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# Valorisation of freshwater weeds biomass to produce bio-based composites through *do-it-yourself* approach

Laura Dominici [a,*], Anna Fornaseri [a], Martina Grassi [a], Dumitru Moraru [b], Marco Sangermano [b], Raffaella Sesana [c], Elena Comino [a]

[a] *Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy*
[b] *Department of Applied Sciences and Technology (DISAT), Politecnico di Torino, corso Duca degli Abruzzi 24, 10129, Torino, Italy*
[c] *Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino, corso Duca degli Abruzzi 24, 10129, Torino, Italy*

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ABSTRACT

Bio-based composites have gained increasing attention in recent years due to the rising of ecological and sustainability consciousness in disciplines of material science and design practice. Opportunities offered by organic waste and by-products as reinforcing fillers for polymer blends are investigated to improve properties of bio-based material with the aim to replace fossil-based plastics. This study focused on the reuse of freshwater weeds biomass as filler for bio-based composite materials obtained using only natural and biodegradable components for matrices. The freshwater weeds biomass involved in this study was mainly composed by the invasive plant species *Elodea nuttallii* collected during environmental management practices of Po River in the city of Turin (Italy). The study was performed in the framework of Material-Driven Design using the *do-it-yourself* (DIY) approach to explore opportunities offered by 27 different protocols defined to create bio-based composites. Material Tinkering was adopted as practice to evaluate strengths and weaknesses of prototypes obtained from abovementioned 27 bio-composites in order to select those that presented elastic behaviour of rubber materials. At the end, a single prototype was selected as the most promising that showed *rubber-like* characteristics. This prototype was characterised through tensile testing and dynamic mechanical thermal analysis (DMTA) to determine their physical and thermal characteristics. The study discusses opportunities and criticalities presented by all 27 bio-composites obtained through DIY approach and evaluated through Material Tinkering, and it suggests potential design applications for the selected rubber-like bio-composite based on its mechanical and thermal properties.

## 1. Introduction

Synthetic materials derived from fossil fuel were developed more than 100 years ago to provide a huge range of properties not found in natural materials. Plastic materials offered the opportunity to produce affordable, lightweight, long-lasting, and low-cost disposable products that completely changed many everyday habits (Freinkel, 2011). Anyway, the diffusion of “*throwaway culture*” led to an excessive use of single-use plastics and low cost synthetic polymers characterised by a slow degradation rate (Chen et al., 2021).

The consistent production of waste and its inappropriate disposal result in a high accumulation of plastic items in natural ecosystems that are broken up into small fragments, known as meso- and micro-plastics, due to the action of biotic and abiotic processes (Jahnke et al., 2017). The widespread presence of plastic and rubber materials in natural ecosystems causes contamination and pollution of soil, rivers, lakes and oceans (Fazli and Rodrigue, 2020; Yu et al., 2020; Boucher et al., 2019). Plastics produce stress and health threats for humans and wildlife releasing chemicals and toxins that enter in food chains (Senathirajah et al., 2021). The Organization for Economic Co-operation and Development revealed that the 82 % of waste in European seas consists of plastic materials, while globally approximately 30 million tons of plastic waste are released into oceans (OECD, 2022). Nowadays, this issue is of capital importance: there is an urgent need to reduce the environmental impact of single-use plastics and to move towards zero-waste models in the production of disposable items.

In the European framework, the Directive (EU) 2019/904, known as

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* Corresponding author.

*E-mail addresses:* laura.dominici@polito.it (L. Dominici), s345058@studenti.polito.it (A. Fornaseri), martina.grassi@outlook.it (M. Grassi), dumitru.moraru@polito.it (D. Moraru), marco.sangermano@polito.it (M. Sangermano), raffaella.sesana@polito.it (R. Sesana), elena.comino@polito.it (E. Comino).

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**Abbreviations**

| | |
|---|---|
| BcFWB | Bio-composite from freshwater weeds biomass |
| DIY | Do-It-Yourself |
| DMTA | Dynamic Mechanical Thermal Analysis |
| $E$ | Young's elastic modulus |
| MT | Material Tinkering |
| UTS | Ultimate Tensile Strengths |
| $T_g$ | glass transition temperature |
| WCA | Water Contact Angle |

"Plastics Directive", focuses on banning and disincentivising the production and use of plastic disposable items promoting the adoptions of alternatives in line with the circular economy mindset (The European Parliament and The Council of The European Union, 2019). The circular economy mindset applied to plastic production requires to increase the use of reusable and recyclable items and the development of sustainable alternatives that transform secondary raw materials and biomass into innovative ones (Genovesi et al., 2022). The development of bio-based and compostable materials is in line with the Sustainable Development Goals (SDGs) and the Agenda 2030, and in particular with the SDG 12 "Ensure sustainable consumption and production patterns" (United Nations, 2015). Considering the Agenda 2030 goals, the plastic industry is focusing on exploring biodegradable and bio-compostable materials to replace plastics from fossil raw materials, anyway sustainable alternatives actually represent a small amount of the total annual plastics output (Fuhr and Franklin, 2019). Exploring alternative raw materials and more sustainable strategies to reuse, valorise and recycle waste and by-products in plastics industry seem to be the desired direction in line with assumptions of circular economy (Kasznik and Łapniewska, 2023). In this framework, increasing consideration is given to waste and by-products derived from biomass that can be valorised as resources to produce bio-based materials composed by all-natural ingredients that are easily biodegradable (Chen et al., 2022).

Plant-based fibrous materials and biomass derived polymers are biodegradable and compostable and in some cases present properties such as flexibility and mechanical strengths equal to petroleum-based plastics (Pandit et al., 2018). Bio-composites are gaining increasing importance in the framework of bioplastics in varied field of application such as packaging, construction and engineering (Pandey et al., 2015). Andrew and Dhakal (2022) reported that the global market trend for bio-composites seems to grow considerably in the period 2016–2024 with the highest usage in the construction sector. Moreover, an increasing number of consumers are interested in bio-based materials used for sports equipment, such as running shoes (Scherer et al., 2018), and apparel (Stahl et al., 2021), outlining promising market opportunities for alternatives to fossil-based plastics.

Bio-composites consist of a bio-based polymer matrix that embeds other materials used as reinforcement for strength, thermal stability and stiffness (Amulya et al., 2021). Natural fibres, agricultural waste, lignocellulosic biomass, and wood-based by-products are increasingly investigated and used as additives or reinforcements for bio-based composites (Santulli, 2021; Rowell, 2014). Natural fibres such as hemp, rice husk, coir, kenaf, and jute are investigated as attractive materials to replace synthetic fibres in composite materials (Bhatia et al., 2019). Indeed, Suárez et al. (2021) reported an increasing trend in the use of natural waste materials and by-products for bio-composites, even if further investigations must be conducted to properly assess their environmental footprint and biodegradation rate. These secondary raw materials are used to enhance and improve properties of bio-based composites, including biodegradability, in a sustainable and resilient way (Väisänen et al., 2017). The abundant availability of food, agricultural, and forestry waste and by-products represent a promising resource that can be use in line with circular economy principles. Some recent studies focused on investigating opportunities provided by unexplored resources from agro-food waste (Armynah et al., 2022; Comino et al., 2021; Santulli et al., 2017a,b), microalgae (Roy Chong et al., 2022), and invasive plant species (Ortega et al., 2021; Zhao et al., 2021). Armynah et al. (2022) used pineapple leaf fibre as reinforcement and zinc oxide as nanofiller of starch/chitosan-based bioplastics that present inferior mechanical properties than synthetic polymers involved in food packaging. Santulli et al. (2017a,b) highlighted the property as anti-mould agent offered by carrot peels as filler of starch-based matrix, while thanks to the high lignin content nutshells where used to develop gluten-based DIY materials for outdoor applications. Ortega et al. (2021) focused on the valorisation of natural fibres obtained from invasive species of *Arduno donax* L., *Pennisetum setaceum*, and *Ricinus communis* to be used in polyethylene-based matrix. The study assessed that mechanical properties of composites obtained through rotational moulding were affected by the introduction of natural fibres in the matrix. This aspect can be caused by particle size and rotational moulding as a low-shear production process during which agglomerations and segregation were formed leading to obtain an non-homogeneous material and affecting its mechanical properties. On the other hand, other studies reported that the introduction of *Arduno donax* L. as reinforcement was able to improve the elastic module of PLA, while reduce strength of epoxy resin matrices (Fiore et al., 2014). Moreover, the use of *Ricinus communis* as reinforcement fibre (30 % in volume) of Polyamide 11 (PA11) led to obtain flexural properties similar those presented by PA11 reinforced with glass fibres (Vinayaka et al., 2017). Zhao et al. (2021) studied the effects of using fibres of Phalaris arundinacea and *Lonicera japonica* as PHBV reinforcing agents observing that lignocellulosic fibres improved thermal stability, and reduced rigidity and cost. Reinforced PHBV-composites showed characteristics similar to polypropylene suggesting potential applications as semirigid packaging. Macadamia nut shell powder has been used to improve material hardness and wear resistance (Pezzana et al., 2023), and the study conducted by Thyavihalli Girijappa et al. (2019) highlights various natural fibres derived from agricultural waste—such as coconut fibre, sisal fibre, flax, pineapple leaf fibre, and hemp fibre—that could be employed as fillers to improve composites thermo-mechanical properties.

