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15th International Conference of the European Academy of Design
ONLINE and in **PERSON** in **Brazil**, **Finland**, **India**, **Spain** and the **UK**.
16-20 October 2023

Bio-based materials from Po River organic waste: a Do It Yourself design.

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Freshwater ecosystems are increasingly affected by the raise of temperatures in urban areas that causes the proliferation of invasive aquatic vegetation, such as the case of *Elodea nuttalii* in the Po River in Turin (Italy). Mechanical eradication is the most efficient method of environmental control, but it produces large amounts of plant biomass treated as organic waste. This study focuses on investigating opportunities to use aquatic plant biomass as raw material to produce bio-based materials to move towards the replacement of fossil-based plastics. A preliminary analysis led to develop almost 31 procedures and the study was performed in laboratory by Do-It-Yourself approach as method to explore potentialities offered by aquatic plant biomass. Material Tinkering was then adopted as method to preliminary evaluate samples of bio-based materials. Some samples showed promising characteristics and properties that suggest interesting real-scale applications in the perspective of circular economy such as in footwear industry.

Keywords: Aquatic vegetation, Bio-based elastomer, Freshwater ecosystem, Circular Economy, Material upcycling

1. Introduction

The discovery of fossil-based plastics over 100 years ago revolutionized the production of low-cost, durable, and disposable items (Nielsen et al., 2020), but nowadays they cause critical environmental impacts that need to be addressed. Plastics durability and extremely low degradation rate cause environmental pollution which is difficult to contrast. This mismanagement of plastic materials is a huge critical issue and threat to both natural ecosystems and human health. Plastics release chemicals and toxins into the environment, and microplastics which affect ecosystems and human health. Plastics account for 82% of the total waste in European oceans, and up to date 30 million tons of plastics float in the oceans worldwide. Sustainable consumption and production developed in the circular economy framework are promoted to achieve the transition to a greener and socially inclusive global economy that also includes the reduction of the use of fossil-based plastics. The market of recycled plastics was increased by increasing the percentage of second raw materials re-injected into the production process, and increasing attention focuses on new bio-based materials obtained by organic waste and by-products (OECD, 2022).

Bioplastics are promising in reducing environmental impact, accounting for about 1% of the 368 million and more tons of plastic produced annually (European Bioplastics, 2019). Circular economy aims to maintain products, components, and materials at their maximum utility and value over the time, and it is effective to address this complex issue of pollution, connected to the issues of global warming, water quality and environmental conservation. In this perspective, the concept of waste and by-products shifted from being a burden that needs to be disposed of, to an asset that can be used to give a second life as bio-based materials. Bio-based materials derive from biomass and they are renewable, biodegradable and compostable. Moreover, they represent a potential replacement for fossil-based plastics due to their sustainable characteristics. Biomaterials imply fewer greenhouse gas emissions compared to the production of fossil-based plastics, aligning with the zero-carbon goals set by many national and international legislation (Venâncio et al., 2022).

The study focuses on the Po River in the urban area of Turin that is stressed by many environmental pressures due to climate change. In recent years, this freshwater ecosystem is affected by the proliferation of *Elodea nuttallii*, also known as "alien algae”, an invasive and fast-growing aquatic plant of Northern America origin. The raise of temperatures in urban areas and prolonged lack of rainfall create perfect conditions for *Elodea nuttallii* proliferation. Moreover, it can grow in adverse environments such as low light and nutrient-poor conditions. This aquatic plant is highly invasive, and it can transform the ecosystem, obstruct drainage channels, hinder navigation and aggregate into dense mats of vegetation which reduce the amount of light and oxygen available for other aquatic living organisms. Currently, the environmental control consists of manual eradication of *Elodea nuttallii* that produces large amount of biomass per year that it is collected and disposed as special organic waste to avoid dispersion in surrounding areas.

