How can Bio-Strategies Inform Design for Sustainability?

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Abstract
This study presents a Nature-based Design project developed using Bio-strategies. Biophilia, Biomimicry and Biotechnology were used to explore seaweed-based materials for reusable food packaging. Biophilia is employed to evoke empathy towards Nature and embrace its natural aesthetics. Biomimicry serves as inspiration for a structure's resilience, hydrophobic properties, and overall system and design. Biotechnology contributes to the development of products and materials derived from renewable biological sources. The expected contributions lie in the realm of design development methods that address the product's circular economy and environmental impact. To create seaweed-based bio-plastic films and bio-yarns, a process was employed using sodium alginate ($NaC_6H_7O_6$) and calcium chloride ($CaCl_2$). The process involved different procedures: Firstly, the sodium alginate hydrogel was prepared by gelification, followed by hydrogel polymerisation using a calcium chloride solution. Moulding and extrusion techniques were employed to produce sodium-alginate bio-based materials. Additionally, commercial natural fibres such as seaweed yarn and thread, linen thread, and sugar cane yarn, were coated with sodium-alginate bio-plastic using both bath and brush methods. The resulting bio-coated threads and yarns were knitted using knitting needles and a round plastic loom. Furthermore, Rhino 6 was used for technical drawings and LaserWorks for the laser cutting to create 3D Design. A plywood 3D loom was developed to fabricate a grocery bag inspired by a spider web biosystem. The results of this study demonstrate the relevance of designing with Bio-strategies in the context of the circular economy, facilitating the development of bio-based and biodegradable materials.

Keywords: Bio-Strategies, Nature-Based Design, Packaging Design, Seaweed-Based Materials

Introduction

Plastics have many applications, spanning the array of the material's physico-chemical properties, with fast and relatively inexpensive production. However, plastics are overused, ineffectively recycled and largely non-biodegradable, resulting in environmental complications (Wang et al., 2020). Marine plastic pollution presents ecological, economic and health hazards: plastic waste pressures marine life through suffocation, intake and absorption; during disintegration, plastic creates micro and nano-plastics contaminating fresh water and marine fauna (Stasiškienė et al., 2022). Related to these impacts, the textile industry was identified as the most chemical-intensive and the second largest water polluter after agriculture (Kumari et al., 2013).

Considering the Sustainable Development Goals 2030 Agenda (Brundtland Report, 1987; Desa, 2016) and the Green Deal (European Commission, 2021), plus the challenging factors mentioned above, significant changes must occur in the textile and packaging industries (Ellen MacArthur Foundation, 2017; Sandin & Peters, 2018). All disposable plastic negatively affects the environment, resulting in high levels of toxicity to all ecosystems through, for instance, microplastics found in the marine context and even in our food chain (O'Donovan et al., 2018).

Recent studies on plastic pollution's effects on humans have already confirmed the presence of microplastics in human blood (Leslie et al., 2022) and breastmilk (Ragusa et al., 2022).

Plastic pollution and textile waste concerns led this project to use seaweed-based materials from brown algae (i.e., with sodium alginate). As a renewable resource, seaweed may be related to sustainable practices of a resource's exploitation and presents an opportunity to be explored within the design field. Bio-based plastics made with sodium alginate are waterproof, biodegradable and compostable (Hoogvliet, 2017), therefore presenting interesting properties for various applications, including packaging. Within the packaging field, these types of materials have immense potential to replace single-use plastics (e.g., beverage and food packaging, low-density plastic films and shopping bags, plastic-foam containers). However, despite having several advantages (such as low cost, ease of production, tensile strength and durability, hydrophobia, flexibility and plasticity), single-use packaging products decrease in value immediately after purchase (Haffmans et al., 2018) and are often discarded with no option to be reused (Bocken et al., 2016).

In addition to confronting the health hazards presented by plastics, the packaging design industry is going through an environmental, economic and social crisis while transitioning to a circular mindset and systems. Additionally, reusing or collecting and recycling these items often presents many challenges. (Dahlbo et al., 2018; Singh & Cooper, 2017). The literature reviewed identifies further issues:

- Plastic consumption quadrupled in the past 30 years and will reach 460 million tonnes in 2019. Only 9% of plastic waste was recycled, while 19% was incinerated, 50% went to landfills and 22% was lost on terrestrial and aquatic environments. Of this plastic waste, 40% is from packaging and 11% from textiles (OECD, 2022).
- From the seven groups of plastics identification, *only two are easy to recycle* if effectively collected, separated and transported to recycling facilities: PET (polyethylene terephthalate) used in beverage and food bottles and lids, and HDPE (High-density polyethylene) used for snack boxes and milk jugs. In contrast, LDPE

(low-density polyethylene) used in plastic film and shopping bags, and PP (polypropylene) used in drinking straws, insulated coolers, bottle tops, are only consider part manageable. PS (polystyrene) used in plastic-foam cups and containers, PVC (polyvinyl chloride) and 'others' (the 7th category), such as those used for baby bottles and watercooler bottles, are difficult to recycle and often discarded (MikaCycle, 2022).