In the Italian scenario and in particular in the city of Turin, climate change led to the spread of invasive alien plant species that causes an important eutrophication issue of freshwater ecosystems of Po River. This critical issue requires the adoption of mechanical methods to control them, as consecutive-cutting, generating a significant amount of biomass (Aree protette Po Piemontese, 2023; ENEA, 2022). Indeed, plant species such as *Elodea nuttallii*, *Myriophyllum aquaticum* and *Lemna minuta* are characterised by rapid growth and propagation reducing the available habitat for native species and the water flow rate, and hindering the navigation and water sports (Bolpagni et al., 2020). *E. nuttallii*, *M. aquaticum*, and *L. minuta* are included in the Union List of Invasive Alien Species (Regulation (EU)1143/2014) (The European Parliament and The Council of The European Union, 2014) and in the Black List of the Piedmont Region (D.G.R. n.1-5738) (Regione Piemonte, 2022). These regulations include specific restrictions on keeping, importing, selling, breeding, growing and releasing them into the environment to limit and reduce negative impacts on biodiversity of freshwater ecosystems. Indeed, the biomass of these aquatic weeds must be properly handled to avoid massive reproduction through vegetative propagation that may led to ecosystem eutrophication and negatively affect other aquatic living organisms (Zhao et al., 2021). Nowadays, the biomass derived from activities of environmental management aquatic weeds is collected and treated in landfills as special organic waste with significative costs for disposal. However, eutrophication issue may inspire alternative bio-design applications to valorise biomass through a win-win strategy and an ecological multi-perspective approach (Fakhfakh and Taieb, 2024).

### 1.1. Research goal

Considering new trends in bio-based materials framework, this study focuses on exploring the opportunity offered by biomass derived from invasive freshwater vegetation, or aquatic weeds, of the Po River in the city of Turin (Italy) to be used as filler for a bio-based composite material. The aim is to use this biomass derived from the eradication of these freshwater aquatic weeds as filler to produce a bio-based composite that present rubber-like characteristics. This study presents laboratory experiments that are performed involving only natural ingredients to create bio-based composites with high tensile strength and elastic recovery even at large deformation.

The study was performed through a creative *do-it-yourself* (DIY) approach to upcycle and valorise aquatic weeds biomass. DIY applied to material design is an iterative and explorative approach based on a *trials and errors* innovation process to create and test new materials (Comino et al., 2021; Caliendo et al., 2019; Cecchini, 2017; Galentsios et al., 2017; Rognoli et al., 2015). In the framework of Material-Driven Design, the DIY approach is adopted to unconventionally investigate design opportunities of secondary raw materials through *hand-on experimentations* and tinkering practices (Karana et al., 2018; Giaccardi and Karana, 2015). In this study, prototypes of bio-based composites were obtained by combining and manipulating natural ingredients through iterative trials and errors process that led to obtain materials with varied characteristics and properties. Then, these properties and sensorial characteristic were preliminary assessed using the practice of Material Tinkering (MT) that include the direct handle and manipulation of sampled produced (Rognoli and Parisi, 2021; Parisi et al., 2017). Strengths and criticalities of these bio-based composites were evaluated and compared in order to select promising samples that present elastic properties similar to rubber-like materials. Then these selected samples were analysed in order to assess and characterise their physical and thermal properties as bio-based polymers. Quantitative data, qualitative considerations and criticalities were collected to build new directions in the design of innovative and sustainable bio-based composites able to replace fossil-based plastic materials.

## 2. Materials and methods

### 2.1. Selection of all-natural ingredients for polymer matrices

Biodegradable plastics can be categorised based on their origin as synthetic or natural biodegradable polymers. In this framework, biocomposites are obtained by combining a bio-matrix and bio-based fillers as reinforcement. Natural or synthetic additives are added to improve chemical and physical material properties. Biomass derived from animals and plants as agricultural and food waste, and microbial organism are used as renewable and biological resources to produce bioplastics, plasticizers and additives (Samir et al., 2022), and this study was performed involving only natural components and ingredients. Stevens (2020) cited and investigated various types of polysaccharides, polypeptides, lipids and natural rubber as natural components used and mixed to obtain biodegradable polymer matrices. All bio-based matrices were obtained by using distilled water as solvent.

Agar, carrageenan and corn starch as polysaccharides-based ingredients, and animal gelatine and isinglass as polypeptides-based ones (proteins) are involved in this study to obtain matrices for bio-composite materials. All abovementioned ingredients involved in this study are commercial products used for human consumption and nutrition.

Starch is a white-colour powder generally extracted from plants such as corn, rice, potatoes and wheat, agrowaste considered as sustainable and renewable resources (Scott, 2002). In detail, 100 % corn starch (Unilever Italia, London, UK) was involved in this study to produce polysaccharides-based matrix for bio-composites. Starch-based polymers are the most commercial types of bioplastics adopted to produce packaging (Gadhave et al., 2018) thanks to the wide range of physical and chemical properties such as water resistance and low water-vapor permeability (Marichelvam et al., 2019). Starch-based bioplastic has poor mechanical properties that can be improved by mixing with additives or fibres (Jha et al., 2019). Moreover, additives are used to produce biodegradable films with various thermal, mechanical and structural properties (Edhirej et al., 2017).

Agar is extracted from Gelidiaceae and Gracilariaceae families of seaweeds and is composed of agarose and agaropectin (Lyons et al., 2009). Thanks to the ability to form hard gels at low concentrations, agar is used as gelling agent, thickeners and stabiliser in food and pharmaceutical industry (Jumaidin et al., 2017; Prachayawarakorn et al., 2012), and as growth medium for bacterial cultures (Armisén and Gaiatas, 2009). In bioplastics production, agar is used due to the excellent gelling characteristics (Jumaidin, 2023) and for the ability to enhance tensile strength and reduce water vapor permeability of starch-based bioplastic films (Phillips and Williams, 2000).

Similar to agar, also carrageenan is a marine-derived sources, specifically extracted from Rhodophyceae red seaweeds, and it is often adopted in food industry thank to good gelling and stabilising ability (Genecya et al., 2023). The use of carrageenan in bio-based materials production is increasing: Mangala et al. (2024) and Adam et al. (2022) investigated properties and characteristics of bioplastics from carrageenan and tested opportunities and various production techniques to obtain commercial-scale bioplastic film. In this study, powder of pure agar (E406) (ERBOTECH, Brescia, Italy) and k-carrageenan (E407) (SaporePuro, Turin, Italy) used as thickeners in food industry were involved to carry out laboratory experiments in this study.

Protein-based matrices are obtained by various type of animal gelatines (Dzeikala et al., 2024; Mroczkowska et al., 2021) and isinglass (Sarkar et al., 2023; Pompei et al., 2020). Protein-based bioplastics are characterized by better mechanical properties than those derived from polysaccharides and lipids thanks to strong molecular interactions of the matrix (Omrani-Fard et al., 2020; Nur Hanani et al., 2012). Animal gelatine and isinglass are often extracted from biowastes and by-products derived from food industry such as poultry, bovine, porcine and fish processing in order to adopt a circular economy mindset (Álvarez-Castillo et al., 2021). In this case, powder of animal gelatine derived from pork (SaporePuro, Turin, Italy) and leaf of isinglass gelatine (Icielle s.a.s., Milan, Italy) were used to prepare matrices.

Pure vegetable glycerin (AIESI®, Naples, Italy), also known as glycerol, was added as odorless and colorless plasticizers. Glycerin is involved to increase flexibility and brittleness of bio-matrices (Kiran V et al., 2022; Sagnelli et al., 2017). Glycerin is the most adopted plasticizers used for bio-plastic films for food packaging applications thanks to the capability to maintain transparency (Benitez et al., 2024a). Glycerin is characterized by excellent biocompatibility, non-toxicity, and chemical stability, as reported by Zhang and Grinstaff (2014) and Kainthan et al. (2006).

Commercial vinegar, or acetic acid, used for human consumption was adopted as co-plasticizer able to increase the density of biocomposite materials (Nasution et al., 2018) and to create more homogeneous matrices (Kingsley et al., 2020).

At the end, baking soda was used as preservatives and plasticizer additive to strengthen bio-composite materials and make them more durable (Nguyen et al., 2022; Jiugao et al., 2005).

