with the timing of their decomposition. After the planting phase, the decomposition process was monitored for fourteen days using photographic documentation. Garden soil (with a decomposition time between fifteen and forty days) halved the biodegradation compared to potting soil (which required

Fig. 4. The material library consists of bio-based materials samples with different properties and growing substrates like wool felt integrated with chia seeds. Photos by Nicla Guarino.

between thirty and eighty days to decompose), thanks to the natural presence of microbes and nutrients. Unluckily, in most cases, seeds did not germinate due to suboptimal temperatures.

4 Research Results

Besides the theoretical results derived from the conducted analysis, the experimentation journey produced three main practical outcomes, which are described hereafter.

4.1 Material Library

The materials research—based on the Tinkering activities and the biodegradability testing—has resulted in the creation of a total of more than fifty material drafts and different demonstrators, such as seed-encapsulated buttons and growing textiles (Fig. 4). Thus, it was possible to label all the samples with key information, such as recipe number, date, components, quantities and date of production and collect them in a material library.

4.2 Speculative Fashion Collection

The second outcome is a speculative fashion collection that combines the scenario and all the materials derived from the BioTinkering activities. Inspired by symbiosis and biomimetic principles and aesthetics, this capsule collection consists of six full looks that combine living plants, organic fabrics and bio-based materials. The integration of seeds, flowers and leaves donates a colourful essence to the outfits, inviting people to reconnect with Nature and feel the positive message of plants' growth.

One of the designed garments was realised in the form of an archetypal prototype to make visible the possibilities outlined in the study (Fig. 5). The minimalistic tank top is composed of an outer layer of wool felt, on which growing chia sprouts are placed all over the shoulders, ensuring its wearability. Additionally, it is designed to be opened on the sides using bio-resin buttons, made from gelatine and encapsulating chia seeds. This allows it to be deployed and placed horizontally on a flat surface in order to water and grow the seedlings (see Fig. 6). Considering the need to wear the top without getting wet, the lining is made from waterproof cotton and is left open at the bottom to allow excess water to drip off. Moreover, tests confirmed that the planting process can be repeated as many times as desired and the garment can be buried in the ground at the end of its life.

Fig. 5. Details of the archetypical garment. Photos by Nicla Guarino.

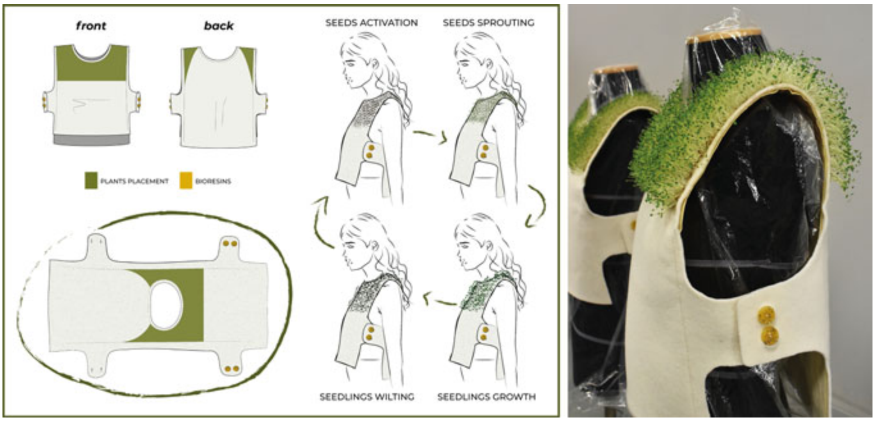

Fig. 6. Study of the archetypical garment and final top with growing chia seedlings. Image and photo by Nicla Guarino.

4.3 Lab Book

Ultimately, to address the gap identified by the state of the art, all the resources produced during the research were collected into a material experimentation handbook named *Lab Book A guide for innovative materials* (Guarino 2022). It is a manual that enables anyone to replicate the production of bio-based and growing materials at home (Fig. 7). The *Lab Book* consists of three main sections representing the three most important activities carried out for this study. The first section focuses on tinkering with bio-based materials and contains recipes, preparation procedures, photographic documentation, descriptive information, properties observed before and after the drying process, notes for improvement and sustainability tags. The second section is dedicated to the experimentation with growing materials and offers visual and textual information sheets for each used seed. It documents the conducted experimentations and tests through a tinkering diary, supplemented with notes and personal comments. Lastly, a section presents the biodegradability tests, showing the tools used for each activity and reporting the main factors recorded in the various analyses.