1.1 Research goal

This article investigates the opportunity to enhance aquatic plant biomass as valuable raw material to produce bio-based materials. The study was performed through the Do-It-Yourself (DIY) approach to explore the opportunity to use river fronds as filler for bio-based material by mixing them with other bio-based components. Different samples of aquatic biomass-based material were designed and produced to test varied mechanical properties and characteristic of durability. The aim is to obtain a biodegradable rubber-like materialthat can be used for flip flops. Samples properties were preliminary evaluated using Material Tinkering method (Parisi et al., 2017), which adopts direct manipulation as tool of testing. This method was adopted by Karana et al. (2018) at the University of Technology in Delft to develop and test the “Second Skin” research project, a mycelium-based packaging for wine bottles. Material Tinkering method led to observe that not all substrates are suitable for mycelium growth and that growth rate and density vary according to fungal species. Sheets of material description were also prepared to perform Material Tinkering using suggestions for sensory testing scale presented by Karana et al. (2009). This approach looks to reduce the production of plastic waste and to move towards a circular economy approach. Furthermore, this study contributes to the growing interest in the use of bio-based materials as a sustainable alternative to fossil-based plastics and to highlight the potential of reusing waste as secondary raw material.

2. DIY in Material Design

The DIY movement started with product design and then moved towards material design (Brownell, 2015). The DIY approach in material design involves a hands-on, experimental approach to create new materials. This method differs from traditional scientific and theoretical methods because it is based on a more iterative and exploratory approach. Moreover, it emphasizes the importance of exploring new materials and experimenting with combinations of different raw materials. DIY approach focuses on creating materials through trial and error, test and iteration until the desired properties are achieved. Therefore, this method is undoubtedly characterized by randomness, especially in preliminary experiments, yet there is a certain intention in the initial choice of raw materials with which the experiment will be carried out, and in the selection of precise characteristics to aim it. In DIY materials research, the designer implements variations on the starting ingredients, toward one of the best possible solutions (Rognoli et al., 2015). During initial experimental phase, material development is based on choices according to the data collected from the samples. Then, through categorization and data analysis, it is possible to modify the starting recipe, narrowing it down to better solutions. Also, the errors are very important to consider, because they represent important data to be analysed and included in subsequent material testing. The error can often lead to the discovery of new results and materials not expected at the beginning of experiments.

This method of material design generally involves common everyday materials found in the home or experimenting with ingredients that are not typically used in manufacturing processes. One example of the DIY approach in material design is the use of bio-based components as ingredients of everyday life, such as coffee grounds or eggshells. By exploring the properties of these natural materials and combining them with others, such as biopolymers or natural fibres, new materials can be created. DIY material design can also involve waste materials as main ingredients, such as industrial byproducts, thus applying circular economy concepts, reducing the amount of waste generated and promoting sustainability (Karana et al., 2015). By reusing materials that would otherwise be disposed of, DIY designers can reduce the demand for new raw materials and the environmental impact of production (Wastling et al., 2018). Moreover, when bio-based resources are used, it is possible to create new materials and products that can be easily recycled or disposed of at the end of their lifecycle. The DIY material design approach can be a ground-breaking tool for promoting circular economy and sustainability, encouraging resource efficiency and the use of secondary raw materials obtained by waste of by-products (Rognoli & Ayala Garcia, 2019).

DIY materials are generally low-cost and they can be self-produced safely at home. They can be completely new materials or modified versions of existing ones (Rognoli et al., 2015). Their production processes and tools are usually low-tech and accessible, while their aesthetic characteristics can be associated with a very handcrafted and imperfect appearance. This kind of process promotes innovation and creativity in the field of material science, and in the creation of DIY materials, design skills are influenced through "learning by doing" and "learning by interacting" processes (Comino et al., 2021).

2.1 Significant case studies of DIY materials

With the development of the internet and social media, DIY has become increasingly popular and open source so that people can experiment and design projects inspired by others (Sarpong et al., 2020).

After analysing the world of DIY materials in general, the investigation focused on vegetation-based materials. The collection of data after this research made it possible to draw up a list of ingredients and tools that would later be useful in the production of our material from aquatic vegetation waste. Almost fifty case studies were analysed, of which the eight most significant are listed in *Table 1*. These case studies provide real-life examples of successful products created through a DIY approach, ranging from furniture products to fashion products, packaging or objects for everyday life consumption.

Table 1. Bio-based materials from organic resources.