- *Recycling reduces waste by consuming other resources* (e.g., energy, transportation, water, chemicals),(Cooper, 1994). Design must consider a circular economy and consumers' behaviour change (Wastling et al., 2018).
- Moreover, plastic disintegration in the environment—by sun, oxygenation or microorganisms—creates plastic fragments (i.e., micro- and nano-plastics) and toxic chemicals (Dahlbo et al., 2018; Singh & Cooper, 2017).
- *Non-reusable paper bags* require a lot of resources (i.e., water and energy, raw materials and chemicals) (Braungart & McDonough, 2014; Leonard, 2010).
- Furthermore, *biodegradable plastics* have a short shelf life and are not recognised on recycling separation lines. They are considered wasted as a resource, and end up in landfills or incinerated (Leonard, 2010).

Considering these issues, this work explores methods for producing bio-based materials from renewable sustainable sources to create packaging's for bulk food shopping. The overall system intends to be zero-waste, hydrophobic, food safe, sustainable, home-compostable and, importantly, reusable. In addition, design and aesthetic values have been considered to promote the consumer behaviour.

To this end, solutions must be created, and methodologies explored to achieve different mindsets and alternatives.

Selected Bio-Strategies

Bio-strategies were embraced to inform the design methodology, approaching Nature-based solutions. Nature-based solutions inspire designs through empathy, observation, mimicry and collaboration with Nature (Macnab, 2012). The process can be achieved using different Bio-strategies, namely:

- The *Biophilia Hypothesis* was first presented by E.O. Wilson (1984) as "*the innate human need for contact with a diversity of life forms*" (Wilson, 1984). Keller and Wilson (1993) developed the thesis that a biophilia revolution, encompassing organic life and rational calculations, results in a more efficient and sustainable lifeway, mitigating environmental crisis and species extinctions while improving life quality (Kellert & O. Wilson, 1993).
- *Biomimicry* researches Nature's examples, whether in biological structures and their strategies or functions (Benyus, 2008). It approaches projects by developing nature-based solutions, modelled after organisms and ecosystems (Uchiyama et al., 2020). This methodology offers solutions for design, architecture and engineering problems by mimicking organic characteristics and practices (Chen & Lee, 2017).
- *Biotechnology* fabricates new products using biological systems, resorting to natural constructions and their manipulation (Ferraro & Pasold, 2020), enabling opportunities for design and manufacturing of products by fabrication with living organisms (e.g., fungi, bacteria) (Camere & Karana, 2018).

Moreover, two holistic methodologies were identified in the literature as a reference for educational purposes and relating to sustainable design processes: Ruano's (2016) thesis *Symbiotic Design Practice* and Monteiro-De-Barros's (2011) thesis on *Creating sustainability using explorative dialogues respecting Biosphere boundaries* (Ruano, 2016; Monteiro-De-Barros, 2011). Both included the *Biophilia hypothesis* and Biomimicry, but Biotechnology was not considered in the design development. More recently, Kanwal & Awan, (2021) add the *Eco-philic design thinking* in the creative approach using biophysics and biomimicry to solve natural and human problems, achieved by developing solutions that promote sustainability and human wellbeing. *Eco-philic design thinking* introduces the collaboration of Biophilia, Biomimicry and Biophysics to design products with environmental benefits, by seeking and analyse natural patterns and shapes.

Overall, when considering the current limitations on packaging recycling, as well as plastics' toxicity and its effects on humans and marine eco-systems, Biophilia, Biomimicry and Biotechnology were identified as main essential strategies to design development for sustainability.