At a glance, this handbook represents a stimulating tool for creators in the Biodesign field and ordinary people, allowing everyone to become innovators. The guide teaches how to deal with the typical unpredictability and imperfection of bio-based materials. By these means, everyone could experience an evolving and symbiotic connection with their growing artefacts, defined by Karana et al. (2020) as "Mutualistic Care", enriching "the (re)enlivening of the world by establishing a culture of life" (Armstrong 2022, p. 1).

Fig. 7. The mock-up shows the final design of the *Lab Book—A guide for innovative materials*. This online open-source book collects the whole experimentation journey and promotes DIY-Materials investigation. Images by Nicla Guarino.

5 Discussion

This research proposes an innovative and circular approach to fashion by integrating seeds and plants into clothing, with the aim of building a bond between the designer (or user) and Nature and offering "plantable" garments as tangible tools of the "closed loop" concept.

A significant contribution of this chapter is undoubtedly represented by the role that plants play in being integrated with textiles. It is evident how materials can create a bond with the designers and the users by nurturing and enriching their lives (Guasch Sastre 2021). A biomimetic approach to the fashion industry could even strengthen the connection with garments by exploiting the empathy that living and growing organisms could impart (Conners 2020). The BioTinkering phase carried out in this study—based on seeding plants into fabrics and bio-based materials—provided first-hand experience of these emotions. Observing the growth phases of the seedlings from dormancy to deactivation was stimulating and captivating, fostering "forms of interaction and symbiosis", as suggested by Keune's research (2018, p. 28). Not all of the plants initiated a growth process due to various reasons, including unsuitable substrates or adverse external conditions. In other cases the growth of the seeds was sudden and always surprising, creating an evident sense of protection for the small seedlings. Therefore, caring for the seeds was a spontaneous act, reflecting a natural and beneficial symbiotic state (van den Broek et al. 2022, p. 3). This demonstrates the importance for designers dealing with living materials, above all others, to be educated in understanding and connecting with Nature.

Drawing inspiration from the synergism of plants and learning what lies behind these intelligent lives—even if different from the human one—can represent the means for a regenerative and meaningful design (Karana et al. 2023). Thus, an exciting point to highlight is the acknowledgement of the "intelligence of plants", a factor widely studied by Mancuso (2017). He proves that the Vegetal Kingdom dominates the world by being smart and modern—contrary to common perception—thanks to its flexibility, modularity, altruistic behaviour and ability to communicate with other organisms (Mancuso 2017; Mancuso and Viola 2013). Viewing plants from this unusual and suggestive perspective allows for a consideration of their sensitive approach as a valuable tool to tackle contemporary challenges. In addition, this acknowledgement positions plants within the category of smart or becoming materials that "come to be or become, only over time and in context", representing sensitiveness in relation to circumstances (Bergström et al. 2010).

Another noteworthy aspect of this analysis is the unpredictability of bio-based and growing materials, typically characterised by randomness, mutability and non-programmability (Parisi and Rognoli 2016). While these attributes and the limited lifespan of garments could be a downside of this project, they actually make materials the "bearer of uniqueness and exclusivity" (Parisi and Rognoli 2016, p. 81). Thus, the imperfection of Living and Growing Design products must be considered a valuable element of this project. Indeed, becoming accustomed to imperfect artefacts allows users to establish long-lasting connections with them until the end of use, extending their lifecycle and appreciating their signs of ageing.

The speculative nature of the project could represent another limitation. However, it must be said that the one of growing materials represents a nascent market and further research and development are required to reach the next steps. Additionally, to become a dominant market, growing and bio-based materials require a lot of implementations, such as the creation of novel technologies and tools, the application of industrial synergies and investments by companies.

As a last point, future research directions could explore different substrates, seeds and bio-based materials to expand the range of combinations applicable to the fashion sector. Realistic exploration of the concept could lead to market-ready products. Moving beyond the DIY methods employed in the research, the production of the entire collection could be facilitated by developing tools that streamline and control the production of bio-based and living materials. For example, introducing patterns in the sowing process could yield new textile effects, and further investigation into the technical properties of plant roots could increase resistance.

6 Conclusion

This chapter addresses the global environmental impacts caused by the fashion system within the Anthropocene and Industry 4.0. The study advocates a paradigm shift by emphasising the role of materials in a circular and regenerative approach. In particular, it focuses on a specific branch of Biodesign, i.e. Growing Design, showcasing the integration of plants in design and fashion practices. Therefore, the research presents a case study that explores textiles as a medium for living and growing seeds. The speculative fashion project specifically proposes a "plantable" type of clothing where integrated plants serve as vehicles to enhance the emotional connection between Nature and the designers or customers.