Project	Year	Designers	Main ingredients	Characteristics
SEAcell	2007	Smartfiber	Seaweed in powder form, water and cellulose pulp	It uses Lyocell/Viscose manufacturing process.
Algae foam	2016	Bloom	Algae in powder form and EVA compound	Algae are dried and then mixed with EVA compound, the foam is formed in heated moulds.
AlgiKnit	2017	Keel.labs	Alginate combined with renewable biopolymers	Alginate is extracted from seaweed and then mixed with biopolymers. Then the mixture is subjected to an extrusion process in a salt bath.
Biofilm	2022	Studio Tang	Agar, water, glycerine and other ingredients such as spirulina	The ingredients are mixed and boiled until they become sticky. Then put in the mould and air-dried for 2-3 days.
Food packaging	2019	Margarita Talep	Agar, water, natural plasticizer	Agaris extracted from red algae by boiling and then it is mixed with water and a plasticizer. The material includes only natural ingredients, including the dyes used to color it,

				which are extracted from fruits and vegetables.
Terroir	2014	Jonas Edvard and Nikolaj Steenfatt	Seaweed and paper	Seaweed and paper are combined to create a strong and durable material. The colour is determined by different species of seaweed.
Seacrete	2022	Studio Tang	Crushed oyster shells, alginate and algal biomass	Crushed shells are mixed with an alginate solution and dried seaweed pieces, then the mixture is transferred into a mould and put in an oven for 2 hours.
En Route	2021	Brigitte Kock and Irene Roca Moracia	Powdered crayfish shells and wood ash	Crayfish shells and ash are mixed with binder and water, then they are baked. The final colour and textures depending on the curing time and chemical reactions.

3. Experimental Design through a DIY approach

Biomass of aquatic vegetation was tested as components for bio-based materials by implementing a "sustainable biomass supply strategy" that consider this aquatic plant as a carbon neutral component. The experimental stage was designed by considering previous studies conducted by Studio Tang and other open-source projects. No previous case studies concerning the use of freshwater aquatic vegetation for bio-based materials can be found in scientific literature, but only in some case studies from the grey literature. For this reason, the DIY approach was adopted as the most suitable method to test and explore opportunities offered by fronds ofaquatic vegetation through "trial and error" method.

The preliminary step consisted in investigating properties of various material components commonly used in analysed DIY case studies:

- Water, as the essential solvent in which the other substances are dissolved;
- Vegetable glycerine, as a natural plasticiser that is often added to materials to improve their flexibility, durability and workability. Glycerine is an excellent natural plasticiser due to its ability to attract and retain water molecules, which makes it a very effective moisturiser. It is also non-toxic, biodegradable and renewable;
- Animal gelatine or agar. Gelatine is a protein-based material derived from animal collagen and it is generally adopted in food industry as a gelling and stabilising agent. Agar, on the other hand, is a biopolymer extracted from red algae and it is abile to form gels. Therefore, both act as binders with other substances for the creation of strong and flexible materials.

The first step consists of the collection and subsequent dehydration of the aquatic vegetable fronds. Once the vegetation was collected from the Po River, fronds were left to dry at room temperature (17-19°C) for a week. Once fronds were dried, they were grinded using a laboratory blender until obtaining a powder-like material, consisting of fragments ranging from 0.01 cm to 0.3 cm. Thus, six basic experimental protocols were firstly designed and then 31 variants of these protocols were then experimented, changing doses of components to obtain varied final characteristics and properties (Figure 1).

Figure 1. Samples of materials obtained by experimenting with different recipes and further variations.

Another step consisted of mixing all previous ingredients by using varied procedures. When water, glycerine and agar are heated together, the agar dissolves and forms a thick, gel-like mixture. This happens because agar is a hydrocolloid that can absorb and retain water, while glycerine has hygroscopic properties that attract and retain moisture. Since the hot mixture is more fluid and easier to work with, it is possible to pour it into silicone moulds when it reaches a homogeneous aspect. As the mixture cools and solidifies, it forms a strong and stable gel that can hold its shape. Depending on the sample, the time remaining in the mould can vary from 10 minutes to an hour. Samples can be removed as soon as they have thickened, and they do not leave any residue into the mould. The drying process is then completed on a breathable surface (consisting of a wooden frame and mesh fabric). This will prevent the formation of condensation, which would form in the silicone mould and then lead to the formation of mould, and ensure uniform drying, and thus moisture loss. Various drying methods were investigated, such as drying with UV lamps and hot thermoforming using electric hot plates. First trials were used to identify two more recipes, which differ from the first one in the addition of further ingredients at the mixing stage.