Commercial liquid dishwashing soap containing only natural ingredients (Nivel srl, Lucca, Italy) was used as an compatibilizer additive. Liquid dishwashing soap was used as source of surfactants, in particular non-ionic surfactants, that are involved in the production of bioplastics as compatibilizers (Cortés et al., 2021). Coco-glucoside is non-ionic surfactant that compose the dishwashing soap involved in this study. Compatibilizers are adopted to increase the compatibility of immiscible polymers by reducing the internal tension and improving interfacial adhesion between varied phases, stabilize their morphology and ameliorate the final surface finishing (Fredi and Dorigato, 2023).

### 2.2. Collection and preparation of freshwater weeds biomass

Biomass derived from aquatic weeds was collected from the urban stretch of the Po River in the city of Turin. Aquatic weeds were collected during manual consecutive-cutting activities organized by the local municipality in July 2022 with the collaboration of other local institutions such as universities, the environmental protection agency, members of Po River Park Authority and rowing clubs. Part of this aquatic weeds biomass, mainly composed by *E. nuttallii*, was transferred in a university laboratory and processed before being used as filler for bio-composite materials. Considering that the most aquatic weed are relatively rich in cellulose and hemicellulose and that present low content of starch and lignin (Fujiwara et al., 2022; Kaur et al., 2018; Rabemanolontsoa and Saka, 2013), this biomass was used without any special pre-treatment step. Firstly, the biomass was dried at room temperature (18 ± 1 °C) for 7 days and then ground using a laboratory blender to obtain a powder mixture consisting of 0.01–0.3 cm size particles (Fig. 1). No further treatments were carried out on aquatic weeds biomass that was preserved in glass containers equipped with hermetic seal at room temperature (21 ± 1 °C).

### 2.3. Bio-composite from freshwater weeds biomass (BcFWB): definition of protocols through DIY approach

Natural ingredients described in Section 2.1. were manipulated and embedded through DIY approach to obtain 27 protocols. Table 1 shows type and quantities of ingredients used for matrices, and quantities of freshwater weeds biomass involved in each protocol. These 27 protocols (BcFWB 1 – BcFWB 27) were identified using an iterative *"trials and errors"* method characteristic of the DIY approach (Sarpong et al., 2020).

The "*trials and errors*" method was supported by the application of MT to formula and production processes in order to understand and explore how variations of ingredients and potential manufacturing processes can impact final results (Rognoli and Parisi, 2021). Fig. 2 shows steps followed to produce material prototypes.

At this stage, MT led to adjust typology and quantities of ingredients, the use of specific tools, or experiment conditions such as temperature adopted in production processes. Ingredients were blended using an electric laboratory heater set at the temperature of 90 ± 2 °C for 3–5 min until the matrix being sticky. Then, the aquatic weeds biomass was added and blended with the matrix in order to obtain a homogeneous mixture. The obtained mixture was consequently transferred in reusable silicon circular moulds of 28 $cm^3$ and left to thicken for 30–60 min depending by protocols, as shown in the second column of Table 2. After the thickening period, the sample was removed from the silicon mould and left to dry on a plan drying frame equipped with a highly breathable mesh fabric. Drying stage was conducted (i) at room temperature (21 ± 1 °C) for 48–72 h; or (ii) using two infrared heat lamps (250 W) for 2–5 h, as indicated in Table 2.

**Fig. 1.** Powder mixture of freshwater weed biomass obtained after drying and blending.

### 2.4. BcFWB prototypes selection through material tinkering (MT)

A set of preliminary 27 DIY new bio-composite prototypes were obtained from abovementioned protocols. These prototypes were compared and evaluated through MT method in order to select the most promising ones for potential design applications. MT refers to the practice of directly manipulation and early stage exploration of materials, it is often adopted in Material Design disciplines and it is based on the "learning-by-doing" approach and iteration processes (Parisi et al., 2017). This practice consists in creative and informal interactions with materials in order to acquire hands-on knowledge for their potential practical applications in line with *material-driven* design nature (Giaccardi and Karana, 2015; Karana et al., 2015). This practice can be performed through two different ways that are strictly linked on the each other: *tinkering with materials* and *tinkering for materials* (Rognoli and Parisi, 2021). Through the tinkering with materials, the designer understands materials opportunities and potentialities thanks to the experiential learning. While the designer that performs *tinkering for materials* expresses the intention to explore potential applications of material prototypes going beyond their limits and criticalities. DIY materials are often explored and preliminary evaluated based on colour, thickness, flexibility and texture that can lead to the iteration of bio-composites production process to improve their characteristics (Barati and Karana, 2019).

In this study, the 27 DIY material prototypes were observed and manipulated in order to preliminarily evaluate following technical and sensorial properties: the surface texture, the flexibility and elasticity, the hardness, the tensile and compressive strength. The MT was applied directly on the 27 samples with the aim to preliminary evaluate which of them presented properties and characteristics similar to rubber-like materials. The behaviour of 27 DIY prototypes was evaluated through MT method taking into account characteristics such as high flexibility and mobility typical of elastomers (Dos Santos et al., 2014). Through direct manipulation and the application of manual tensile stress on each material prototype, deformation and ability to recover their initial shape after unloading was observed and evaluated. Moreover, the *shrinking* behaviour of 27 prototype were preliminary observed during 20-days of drying stage: prototypes that presented the final volume, shape and surface morphology similar or equal to the initial ones have been considered as more promising than the others. The development of moulds on prototypes surface was also monitored during 20-days as an essential driver in the preliminary selection.

The application of the preliminary MT method led to select some prototypes that presented characteristics similar to rubber-like materials. In line with the iterative nature of DIY materials creation, the production process of these prototypes was reproduced following same procedures described in Section 2.3 but using a larger rectangular silicon mould (length 270 mm, width 165 mm, height 50 mm). The volume reduction (%) of each prototype was measured daily during the drying stage (20 days). A specific MT sheet was developed based on the *Sensorial evaluation scale* reported by Parisi et al. (2017) and Karana et al. (2009) to experientially characterise and evaluate material prototypes obtained. The sheet used in this study was composed of 12 sensorial properties divided in three main categories as described in Table 3. The MT sheet was designed using the *9-point hedonic scale* that is one of most useful sensory method adopted to evaluate a wide range of products, especially in food industry but also for personal care items, household products and cosmetics (Stone et al., 2021; Lim, 2011). Each prototype was qualitatively described using the MT sheet designed using the *9-point hedonic scale* during a 90-min focus group composed by ten

**Table 1**
Ingredients and quantities expressed in grams used to obtain the first 27 protocols to obtain bio-composites from freshwater weeds biomass.

| Protocol n° | Quantities of ingredients | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Matrix | | | | | | Additives | | | | Filler |
| | *Water* | *Agar agar* | *Carrageenan* | *Corn strach* | *Animal gelatin* | *Isinglass* | *Glycerin* | *Acetic acid* | *Baking soda* | *Soap* | *Freshw. weeed biomass* |
| *Polysaccharides-based matrix* | | | | | | | | | | | |
| 1 | 100.0 | 4.0 | – | – | – | – | 5.0 | – | – | – | 10.0 |
| 2 | 100.0 | 33.0 | – | – | – | – | 4.0 | 50.0 | 13.6 | – | 4.0 |
| 3 | 80.0 | 3.0 | – | – | – | – | 12.0 | – | – | – | 4.0 |
| 4 | 50.0 | 16.5 | – | – | – | – | 2.0 | 25.0 | 6.8 | – | 2.0 |
| 5 | 50.0 | 8.0 | – | – | – | – | 2.0 | 25.0 | 6.8 | – | 2.0 |
| 6 | 50.0 | 2.0 | – | – | – | – | 2.0 | 25.0 | 7.0 | – | 4.0 |
| 7 | 50.0 | 2.0 | – | – | – | – | 6.0 | 25.0 | 7.0 | – | 4.0 |
| 8 | 40.0 | 5.0 | – | – | – | – | 5.0 | – | – | – | 5.0 |
| 9 | 40.0 | 1.6 | – | – | – | – | 2.7 | – | – | 3.0 | 6.0 |
| 10 | 33.0 | 11.0 | – | – | – | – | 1.3 | 16.0 | 4.5 | – | 4.0 |
| 11 | 30.0 | 1.0 | – | – | – | – | 8.0 | – | – | – | 2.0 |
| 12 | 30.0 | 8.0 | – | – | – | – | 1.0 | – | – | – | 2.0 |
| 13 | 25.0 | 5.0 | – | – | – | – | 1.0 | 13.0 | 3.6 | – | 3.0 |
| 14 | 25.0 | 3.0 | – | – | – | – | 1.0 | 13.0 | 3.6 | – | 3.0 |
| 15 | 25.0 | 1.0 | – | – | – | – | 1.0 | 13.0 | 3.5 | – | 3.0 |
| 16 | 25.0 | 1.0 | – | – | – | – | 3.0 | 13.0 | 3.5 | – | 1.0 |
| 17 | 25.0 | 4.0 | – | – | – | – | 1.0 | 13.0 | 3.5 | – | 3.0 |
| 18 | 25.0 | 1.0 | – | – | – | – | 4.0 | 13.0 | 3.5 | – | 3.0 |
| 19 | 40.0 | – | 2.0 | – | – | – | 5.0 | – | – | – | 5.0 |
| 20 | 100.0 | – | – | 4.0 | – | – | – | – | – | – | 16.0 |
| 21 | 100.0 | – | – | 11.0 | – | – | 5.0 | – | – | – | 24.0 |
| 22 | 40.0 | – | – | 10.0 | – | – | 10.0 | 10.0 | – | – | 16.0 |
| *Protein-based matrix* | | | | | | | | | | | |
| 23 | 50.0 | – | – | – | 2.0 | – | 3.0 | – | – | – | 5.0 |
| 24 | 50.0 | – | – | – | 7.6 | – | 4.6 | – | – | – | 5.0 |
| 25 | 30.0 | – | – | – | 23.0 | – | 30.0 | – | – | 3.0 | 3.0 |
| 26 | 12.0 | – | – | – | 5.0 | – | – | – | – | – | 2.0 |
| 27 | 40.0 | – | – | – | – | 2.0 | 5.0 | – | – | – | 5.0 |