Materials and Methods

This study utilised different household and Fab Lab materials: a plastic circular loom; pots; blending mixers; precision scale; moulds; glass jars with lids; sprayer; plastic colanders and funnels; spoons; 150ml syringe; electric kettle and stove. All other specific materials used are described as follows:

For the bio-plastics and bio-films: sodium alginate (NaC6H7O6 [E401], Unique Products®—Netherlands (made from different brown seaweeds [i.e., Fucus, Laminaria, and Macrocystis genera). Seaweed thread (100% Sud African seaweed), Bart & Francis—Belgium. Sugar cane yarn and Linen thread, Rorários4®—Portugal.

Several chemical reagents used in the procedures were: calcium chloride ($CaCl_2$, 94-97% [E509], Arsegan®), glycerine; sunflower oil, tap and demineralised water; natural food colours and spirulina powder.

For the 3D loom: Rhino 6 and LaserWorks software; 5mm plywood board; stainless steel screws, BRM-Lasers laser-cut machine; hand screwdriver. The alginate bio-plastics fabrications (i.e., bio-film, bio-yarn) followed gelification (Gulrez et al., 2011; Dianursanti et al., 2018) and gelation (van der Linden & Foegeding, 2009) procedures.

In addition, different procedures and techniques were used in the materials design and fabrication to achieve the following materials:

1. *For the Bio-Films (see Fig. 1. #1):*
   1.1. Gelification—preparation of hydrogel: with an electric blender, the plasticisers (i.e., sodium alginate [C = 60 g/L], glycerine [C = 100 g/L], sunflower oil [C=50 g/L]), were mixed with tap water (vehicle), half a part was coloured with drops of food pigment (green and blue), the other half stayed uncoloured; hydrogels rested twelve hours (to release air bubbles).
   1.2. Gelation and drying—moulding and curing the hydrogel casting into a Petri dish sprayed with a 10% $CaCl_2$ hydrate before and after casting; the bio-films rested to dry in the air at room temperature for two weeks.

2. *For the Bio-Yarns (see Fig. 1. #2):*
    2.1. Gelification—preparation of hydrogel as in 1.1. with food colours.
    2.2. Gelation and drying—extrusion and curing with a syringe into the 10% $CaCl_2$ hydrate for 1min. The resulted bio-yarns were washed in tap water and extended on a horizontal plastic surface to dry at room temperature for two weeks.
    2.3. Finishing—the bio-yarn was knitted using 5mm knitting needles, creating samples.

3. *For the Bio-Coated yarn (see Fig. 1. #3):*
    3.1. Gelification—following process as in 1.1; some samples used natural-based colours (i.e., clementines dye).
    3.2. Coating bath and gelation—the yarn was immersed in the bio-plastic hydrogel, removed, and bathed in a 10% $CaCl_2$ for 1min and washed with tap water. Next, it was extended on a horizontal plastic surface to dry for one week in the air at room temperature.
    3.3. Finishing—the bio-coated yarn was knitted using 5mm knitting needles, creating a mesh bag.

4. *For Bio-Coated mesh and bags (see Fig. 1. #4)*:
    4.1. *Gelification*—following process as in 1.1, without pigments.
        4.1.1. Coating bath—loom knitting, coating bath and gelation— the yarn was knitted in a plastic loom creating a mesh, and immersed in the bio-plastic hydrogel, removed, and cured in a 10% $CaCl_2$ hydrate bath for 1min and removed to dry.
        4.1.2. Brush coating—loom knitting, brush coating and gelation—after knitting the yarn in the plastic loom and the 3D plywood loom, a bio-plastic coat was applied with a brush and sprayed with a 10% $CaCl_2$ hydrate.
    4.2. Finishing—the pins were removed from the plastic loom and the mesh was removed. The screws were unscrewed from the 3D loom releasing the funnel-bag. In addition, a string was attached to close the bag.

5. *For 3D loom (see Fig 8.):*
    5.1. Design—draft measures in paper and design technical drawings using Rhino 7. The file was exported as a .dxt file.
    5.2. Laser cut—a material sample was tested to choose the laser cut parameters for 5mm plywood. The best result in the BRM-Lasers laser-cut machine was identified at speed 60**,** power 25**,** corner 20.
    5.3. Assembling—the boards were assembled and the screws hand-screwed.

Results

The materials fabrication followed a procedures flow resulting in different final products: the use of equal alginate hydrogel base and $CaCl_2$ hydrate allowed the reuse of leftovers to create more studies and samples, as described in Figure 1.