The first formula involves the addition of a natural acid and a base. These elements mixed give rise to a neutralisation reaction, and the result is the production of carbon dioxide gas, which causes bubbling and fizzing in the compound. The second involves the addition of a surfactant, into the base compound. In this case, foam is formed from the entrapment of air in the liquid, due to the mechanical work of mixing. The use of a surfactant helps to reduce surface tension and stabilise the foam as it increases the elasticity of the compound itself.

Samples obtained are promising and their characteristics depend by quantity of components and processing methods. It is possible to obtain more elastic and easily deformable materials by increasing the amount of glycerine in the compound: for example, in order to obtain a foam-like material used for making soles of shoes, the suitable ratio of glycerine to water is 1:2. It was then observed that the two gelatinisers, agar and animal gelatine, behave differently during the drying stage. Samples made with agar lose a lot of water during this phase, deforming and reducing their volume, more than the samples made with animal gelatine. However, at the end of the drying period, samples show elastic behaviour (Figure 2).

Moreover, it is possible to obtain a spongy appearance in samples thanks to the reaction between an acid and a base. If the reaction takes place with the fire off, we obtain very light samples, however, if the reaction takes place with the heat on, we obtain a spongy material but heavier than the first. In this case, during the drying phase, this kind of samples reduce a lot in volume and harden more and more until a material similar to a resin, with a regular, homogenous surface and a waterproof surface finish. The introduction of a surfactant, on the other hand, makes it possible to obtain samples with very elastic behaviour. In the drying phase samples use to shrink a lot, losing 15% to 60% of their initial volume. Generally, these samples present a better and smoother surface finishing.