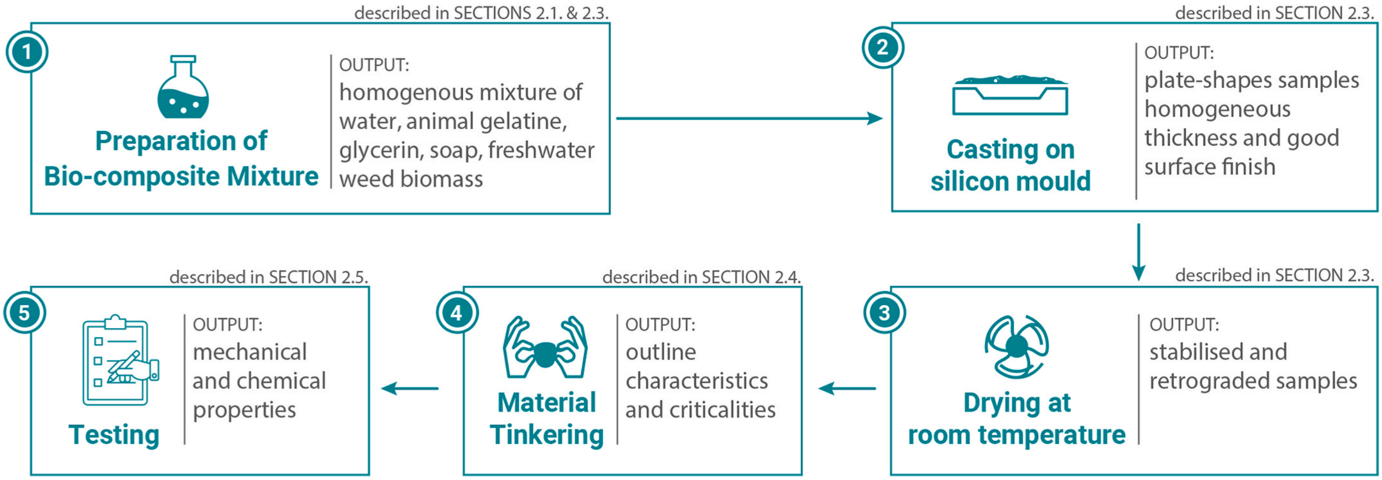

**Fig. 2.** Flowchart of steps followed to produce bio-composite prototypes. The flowchart illustrates steps carried out to produce the prototype n° 25.

participants external to this research study with varied expertise in design, architecture, engineering and environmental science. The choice to organise a focus group was based on potentialities highlighted by Bruseberg and McDonagh-Philp (2002) and McDonagh-Philp and Denton (1999) for data-gathering about user preferences in material design context. Focus group technique is often adopted in the field of industrial design to support the development of new products in the market and to collect data, observations and comments expressed by participants that discuss about a specific topic (Muratowski, 2016). In this study, focus group technique was also adopted to support design creativity through external stimuli (Santulli and Rognoli, 2020) provided by participants who are asked to discuss about strengths and weaknesses presented by selected prototypes. The MT performed through a focus group is a collective and participatory experience that allows to gather material design-related data.

Moreover, each of these selected prototypes was tested to assess their *water resistance*. Samples (in triplicates) of each prototype was place in containers of 0.07 $m^3$ filled with tap water and set for 30 min, 1 h and 2 h. After the testing period, each sample was removed from the container and was observed and evaluated to determine changes in consistency

**Table 2**

Details about thickening and drying periods adopted in varied protocols.

| Protocol n° | Thickening period (min) | Drying method | Drying period (h) |
|---|---|---|---|
| 1 | 60 | Room temperature | 48 |
| 2 | 30 | Room temperature | 72 |
| 3 | 60 | Room temperature | 48 |
| 4 | 30 | Infrared heat lamps | 2–5 |
| 5 | 30 | Infrared heat lamps | 2–5 |
| 6 | 30 | Room temperature | 72 |
| 7 | 30 | Room temperature | 72 |
| 8 | 60 | Room temperature | 48 |
| 9 | 30 | Room temperature | 72 |
| 10 | 30 | Room temperature | 48 |
| 11 | 60 | Room temperature | 48 |
| 12 | 60 | Room temperature | 48 |
| 13 | 30 | Infrared heat lamps | 2–5 |
| 14 | 30 | Infrared heat lamps | 2–5 |
| 15 | 30 | Infrared heat lamps | 2–5 |
| 16 | 30 | Infrared heat lamps | 2–5 |
| 17 | 30 | Room temperature | 72 |
| 18 | 30 | Room temperature | 72 |
| 19 | 60 | Room temperature | 48 |
| 20 | 60 | Room temperature | 48 |
| 21 | 60 | Room temperature | 48 |
| 22 | 30 | Room temperature | 72 |
| 23 | 60 | Room temperature | 48 |
| 24 | 60 | Room temperature | 48 |
| 25 | 30 | Room temperature | 72 |
| 26 | 60 | Room temperature | 48 |
| 27 | 120 | Room temperature | 48 |

**Table 3**

Details about the MT sheet adopted in this study.

| Macro-categories | Categories | Properties | Attributes |
|---|---|---|---|
| Tactual | Pressure Force | Softness | Soft - Hard |
| | | Weight | Light - Heavy |
| | | Ductile | Ductile - Tough |
| | | Elasticity | Low - High |
| | Friction | Roughness | Rough - Smooth |
| | | Fibrousness | Low - High |
| | | Stickiness | Low - High |
| Visual | Light reflection | Transparency | Opaque - Transparent |
| | | Glossiness | Glossy - Matte |
| | Colour | Intensity of colour | Subtle - Vivid |
| | | Temperature of colour | Cold - Warm |
| Olfactory | Odor | Odorous | Neutral - Smelly |

and morphologies.

### 2.5. Mechanical and thermal properties characterisation of selected BcFWB

The MT led to select a single prototype that was considered as the most promising in terms of design application. This prototype was characterised following procedures used by Pezzana et al. (2022) to determine: (i) tensile testing to determine the ultimate tensile strength (UTS) and the Young's elastic modulus (*E*); (ii) dynamic mechanical thermal analysis (DMTA) to observe the viscoelastic behaviour and to establish the glass transition temperature ($T_g$); and (iii) water contact angle (WCA) to evaluate the wettability of the selected BcFWB.

Samples were prepared for tensile tests for plastic materials following indications provided by regulations ISO 527–1:2019 (International Standard Organization, 2019) and ISO 527–2:2012 (International Standard Organization, 2012). All samples presented average 2.5 mm thickness and 40 mm central section width, and tests were performed in five replicates using a universal testing machine MST QTest/10 Elite (MST System Corporation), 500N load cell combined with the software TestWorks® 4 (MST System Corporation) to register the stress-strain curve. All tests were conducted at room temperature (20 ± 1 °C) and at the traverse speed of the machine was set at 20 mm/min until sample fails. The Young's modulus was determined as the slope of the straight curve approximating the data between 0 and 0.293 MPa which show a linear trend.

The DMTA was performed using three replicates (dimension 2 × 6 × 23 mm) of the selected prototype. Tests were conducted using the TTDMA instrument (Triton Technology, Inc.), which was set to exert an oscillatory uniaxial tensile stress at a frequency of 1 Hz with a displacement of 0.02 mm. The heating rate was set at 3 °C/min starting from $-60$ °C to $+60$ °C. The initial temperature ($-60$ °C) was reached by cooling down the test chamber with liquid nitrogen. The $T_g$ was defined as maximum of the damping factor curve, *Tan* $\delta$ (as E''/E'), and the test was stopped after the rubbery plateau.