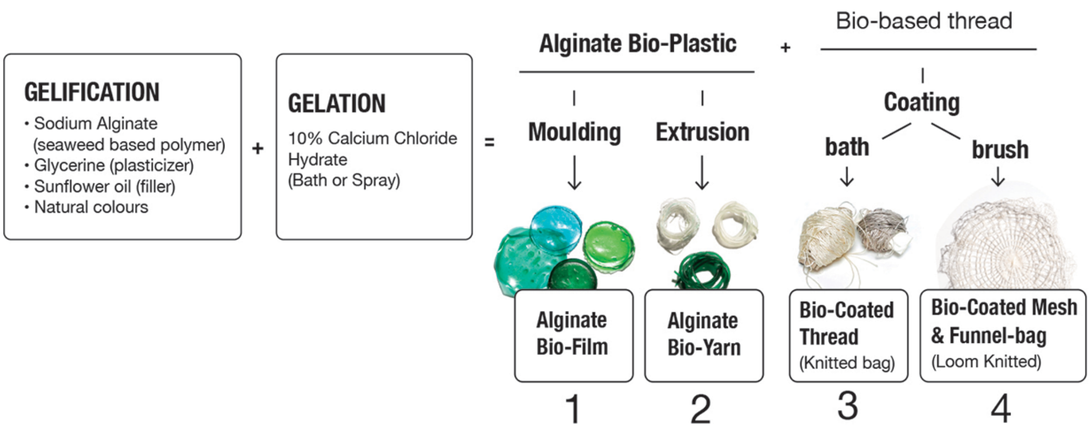

Figure 1: **Procedures flow diagram**, by author

Approaching Nature-based solutions by feeling, caring, observing, mimicking and with Nature resources, and applying the Bio-strategies resulted in different food packaging designs and materials samples. Firstly, Biophilia was used to engage with Nature, exploring empathy and aesthetics. Secondly, Biomimicry contributed to developing the materials inspired by spider silk and a web structure's resilience, hydrophobic qualities and overall system and design. Finally, Biotechnology contributed to developing materials and packaging from renewable biological sources (i.e., seaweed-based bio-films, bio-yarns, bio-coated yarn, and bio-coated threads). In this order, the Bio-strategies—Biophilia, Biomimicry and Biotechnology—were used to inform the Design process by promoting and supporting three main phases: exploration, ideation and fabrication, as described in the diagram in Figure 2.

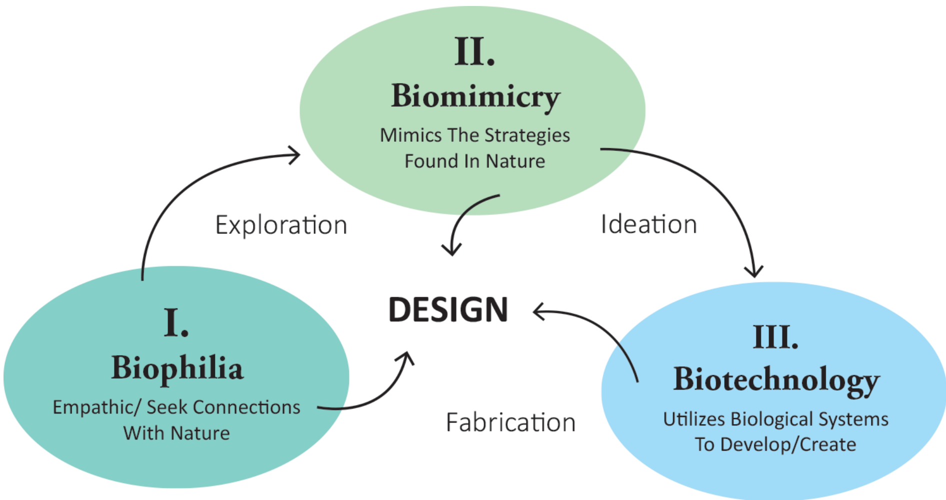

Figure 2: **Bio-strategies Diagram**, by authors

Following the procedures described earlier in Fig. 1—moulding, extrusion and coating techniques—resulted in the first samples: bio-films, bio-yarns and bio-coated threads, as presented on Fig. 3. a), b) and c).

Figure 3. **Procedures Experiments** – a) alginate Bio-films; b) alginate Bio-yarns; c) bio-coated seaweed thread, from authors, photos by Luís Silva Campos

These samples introduced the fabrication of the final materials. The procedure described in Fig. 1. step 1—moulding, alginate bio-plastic with food colour—was cast into a mould previously sprayed with a 10% $CaCl_2$ solution to create textured bio-film. This resulted in an ocean-inspired hydrophobic bio-film, safe for wrapping (see Fig. 4).