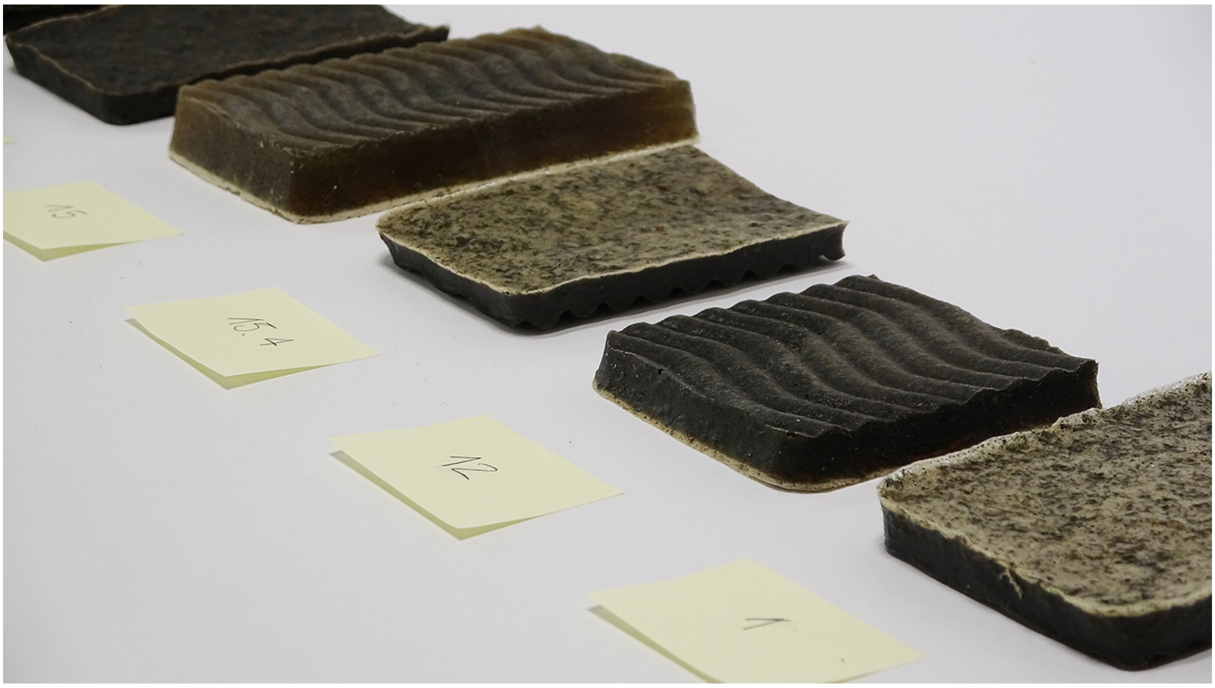

Figure 2. Samples of dried materials with different surface finishes.

4. Discussions

The drying phase has demonstrated to be the most challenging for developed samples, as water loss is difficult to control. Analysing the data collected, we observe that the materials lose 1-1.2 cm, in the best case, while, in the worst case, some samples have shrunk by 3-4 cm.

However, air drying isthe best method tested. Certainly, working in an controlled environment with the opportunity to regulate paramenters such as temperature, pressure and humidity would lead to more precise results. The use of UV lamps tends to stabilise the materials in a very short time, but at the same time, it is a too-fast drying method that tends to burn the samples, causing them to harden too much and lose their elasticity. Drying using heated plates, on the other hand, works well because the samples only shrink by 10-15%, but it is not a suitable technique for this project purpose because it is only possible to obtain very thin thicknesses samples of about 0.3-0-4 cm.

Samples of bio-based materials obtained from experimental stage were manipulated using Meterial Tinkering method to preliminary evaluate their properties and characteristics and it support designers to define the most suitable process to achieve the desired results (Parisi et al., 2017) (Figure 3).