At the end, the WCA was performed in three replicates (dimension 2 × 6 × 12 mm) using the Drop Shape Analyser DSA100 combined with the DSA1 v1.9 software (KRÜSS Scientific) and distilled water placed on the prototype free surface. If the contact angle $\vartheta$ is lower than 90° the distilled water wets sample surface and adhesion forces prevail over cohesion forces (hydrophilic behaviour). On the other hand, if the contact angle $\vartheta$ is higher than 90° the distilled water doesn't wet sample surface and cohesion forces prevail over adhesion forces (hydrophobic behaviour). The WCA provides insight into the surface wettability, which influences how a material interacts with water and other liquids. This property is essential to outline bio-composite's behaviour in various applications (i.e. outdoor application or packaging) and if the material require waterproof coating treatments.

## 3. Results

### 3.1. Preliminary selection of BcFWB prototypes through MT

The material design process performed through DIY approach led to obtain 27 BcFWB prototypes that present varied surface finishings, and technical and mechanical properties (Fig. 3). Results demonstrate how final characteristics vary depending by quantities and qualities of ingredients and laboratory conditions adopted during the production process. Table 4 summarises main characteristics and criticalities (descriptive and qualitative) defined through preliminary MT and direct manipulation of prototypes.

Preliminary MT performed on prototypes obtained from protocols n° 1, 3, 8, 11, 12, 19, 20, 21, and 22 revealed that they presented characteristics similar to EVA rubber, in addition to smoothy and glossy surface finishing. However, prototypes n° 8, 12, 19, 21, and 22 presented high volumetric reduction and surface modification during the drying stage, while prototypes n° 1 and 3 presented final volumes similar to initial ones. Prototypes n° 1 and 21 developed moulds on their surface during 20-days of monitoring.

The direct manipulation of prototypes obtained from protocols n° 6, 7, 9, and 15 revealed that they were light, porous, flexible, and presented opaque and light-colour surface finishing. These prototypes presented a behaviour similar to "spongy" materials, but with a really low water resistance. Initially, they started to float on water surface, but after few seconds they sank and in 10 min changed their features starting to crumble.

Preliminary MT on prototypes obtained from protocols n° 2, 4, 5, 10, 13, 14, 16, 17, and 18 stated that they were rigid and dense with a considerable compressive strength similar to resin-like materials. They presented really low flexibility and elasticity, and regular, matt, smooth, and homogeneous surface finishing with variable colour depending by the amount of biomass of freshwater vegetation used for preparation. All these prototypes decreased significantly in volume and changed their morphology during the drying stage, except for prototype n° 2. On the other hand, they presented a promising water resistance: these prototypes slightly increased the surface smoothness after 30–40 min of

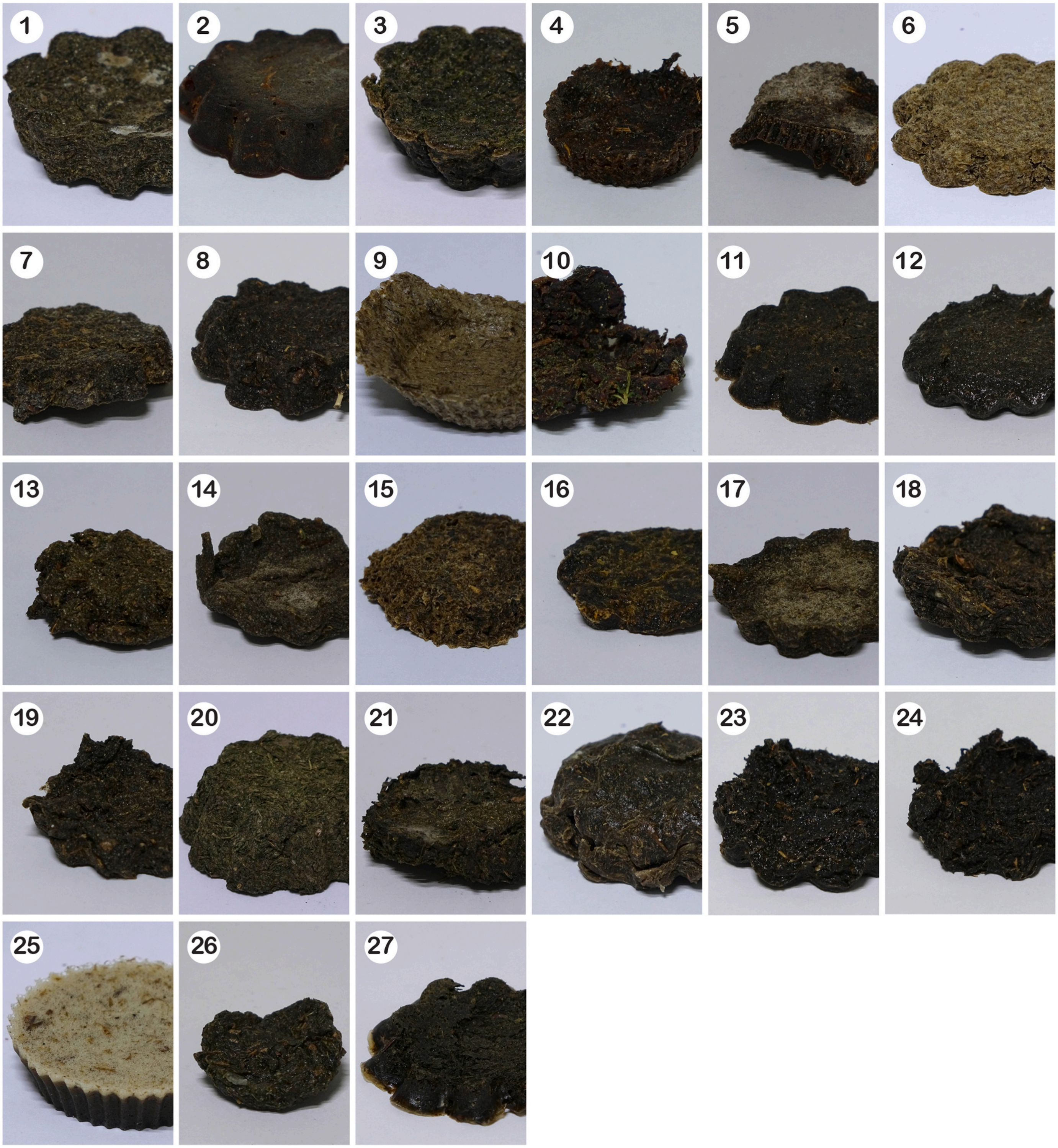

**Fig. 3.** 27 BcFWB prototypes obtained through the DIY approach applied to material design.

immersion in water without reporting any significant structural modification or material deterioration.

At the end, prototypes produced following protocols n° 23, 24, 25, 26, and 27 resulted in flexible and elastic materials with high tensile strength. In terms of aesthetic features, the direct manipulation and observation revealed that the prototype n° 25 presented features greater than prototypes n° 23, 24, 26, and 27. The prototype n° 25 was double-coloured and presented smooth surface finishing. The top layer part of the prototype reported a foamy-like behaviour and the volume reduction during the drying stage was minimum. On the other hand, prototypes n° 23, 24, and 26 didn't present an homogeneous morphology and presented relevant difference between initial and final volume.

Prototype n° 3, 11, and 25 were selected as the most promising ones using preliminary MT, taking into account that the goal of this study is to obtain a rubber-like material. Replicates of those prototypes are shown in Fig. 4, while the volume reduction monitored during 20-days of drying stage was reported in Fig. 5. Prototype n° 3 presented the final

**Table 4**
Characteristics and criticalities observed on 27 prototypes evaluated using preliminary MT and direct manipulation of prototypes.

| n° of prototype | Characteristics | Criticalities |
|---|---|---|
| 1, 3, 8, 11, 12, 19, 21, 22 | Flexible and elastic<br>Smoothy and glossy surface finishing | n° 8, 12, 19, 21, 22 high volumetric reduction and surface modification during drying stage<br>n° 1 and 21 developed mould during drying stage |
| 6, 7, 9, 15 | Light, porous and flexible<br>Opaque and light-colour surface finishing<br>Spongy behaviour | Really low water resistance |
| 2, 4, 5, 10, 13, 14, 16, 17, 18 | Low flexibility and elasticity<br>Regular shape<br>Matte, smooth and homogeneous surface finishing<br>Various colours depending by quantities of freshwater biomass<br>Promising water resistance | n° 4, 5, 10, 13, 14, 16, 17, 18 high volumetric reduction and shape modification during drying stage |
| 23, 24, 25, 26, 27 | Flexible and elastic n° 25 high aesthetic features: double-coloured, smooth surface finishing, foamy-like behaviour, low volume reduction | n° 23, 24, 26, 27 high volumetric reduction and not homogeneous final morphology and shape |

volume of 41 % than the initial one, the final volume of the prototype n° 11 was 61 % than the initial one, while the n° 25 reported the final volume of 85 % than the initial one.