Through MDD, Material Tinkering and DIY methods, the experimental journey has been illustrated through investigation activities in fashion and textile design. The study focuses on tinkering with bio-based materials containing seeds, monitoring fabrics combined with plants and, finally, performing biodegradability tests.

The results prove that the employment of bio-based materials and textiles fosters seed growth, supporting the roots' structure against movement and gravity. Furthermore, the study examines the biodegradation rate of biomaterials in contact with the soil and proves its relevance in a circular approach.

The experiments not only allowed to imagine a future-oriented fashion collection but also to create an extensive material library culminating in the *Lab Book*, an open-source handbook collecting all the activities carried out in eight months of research.

All these outcomes are crucial in two respects: on the one hand, they open up the possibility of engaging clothing, in which the garment can be worn, re-seeded and grown for several cycles, proving a symbiotic bond between user and plants; on the other hand, they demonstrate the feasibility of designing compostable fashion collections which can be disposed of in Nature at their end of life, becoming the matrix for the growth of new plants. Thus, the project reinforces a commitment to ecological consciousness and responsible consumption by appreciating plants' intelligence and unpredictability. It encapsulates a powerful message of sustainable fashion, urging individuals to embrace the transformative potential of their clothing and actively participate in the regeneration of our environment.

Finally, the chapter discusses the opportunities and potential areas for improvement that this study could offer. In light of all these considerations, the presented case study pushes the boundaries of traditional design and serves as a catalyst for a profound connection with Nature.

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References

Armstrong R (2022) Biodesign for a culture of life: of microbes, ethics, and design. In Lockton D, Lenzi S, Hekkert P, Oak A, Sádaba J, Lloyd P (eds) DRS2022: Bilbao, 25 June–3 July, Spain, pp 1–20. https://doi.org/10.21606/drs.2022.144

Ayala-Garcia C, Rognoli V, Karana E (2017) Five kingdoms of DIY materials for design. In: Karana E, Giaccardi E, Nimkulrat N, Niedderer K, Camere S (eds) Alive active adaptive: international conference on experiential knowledge and emerging materials EKSIG 2017. TU Delft OPEN Publishing, pp 222–234

Bergström J, Clark B, Frigo A, Mazé R, Redström J, Vallgårda A (2010) Becoming materials: material forms and forms of practice. Digit Creat 21(3):155–172. https://doi.org/10.1080/14626268.2010.502235

Biofabricate, Fashion for Good (2020) Understanding 'Bio' Material Innovation: a primer for the fashion industry. https://fashionforgood.com/wp-content/uploads/2020/12/Understanding-Bio-Material-Innovations-Report.pdf

Biomimicry Institute (n.d.) Our mission. https://biomimicry.org/ourmission/

Biomimicry Institute (2020) The nature of fashion: why it's time to leave petroleum behind. https://biomimicry.org/the-nature-of-fashion-why-its-time-to-leave-petroleum-behind/

Bogers L (2020) Files. https://class.textile-academy.org/2020/loes.bogers/files/presentation/

Camere S, Karana E (2017) Growing materials for product design. In: Karana E, Giaccardi E, Nimkulrat N, Niedderer K, Camere S (eds) Alive active adaptive: international conference on experiential knowledge and emerging materials EKSIG 2017. TU Delft OPEN Publishing, pp 101–115

Camere S, Karana E (2018) Fabricating materials from living organisms: an emerging design practice. J Clean Prod 186:570–584. https://doi.org/10.1016/j.jclepro.2018.03.081

Campos L (n.d.) beGrounded. https://lara-campos.com/begrounded.html

Carrete IA, Ghodrata S, Scherer D, Karana E (2022) Understanding the effects of root structure on the mechanical behaviour of engineered plant root materials. Mater Des 225. Article 111521. https://doi.org/10.1016/j.matdes.2022.111521