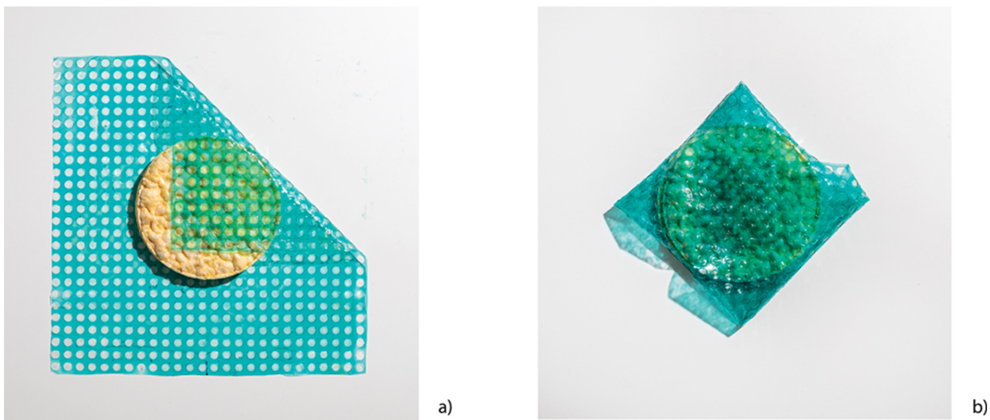

Figure 4. a), b): **Alginate bio-film**, from authors, photos by Luís Silva Campos

In the procedure indicated in Fig. 1. step 2—extrusion—after extruding, the bio-yarns were washed with tap water and left to dry, then knitted. The experiments resulted in different coloured bio-yarns knitted into sturdy mesh, as shown in Figure 5.

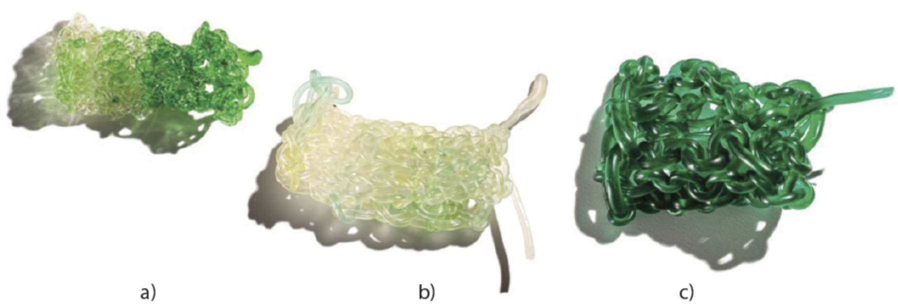

Figure 5. a), b): **Alginate bio-yarns**, from authors, photos by Luís Silva Campos

Following Procedure 3 (see Fig. 1, step 3), a sugar-cane yarn was loom-knitted and bio-coated, creating a protective wrapping Bio-mesh (see Fig. 6).

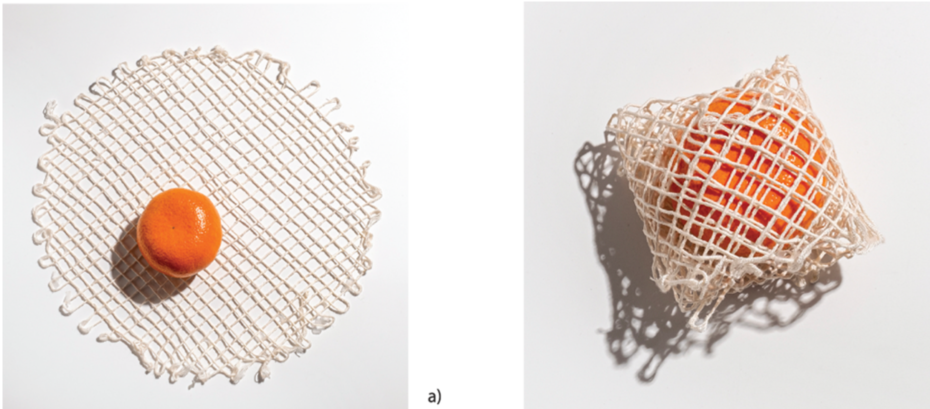

Figure 6. **Alginate Bio-net with sugar-cane thread:** a) open mesh with clementine, b) closed mesh with clementine, photos by Luís Silva Campos

Following procedure 4, a commercial linen-thread loom-knitted as a spider web was coated with a brush resulting in a Bio-net bag (see Fig. 7).