These prototypes were analysed through the sensorial evaluation and results obtained during the focus group are shown in Fig. 6. Moreover, prototypes n° 3 and 11 presented low water resistance: after 40–60 min of immersion in water they irreversibly changed their features becoming brittle to hand manipulation. While, prototype n° 25 started to deteriorate its flexibility and elasticity after 40–50 min of immersion in water, and physical performances decreased significantly as immersion time increased. All selected prototypes presented limited water resistance, and none of them is able to recover their properties when exposed to prolonged immersion without showing significant changes.

The prototype n° 25 was selected as the most promising substitute of a rubber-like material considering results obtained from MT and volume reduction monitoring. Indeed, this prototype presented the lower volume reduction (-15 % of initial volume) than prototypes n° 3 (-59 % of initial volume) and 11 (-49 % of initial volume). On the other hand, in terms of water resistance the prototype n° 25 present characteristics similar to other two prototypes.

### 3.2. *Mechanical and thermal properties characterisation of selected BcFWB*

Results from tensile tests carried out on the prototype n° 25 are shown in Fig. 7 as an example. A bilinear trend can be observed with a transition knee in between. The sample average ultimate tensile strength was 1.274 ± 0.136 MPa; the average Young's elastic modulus ($E$) was 0.161 ± 0.063 MPa (see Fig. 8).

The DMTA diagram (Fig. 9) shows the Young's elastic modulus (Pa) and the Loss Modulus and *Tan δ curve* in relation to the temperature (°C). The DMTA revealed that the $T_g$ of the prototype n° 25 was – 3.0 ± 0.4 °C.

At the end, the contact angle measured for the prototype n° 25 was 80.47° ± 9.48° and in Fig. 10 is reproduced the contact angle obtained between the drop of water and the surface of the sample during the measurement.

## 4. Discussion and future perspectives

### 4.1. *Strengths and criticalities of DIY bio-composite materials through MT*

The adoption of creative DIY approach to explore opportunities offered by aquatic weeds biomass led to obtain a set of bio-based materials with varied properties depending by quantities and qualities of natural ingredients and protocols used to produce them. This study performed through *trials and errors* innovation process investigated the opportunity to use aquatic weed biomass as filler to create a bio-based composite materials. The study was performed using polysaccharides-based matrices, using agar-agar, carrageenan and corn starch, and protein-based matrices, using animal gelatine and isinglass. While additives such as glycerine, acetic acid, baking soda and natural soap are involved during hand-on experimentations to improve or change properties of obtained prototypes.

The preliminary MT was essential to adjust step-by-step first protocols and create new ones in other to obtain desired properties (Santulli and Rognoli, 2020). For example, the protocols n° 2, 4, 5, 10, 13,14, 16, 17 and 18 involved same ingredients used in different quantities: these prototypes are obtained from agar-based matrix combined with glycerine, baking soda, and acetic acid as additives, and aquatic weeds biomass as filler. Moreover, prototypes n° 2 and 18 are obtained performing the drying stage at room temperature, while other seven prototypes were obtained using infrared lamps for drying process. At the end, prototypes produced following similar protocols presented