Clèries L, Rognoli V, Solanki S, Llorach P (2021) Material designers. Boosting talent towards circular economies—MaDe Book. All Purpose. http://materialdesigners.org/wp-content/uploads/2021/03/MaDe-Book-1.pdf
Cole RJ (2012) Transitioning from green to regenerative design. Build Res Inf 40(1):39–53. https://doi.org/10.1080/09613218.2011.610608
Collet C (2013) About. http://thisisalive.com/about/
Collet C (n.d.) Biolace. http://thisisalive.com/biolace/
Conners L (Director) (2020) The Promise of Biomimicry. Resilient design in a climate impacted world [Film]. Tree Media; Biomimicry Institute. https://biomimicry.org/the-promise-of-biomimicry/
Criado L (2016) CAROLE COLLET, exploring biomimicry, living technologies and biofacturing. Clot Magazine. https://www.clotmag.com/design/carole-collet. Last accessed 28 Jan 2023
Crutzen PJ, Stoermer EF (2000) The "Anthropocene". IGBP Global Change Newsletter, vol 41, pp 17–18. http://people.whitman.edu/~frierspr/Crutzen%20and%20Stoermer%202000%20Anthropocene%20essay.pdf
Davis C (2017). The secret of bioplastics. Issuu. https://issuu.com/nat_arc/docs/the_secrets_of_bioplastic_?epik=dj0yJnU9YTFPN2tlVDByWHhqRFFoaE1oUUUxZGg1cmdOMGg3R0cmcD0wJm49SDBtY3JBUGVQaG9wQUc2VW9fdlRWdyZ0PUFBQUFBR0ZFd0pR
DIYbio (2011) Draft DIYbio Code of Ethics. North American DIYbio Congress. https://diybio.org/codes/code-of-ethics-north-america-congress-2011/
Dunne M (2018) Bioplastic Cook Book. Issuu. https://issuu.com/nat_arc/docs/bioplastic_cook_book_3
Ellen MacArthur Foundation (2017a) A new textiles economy: redesigning fashion's future. https://ellenmacarthurfoundation.org/a-new-textiles-economy
Ellen MacArthur Foundation (2017b) The circular economy in detail. https://archive.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail
Franklin K, Till C (2018) Radical matter: rethinking materials for a sustainable future. Thames and Hudson
Giaccardi E, Karana E (2015) Foundations of materials experience: an approach for HCI. In: Proceedings of the 33rd annual ACM conference on human factors in computing systems (CHI '15). Association for Computing Machinery, New York, NY, USA, pp 2447–2456. https://doi.org/10.1145/2702123.2702337
Guarino N (2022) Lab Book—A guide for innovative materials. Issuu. https://issuu.com/niclaguarino/docs/nicla_guarino_labbook_a_guide_for_innovative_mater
Guasch Sastre C (2021) How materials can shape our future. In Clèries L, Rognoli V, Solanki S, Llorach P (eds) Material designers. Boosting talent towards circular economies—MaDe Book, pp 12–13. All Purpose
Karana E (2009) Meanings of materials, Doctoral dissertation, Delft University of Technology. TU Delft Research Repository. http://resolver.tudelft.nl/uuid:092da92d-437c-47b7-a2f1-b49c93cf2b1e
Karana E, Barati B, Giaccardi E (2020) Living artefacts: conceptualizing livingness as a material quality in everyday artefacts. Int J Des 14(3):37–53
Karana E, Barati B, Rognoli V, Zeeuw van der Laan A (2015). Material driven design (MDD): a method to design for material experiences. Int J Des 9(2):35–54
Karana E, McQuillan H, Rognoli V, Giaccardi E (2023) Living artefacts for regenerative ecologies. Res Dir: Biotechnol Des 1(16):1–10. https://doi.org/10.1017/btd.2023.10
Keune S (2018) On textile farming. Seeds as material for textile design, Master's thesis, University of Borås. DiVA—Digitala Vetenskapliga Arkivet. http://hb.diva-portal.org/smash/get/diva2:1193793/FULLTEXT02.pdf
Keune S (2021) Designing and living with organisms weaving entangled worlds as doing multispecies philosophy. J Text Des Res Prac 9(1):9–30. https://doi.org/10.1080/20511787.2021.1912897