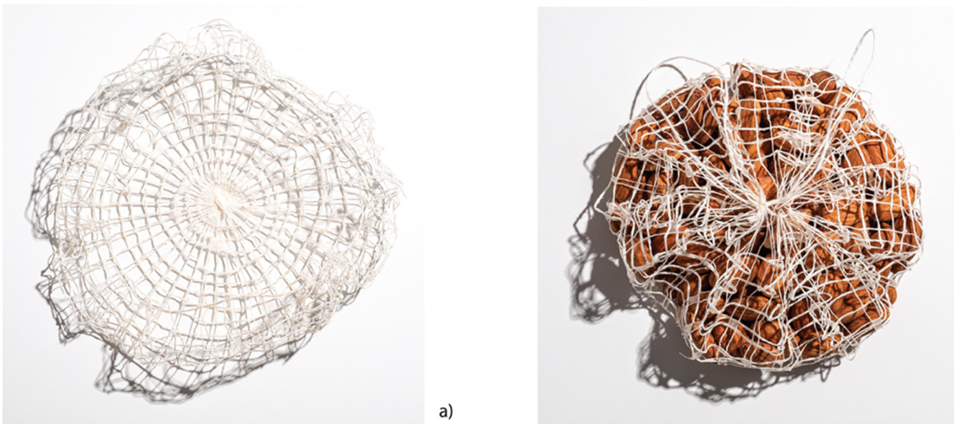

Figure 7. **Alginate Bio-net with linen-thread:** a) open and empty bag, b) closed bag with almonds, from authors, photos by Luís Silva Campos

By repeating Procedure 3, a commercial seaweed-yarn was coated by bath with alginate bio-plastic. The bio-coated yarn was removed and immersed in a 10% $CaCl_2$ hydrate solution. After being washed in tap water and dried, the bio-coated yarn was then knitted. The result was a seaweed-based food-safe mesh bag, shown in Figure 8.

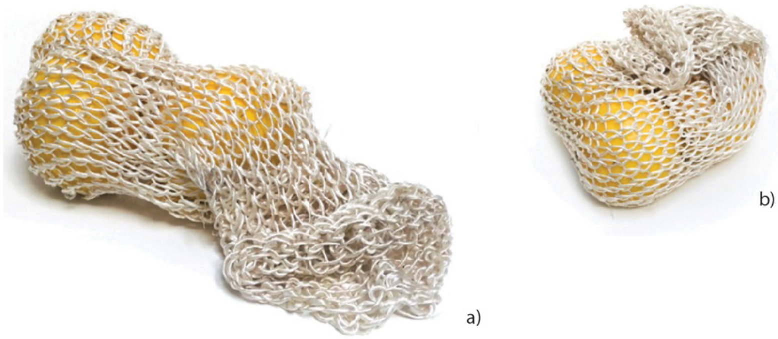

Figure 8. **Knitted bio-coated seaweed-yarn**: a) open mesh bag with lemons, b) closed mesh bag, from authors, photos by Luís Silva Campos

As described in Materials and Methods—Procedure 5 (*For 3D loom)*, a 3D loom was created to develop a grocery bag inspired by a spider's funnel-web (see Fig. 9).