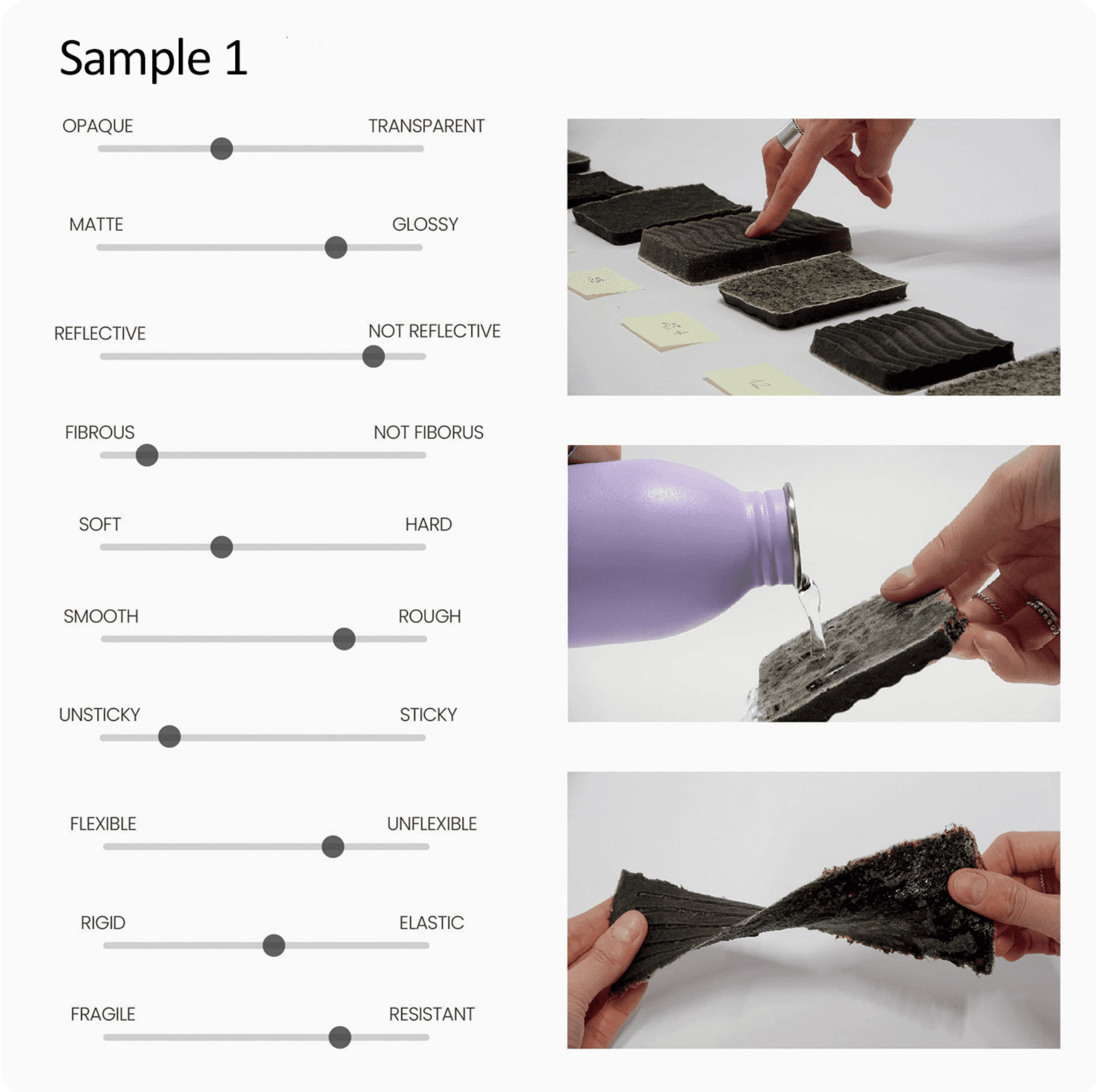

Figure 3. Example of a Material Tinkering sheet to evaluate the properties of the samples obtained, based on the scale theorised by Karana (2009) as a reference.

Based on the exploration and experimentation of different combinations of materials and manufacturing processes, it is possible to discover new solutions and innovative products. All samples presented interesting tensile and compressive strength explored through direct manipulation, as shown in the Figure 3. Tests were also conducted to check the resistance to common domestic disinfectants and detergents, and they presented positive results, as all samples were not damaged when treated with these types of substances. Tests were then carried out to assess heat resistance. Samples obtained are not fireproof and they begin to degrade if placed in direct contact with a flame for a prolonged time, leading the material to melt. If the time is short a slight melting might be noticed. However, the material will re-solidify once the flame is removed.

Another challenge concerns water resistance, a material property that must be improved to be applied for soles of shoes. Samples resist well if immersed in water for about 10 minutes. After this time, samples are subject to a considerable increase in volume caused by the incorporation of water, which is then released once the sample is removed from the water, permanently changing it and causing it to almost completely lose its elastic behaviour. Samples harden and become much more brittle, losing all their tensile and compressive strength. This characteristics must be improved in further investigations in order to obtain a material suitable for desired real-scale application.

5. Conclusions

This study presented promising results in enhancing organic biomass waste collected from the Po River, but would work with any aquatic vegetation of a generic river, and transforming it into a bio-based material through DIY approach. These preliminary results suggest further improvement for efficient real-scale applications. The use of local aquatic plant biomass is an advantageous expedient, and it is in line with the DIY approach to bio-based material. The use of local materials in fact reduces the carbon footprint associated with transport, which means reducing GHG emissions and mitigating climate change. At the end, it may support local economy and it could help to create new jobs in the community following principles of circular economy. This study shows potentials of DIY approach in investigating alternative applications of by-products and waste for which no alternative use is already planned. Indeed, the output of one system (in this case, of a natural ecosystem) becomes the input as secondary raw material for another one. Moreover, aquatic vegetation does not need arable soil to grow, so it does not take away from the cultivation of crops for food industry. The DIY approach represents a ground-breaking tool to explore properties and characteristics of “more-than-concept” materials through “trials and errors” method, and to estabilish further research directions. Nowadays, results obtained still present great potential at the concept level. Next steps consist of material engineering in order to improve samples properties and to make them good candidates for replacing fossil-based plastics for various applications, not limited to fashion and footwear industries.

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