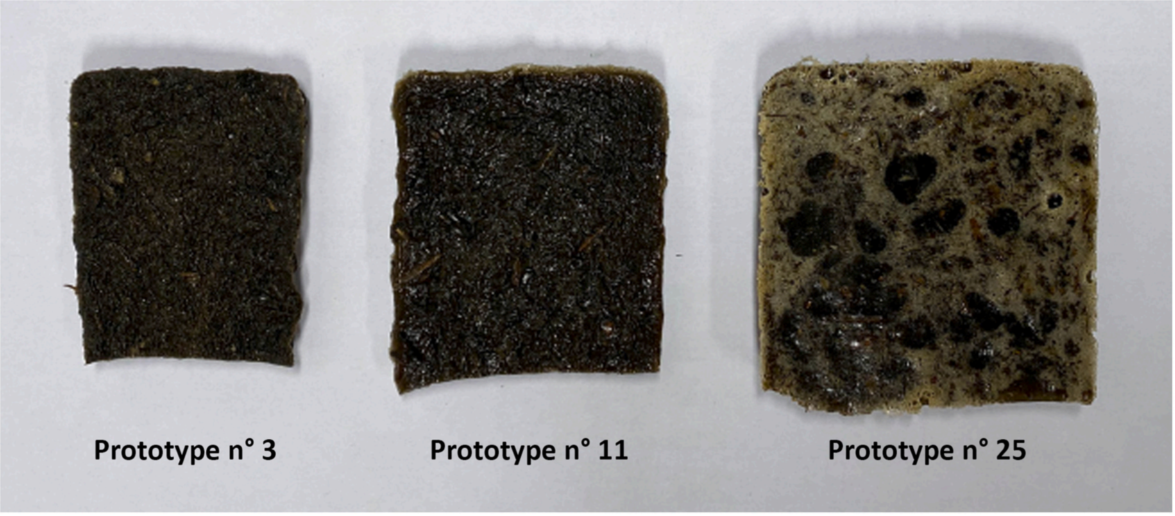

**Fig. 4.** Rectangular replicates of three selected prototypes n° 3, 11 and 25.

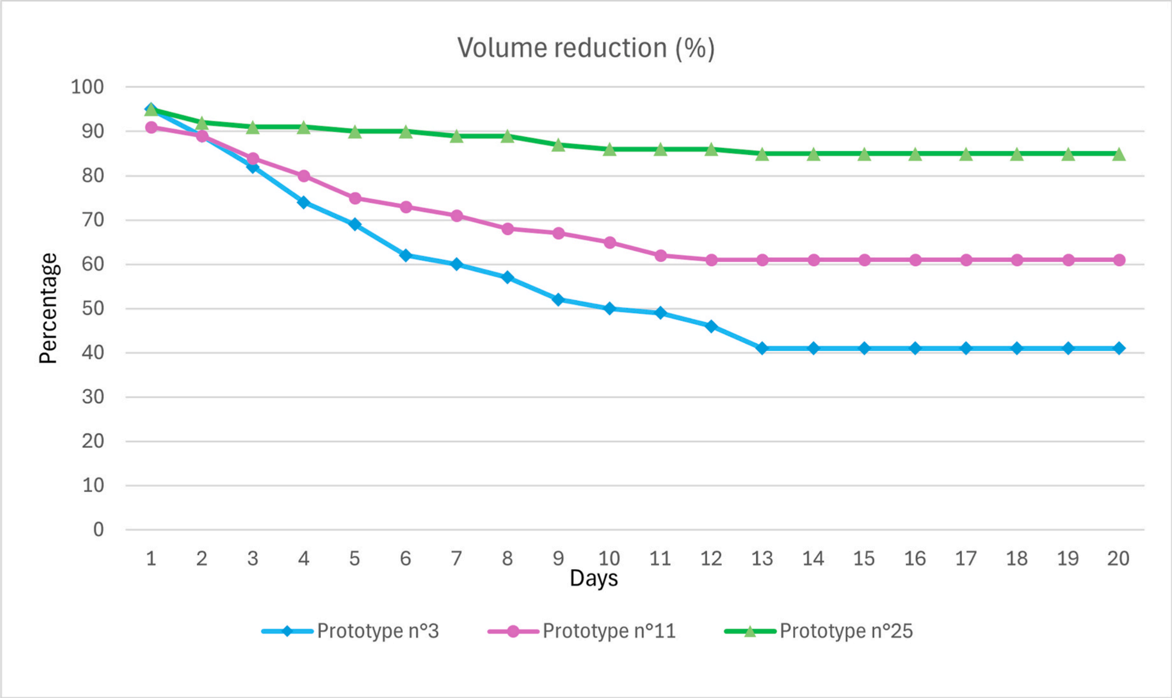

**Fig. 5.** Volume reduction (in %) of the three selected prototypes monitored during the 20-days of drying stage.

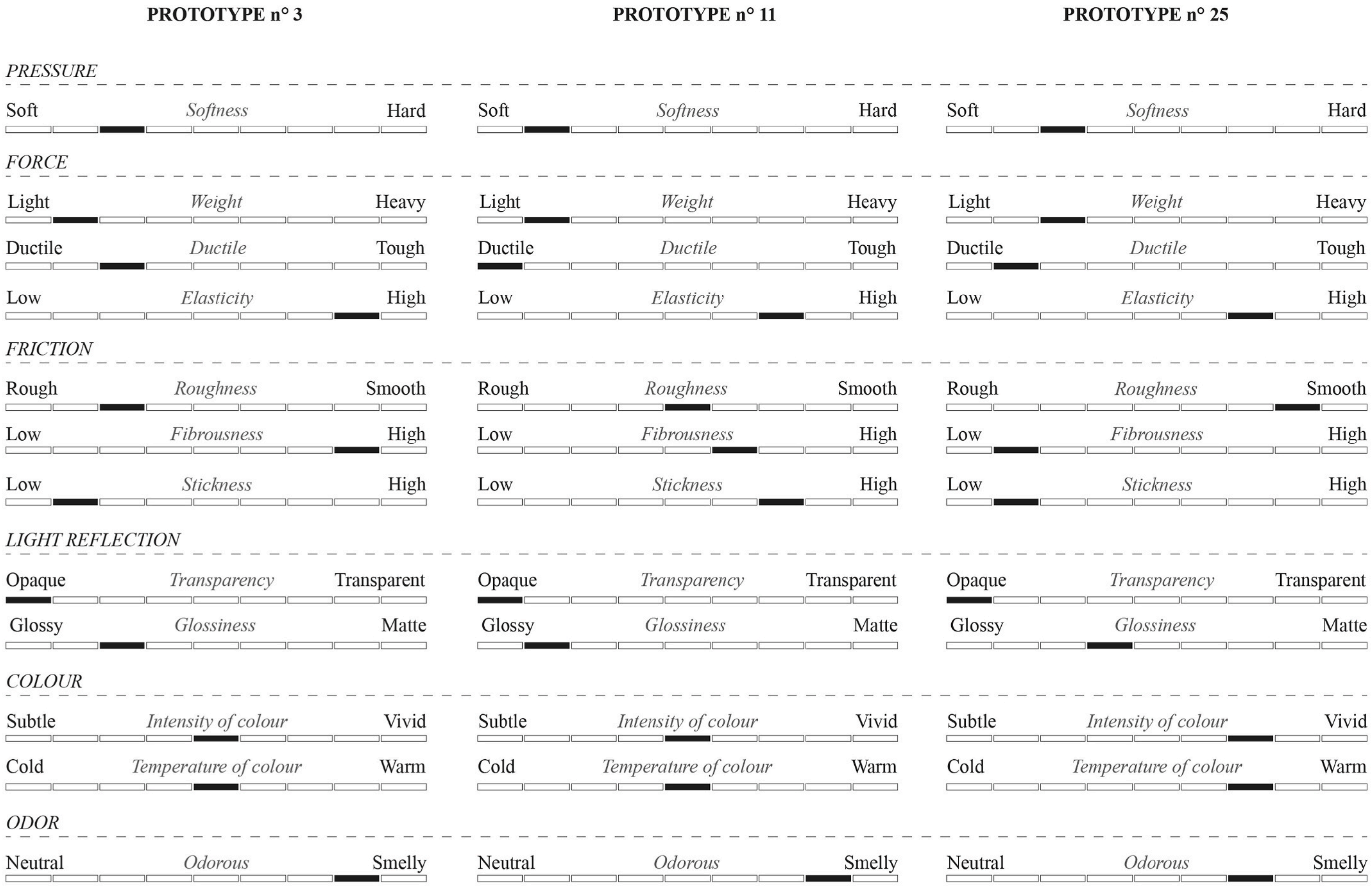

**Fig. 6.** Results of MT carried out using the 9-point sensorial evaluation scale and obtained during the 90-min focus group.

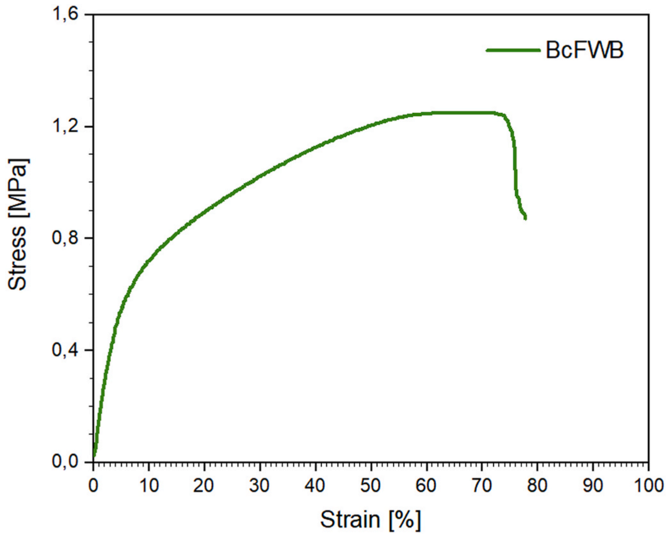

**Fig. 7.** Stress-strain diagram obtained from tensile tests conducted on five replicates of selected BcFWB (prototype n°25).

different characteristics and morphological features. Prototypes obtained using infrared heat lamps (n° 4, 5, 10, 13, 14, 16, 17) presented criticalities concerned volume reduction and morphological uniformity: prototypes tend not to retain their original shape and surface characteristics due to temperature reached and the short time needed for the drying stage. Infrared heating, often adopted in food industry, doesn't seem to be suitable for this production process despite lowering the drying time can increase the productivity (Pawar and Pratape, 2017). Considering critical issues reported by prototypes obtained using infrared heat lamps, the drying stage carried out at room temperature was preferred to maintain properties such as elasticity and surface finishing at the end of the process. Among all protocols, prototypes n° 2, 3, 6, 11, 23, 25 and 27 presented promising final results in terms of consistency, homogeneous morphology and surface finishing. These prototypes were obtained through drying process conducted at room temperature for 48–72 h. Anyway, the drying stage conducted at room temperature requires long periods (20 days) and undergoes variations in temperature and relative humidity that cannot be fully controlled in the DIY material design practice. The drying stage should be improved increasing the control of temperature and relative humidity to ensure dimensional and quality standard of samples.

The study demonstrated that ingredients and prototype compositions influence materials properties and final morphology and consistency. Indeed, between selected prototypes, the monitoring revealed that the n° 25 obtained using animal gelatine-based matrix presented lower volumetric reduction than prototypes n° 3 and 11 obtained from agar-based matrices. Considering the role of glycerine as plasticizer (Fauziyah et al., 2021), varied amount of it may influence the elasticity of bio-based material prototypes (Benitez et al., 2024a,b). Protocols of selected prototypes n° 3, 11 and 25 included higher amount of glycerine than other protocols (respectively 12.12 wt%; 19.51 wt%; 33.70 wt%).

In addition to volume reduction, Armynah et al. (2022) stated that

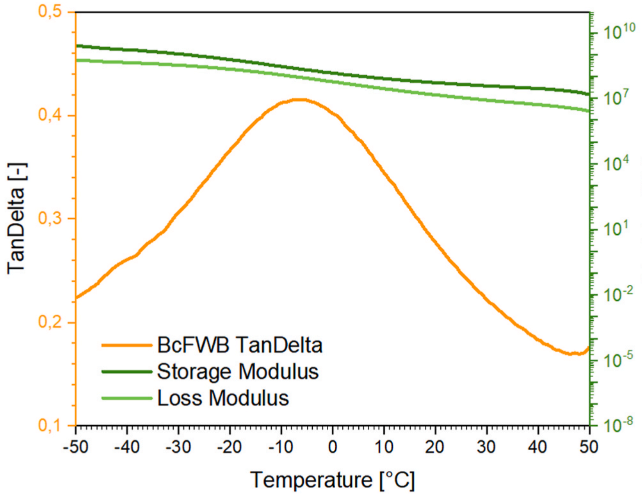

**Fig. 9.** Tan Delta curve obtained from DMA conducted on three replicates of selected BcFWB (prototype n°25).

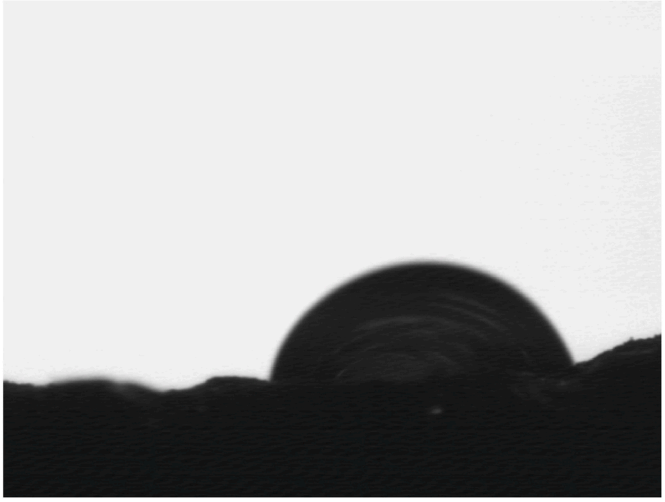

**Fig. 10.** Picture of the contact angle obtained during the wettability test carried out on the selected BcFWB (prototype n°25).