Mancuso S (2017) The roots of the intelligence of plants [Video]. Exhibition for Kosmopolis 2017 by CCCB. https://www.cccb.org/en/multimedia/videos/stefano-mancuso/227141
Mancuso S, Viola A (2013) Verde brillante, sensibilità e intelligenza del mondo vegetale. Giunti Editore
Manzini E (1986) The material of invention. Arcadia SRL
Materiom (n.d.) Materials library. https://materiom.org/search
McDonough W, Braungart M (2002) Cradle to cradle: remaking the way we make things. North Point Press
Mironov V, Trusk T, Kasyanov V, Little S, Swaja R, Markwald R (2009) Biofabrication: a 21st century manufacturing paradigm. Biofabrication 1(2). https://doi.org/10.1088/1758-5082/1/2/022001
Moretto A, Macchion L, Lion A, Caniato F, Danese P, Vinelli A (2018) Designing a roadmap towards a sustainable supply chain: a focus on the fashion industry. J Clean Prod 193:169–184. https://doi.org/10.1016/j.jclepro.2018.04.273
Myers N (2021) How to grow liveable worlds: Ten (not-so-easy) steps for life in the Planthroposcene. ABC's Religion and Ethics. https://www.abc.net.au/religion/natasha-myers-how-to-grow-liveable-worlds:-ten-not-so-easy-step/11906548
Myers W (2012) BioDesign. Nature, science, creativity. Thames and Hudson
Olmedo J (n.d.) Your land is Our land. https://www.jacobolmedo.com/one
Parisi S, Rognoli V (2016) Superfici Imperfette. In Acocella A, Dal Buono V, Scodeller D (eds) MD Journal. Involucri sensibili. Integumentary design, Università di Ferrara, pp 78–91. https://materialdesign.it/media/formato2/allegati_5814.pdf
Parisi S, Rognoli V, Sonneveld M (2017) Material tinkering. An inspirational approach for experiential learning and envisioning in product design education. Des J 20. https://doi.org/10.1080/14606925.2017.1353059
Parsons School of Design (n.d.) 2017 Jacob Olmedo. https://parsons.edu/bfafashion/jacob-olmedo/
Pinto R, Carvalhais M, Atkinson P (2013) Generative designing with biological systems—searching for production tools aimed at individualization. Proceedings of the 10th European Academy of Design Conference, Gothenburg, University of Gothenburg. European Academy of Design. https://shura.shu.ac.uk/8084/
Ribeaux T (n.d.) Bioplastic cookbook for ritual healing from petrochemical landscapes. http://bioplastic-cookbook.schloss-post.com/
Rognoli V, Parisi S (2021) Material Tinkering and Creativity. In: Clèries L, Rognoli V, Solanki S, Llorach P (eds) Material designers. Boosting talent towards circular economies—MaDe Book, pp 20–26. All Purpose
Rognoli V, Ayala-Garcia C, Pollini B (2021) DIY recipes: ingredients, processes and materials qualities. In Clèries L, Rognoli V, Solanki S, Llorach P (eds) Material designers. Boosting talent towards circular economies—MaDe Book, pp 27–33
Rognoli V, Petreca B, Pollini B, Saito C (2022) Materials biography as a tool for designers' exploration of bio-based and bio-fabricated materials for the sustainable fashion industry. Sustain Sci Pract Policy 18(1):749–772. https://doi.org/10.1080/15487733.2022.2124740
Schaedler AC (n.d.) Growing garments. https://www.anoukchristel.com/growinggarments
Scherer D (n.d.) About/CV. https://dianascherer.nl/about/
Schwab K (2016) The fourth industrial revolution. World Economic Forum
Ulargui Escalona P (n.d.) Symbiotic nature. https://paulaularguiescalona.com/NATURALEZA-SIMBIOTICA
van den Broek S, de Rooij A, van Dartel M (2022) Living with living artefacts: Six concepts for designing user acceptance of living artefacts. 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.2022.261
Vert M, Doi Y, Hellwich K, Hess M, Hodge P, Kubisa P, Rinaudo M, Schué F (2012) Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). Pure Appl Chem 84(2):377–410. https://doi.org/10.1351/PAC-REC-10-12-04

Victoria and Albert Museum (n.d.) Fashioned from Nature—Exhibition at South Kensington—V&A. https://www.vam.ac.uk/exhibitions/fashioned-from-nature

WGSN (2021) Macro forecast—future innovations 2022. https://www.wgsn.com/en

Wilson EO (1984) Biophilia. Harvard University Press

Zhou J (2019) INTERWOVEN: designing biodigital objects with plant roots, Master's thesis, Delft University of Technology. TU Delft Education Repository. http://resolver.tudelft.nl/uuid:ffdcf947-06df-4941-a587-bdf008f87783

Zhou J, Barati B, Wu J, Scherer D, Karana E (2020) Digital biofabrication to realize the potentials of plant roots for product design. Bio-Design and Manufacturing. 4:111–122. https://doi.org/10.1007/s42242-020-00088-2