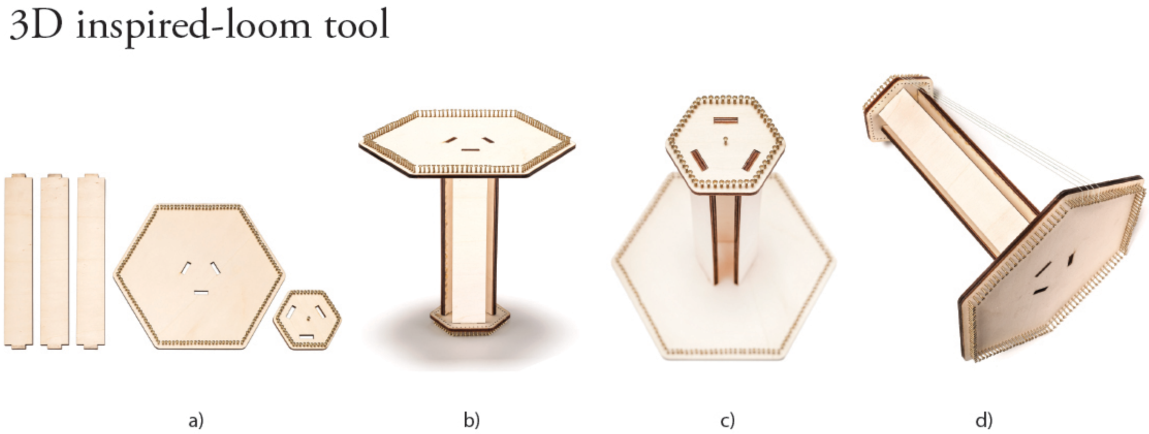

Figure 9. **3D loom boards and assembled views**: a) disassembled boards, b) base view, c) top view, d) weaving seaweed-thread sample, from authors, photos by Luís Silva Campos

Following Procedure 4 (see Fig. 1, step 4), two spiderweb-inspired bags were weaved and coated using the developed novel 3D loom tool. The first one was coated with alginate bio-plastic with clementine dye. The result was a light orange funnel-web bag (see Fig. 10).

A second bag was made following the same procedure but coated without a dye. On top a thread was woven to create a drawstring. The result was a white closable spider's funnel-web bag (see Fig. 11).

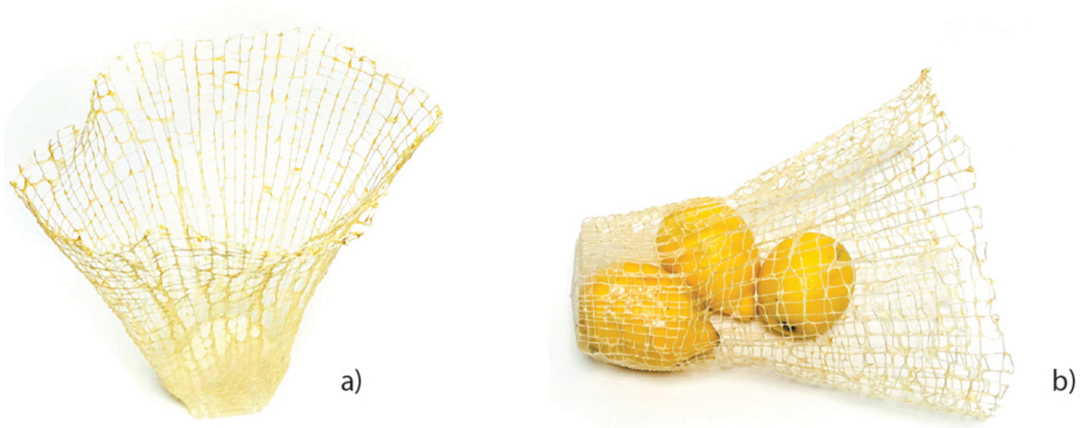

Figure 10. **Spider's funnel-web bag with clementines dye:** a) empty bag, b) testing bag structure with approx. 0,5 kg of lemons, photo by authors

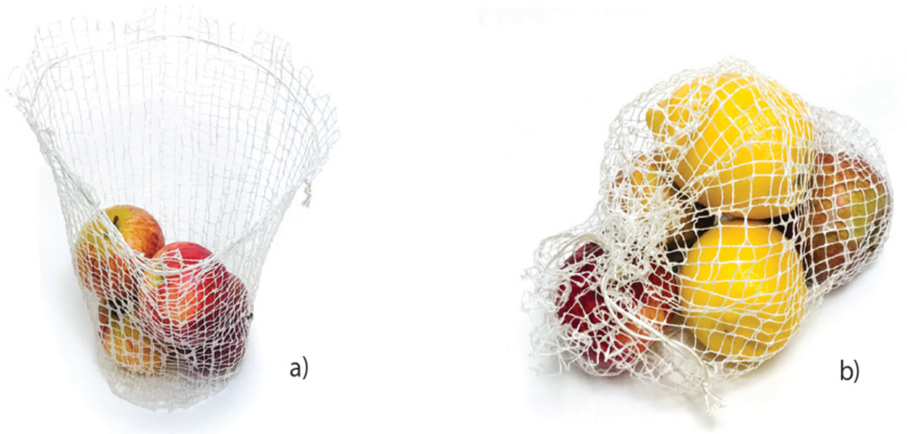

Figure. 11. **Spider's funnel-web bag without colour dye:** a) open bag with approx. 0,5 kg of apples, b) testing bag structure with approx. 1 kg of apples and lemons, photo by authors.

Discussion

Following a sustainable design process, this work was based on holistic approaches identified in the literature. Different methodologies were used as references and three strategies were identified as essential, and therefore applied during the creative process of this specific project: Biophilia to engage with Nature dynamics and aesthetics; Biomimicry to ideate materials inspired in spiders' silk and web structures; and Biotechnology to develop sustainable bio-based materials and products from renewable sources.

This study resulted in the following observations:

1. The wrapping bio-film was water resistant and reusable, and fast material degradation was observed, confirming the easy degradation, and suggesting home compostability.
2. The fabricated bio-yarns showed fragility and fast biodegradation points. Therefore, obtained samples were not considered as ideal materials for reusable shopping bags.
3. By observation, the bath bio-coated knitted seaweed yarn showed more resistance when compared to the fabricated bio-yarn. However, the resulted mesh bag showed some bio-plastic peeling. This result suggests different hypothesis: the fibres did not impregnate completely and needed more immersion time in the bio-plastic bath; improper or weak handling of the fibres during the bio-coating procedure; poor adhesion between materials (i.e., commercial seaweed yarn and alginate bio-plastic).
4. Both bio-coated methods were successfully applied in the plastic loom and the 3D plywood loom and remained hydrophobic and resistant to weight. Nevertheless, when comparing the needle-knitted mesh bag (see Fig. 8) and the loom-knitted net and bags (see Figs. 6,7, 10 and 11), a major difference was observed: the yarn washed after polymerization showed bio-plastic peeling, and the others didn't. This suggests that the water bath stops curing and adhesion between materials, and removing this step improves the product result.
5. The 3D spiderweb-inspired loom successfully allowed the creation of funnel-web bags. Considering the reuse and longer use life of the 3D loom-tool, plywood boards would be improved with a varnish coat, protecting from gelation materials. Another option to consider is changing the plywood with leftover 5mm acrylic laser-cut boards. This would also contribute to a water-resistant loom, although this was not the first choice, considering category seven for recycling (i.e., *Other polymers*, extremely difficult to recycle).

Conclusion

This work questions how Bio-strategies can inform Design for Sustainability.

The limitations of existing packaging recycling, the toxicity of plastics, and the environmental crisis—with its effects on humans and marine eco-systems—triggered and directed the project to select and test Bio-strategies in a way that highly informs the creative process towards a Design for Sustainability mindset. This work aims to inspire others to ideate and explore materials fabrication.

During the creative process, several strategies were employed to enhance products' sustainable and circular design. The literature review identified methodologies for educational purposes and Sustainable design processes: Ruano (2016) *Symbiotic Design Practice*, Monteiro-De-Barros (2011) *Creating sustainability using explorative dialogues respecting Biosphere boundaries* and more recently, Kanwal & Awan (2021) *Eco-philic design thinking*, among others. These approaches emphasize a holistic perspective in designing for sustainability and transition. Considering this, three Bio-strategies were identified as essential by supporting three main development phases: exploration, ideation and fabrication. Therefore, were applied during the creative process of this specific project the following: *Biophilia* to engage with Nature dynamics and aesthetics; *Biomimicry* to ideate materials inspired in spiders' silk and web structures; and *Biotechnology* to develop sustainable bio-based materials and products from seaweed—a carbon-negative and renewable biological matter.

The study successfully embraced the Bio-strategies to develop ecologically aware materials for grocery shopping (i.e., zero-waste, reusable, hydrophobic, food safe, sustainable, and home-compostable). These strategies offer alternative approaches within the design field, with biology as a framework, providing versatility as evidenced by the range of results presented. The Bio-strategies were tested using commercial natural fibres and seaweed-based bio-plastic to incorporate biological principles into the design.

The results demonstrate the relevancy and potential of using Bio-strategies to inform designing for sustainability, by achieving biodegradable and easily compostable materials and packaging from renewable biological sources (i.e., seaweed-based bio-films, bio-yarns, bio-coated yarn, and bio-coated threads). In addition, a plywood 3D loom-tool was developed to fabricate a grocery bag inspired by a spiderweb biosystem. This work has contributed to the successful development of eco-effective bio-based materials through multiple processes, outcomes, and new materials and products.

The expected contributions of this study lie in design education and in assisting designers seeking alternative and safe methods for creating goods. For future studies, our results suggest experiments to further investigate other properties of these materials, such as materiality, product longevity and user acceptance.

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