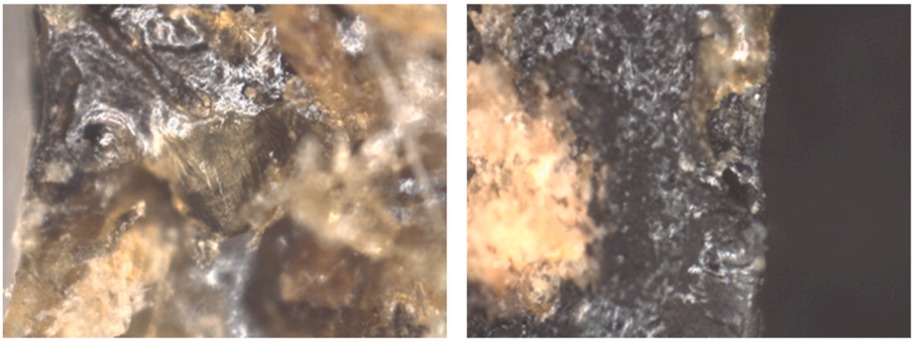

**Fig. 8.** Electron microscope imaging of failure surfaces of samples 5 (left) and 2 (right). In yellow is indicated the matrix of samples, while in black the filler of freshwater vegetation biomass. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

starch-based materials show low water resistance due to high hydrophilicity and poor mechanical properties that must be improved using fillers or additives to enlarge the set of potential applications. Agusman et al. (2021) demonstrated that ingredients ratio and water content in agar-based materials influence permeability, moisture content and contact angle. While, Mohajer et al. (2017) contrasted high hydrophilic nature of gelatine-based films adding agar-agar to improve their water vapor permeability and solubility of mixed composites.

Results obtained in this study are in line with previous investigations: prototypes n° 3 and 11 as agar-based composites showed higher water resistance (50–60 min) than prototype n° 25 (40–50 min). In particular, DIY tests conducted to evaluate water resistance of prototype n° 25 revealed that it irreversibly changed its morphology and properties after 60 min of immersion in tap water.

The direct manipulation adopted in preliminary MT offers suggestions for potential practical applications in varied environmental conditions. For example, characteristics such as flexibility and elasticity shown by prototypes n° 3 and 11 suggest that characteristics of these bio-based materials can be improved to develop non-trauma floors, gymnastics and landing mats or playground floors (Schwanitz et al., 2024; Mills et al., 2006). While, features presented by the prototype n° 6 as lightweight, porosity and flexibility can be enhanced and improved for acoustic and thermal insulation applications (Binici et al., 2016). Similarly, characteristics such as stiffness and notable compressive strength presented by the prototype n° 2 can be further investigated and explored in order to obtain bio-based thermosetting polymers with properties similar to resin-like materials (Liu et al., 2021; Bobade et al., 2016).

The MT conducted using the *9-points hedonic scale* highlighted similarities and differences between selected prototypes n° 3, 11, and 25. Considering tactual properties, the prototype n° 11 (2 points) was considered slightly softer than n° 3 and 25 (3 points), and the most ductile one (1 point). Prototypes n° 3 and 11 (2 points each) were evaluated lighter than n° 25 (3 points), and the n° 3 was the most elastic one (8 points). About surface finishing, MT carried out by participants revealed that the prototype n° 25 presented a surface finishing smoother (8 points), less fibrous (2 points) and stick (2 points) than other two prototypes.

Looking at visual properties, all three prototypes were considered equally opaque (1 point), while the prototype n° 25 presented a less glossy finishing (4 points) than prototypes n° 3 and 11 (3 points and 2 points). Moreover, the prototype n° 25 presented a more vivid and warm colour than other two prototypes.

At the end, the prototype n° 25 was evaluated the less smelly (i.e. the prototype that produced less freshwater biomass odor), and this characteristic was considered particularly important for focus group participants. Considering the whole properties evaluation, the prototype n° 25 was selected as the most promising in terms of practical applications thanks to high visual properties, surface finishing, elastic behaviour and softness to pressure. Moreover, the prototype n° 25 presented the less volume reduction (-15 %) during the drying stage than prototype n° 3 (-59 %) and 11 (-49 %). For this reason, the prototype n° 25 was considered the most stable and most promising BcFWB for product design and practical applications.

### 4.2. Mechanical and thermal properties of selected BcFWB

Looking at the characterisation of mechanical and thermal properties, the UTS of the prototype n° 25 is in the range of values for PU (UTS 0.138–79.3 MPa), but the E value is lower than PU Young's modulus (1.14–3540 MPa) (MatWeb, 2024a). Moreover, the bilinear trend of the stress-strain curve describes a plastic behaviour in which matrix and filler present different tensile strengths and breaking points. The microscopic observation of tensile failure surfaces does not show pull-out phenomena thus showing a comparable resistance to failure of matrix and charge. Nevertheless, the change in the slope of the tensile curve can be related to the "brittle" failure of the charge followed by the elastoplastic behaviour of the matrix. The same microscopic observation shows a good adhesion between matrix and charge which can work for a collaborative and continuous contribution to strain and failure resistance.

For further investigations, this trend suggests to optimise the quantities of matrix and filler in the formulation to improve the tensile strength and resistance to stress of the BcFWB. These improvements can facilitate the BcFWB effective application in plastic industry such as footwear industry as substitute of fossil-based plastics.

The DMTA analysis showed that the Tan δ peak occurred at an average of $-3$ °C, aligning with similar systems reported by Thomazine et al. (2005). The relatively broad peak in the DMTA curve suggests a heterogeneous structure, likely due to filler dispersion, as illustrated in Fig. 9. This dispersion could be further improved. Nevertheless, the material maintains good mechanical properties within the application temperature range, as evidenced by the modest variation in the storage modulus ($E$). In terms of thermal properties, the prototype n° 25 exhibited a Tg of $-3.0 \pm 0.4$ °C which is significantly is higher than that of EVA (~$-33.1$ °C) (Agroui et al., 2012). However, it demonstrates similarities to TPU materials, which have a Tg ranging from $-48.3$ °C to $-5.0$ °C (MatWeb, 2024b), suggesting its potential as a viable alternative to fossil-based materials.

Moreover, the wettability test conducted on the prototype n° 25 revealed that the WCA between water and the BcFWB surface was 80.47° ± 9.48° confirming that the material surface is hydrophilic (Zhang et al., 2024). The standard deviation (±9.48°) indicates that surface finishing of samples involved in wettability analysis are not homogeneous due to the DIY nature of prototypes production. This result is inside the WCA range (60°–100°) of many polymers that are moderately hydrophobic (Vesel et al., 2024). The WCA presented by the prototype n° 25 was similar to results obtained by Long et al. (2022) for ethylene-vinyl acetate (EVA) (WCA = 88.1°) that is a copolymer widely used as thermoplastic or elastomer in footwear industry (Ma et al., 2014). The result obtained in this study is also close to the WCA measured by Ayyar et al. (2017) for polyurethane (PU) (WCA = 86°). While, thermoplastic polyurethane (TPU), well known for its hydrophobic behaviour, high tensile strength and abrasion resistance (Ma et al., 2014), presents WCA between 99° and 110° (Xie et al., 2024; Douglas and Haugen, 2008). Anyway, the result obtained in this study suggests modifying or adjusting the protocol n° 25 to increase the contact angle (>90°) to obtain a hydrophobic material surface and consequently improve the BcFWB durability when exposed in contact with water.

### 4.3. Future perspectives and developments

Further investigations should focus on enhancing properties of the formulation used for the prototype n° 25. Moreover, it is worthwhile to investigate the influence of various fillers or multilayer systems composed of different fillers. Indeed, multilayer systems incorporating different fibres can be tailored to achieve specific properties, depending on requirements of the final application. Preliminary analyses performed on the prototype n° 25 suggest that properties improvement can foster its practical application as a bio-based alternative to produce shoes soles and footwear components, tool handles and covers, gaskets, vibration isolation mounts, non-trauma and non-slip floors, shock-absorbing mats and panels for interiors.

Moreover, specific and more detailed analyses should be performed on the freshwater weeds biomass in order to define its bulk density, particles morphology using a scanning electron microscope (SEM), its chemical composition using Fourier-transform infrared spectroscopy (FTIR) analysis, and its properties performed using thermal analysis. These characteristics can be useful to optimise and improve mechanical properties and thermal stability of the bio-composite, or to define physical or chemical treatments of natural fibres in order to overcome some limitations. Indeed, Sahu and Gupta (2019) reported that natural fibres face some criticalities such as low thermal stability, high moisture uptake and quality variations of particles that influence mechanical and thermal properties of bio-composites. Even more, the definition of chemical composition through FTIR analysis allows to identify the presence of plastic or metal residues in the freshwater weeds biomass that can influence biodegradation processes of bio-composites. Anyway, the composition variability of this biomass must be considered in future investigations. Indeed, it is obtained through environmental management operations of freshwater weeds with lower control and selection during the eradication process of vegetation. Further studies should also consider to use biomass derived from other types of plant species and compare results obtained on bio-based composites.

Another aspect that should be considered and improved in future investigations is the environmental impact assessment and biodegradability of these new bio-based materials. The environmental impact assessment can be important for those prototypes considered most promising for practical applications such as the n° 25. Indeed, as stated by Lago-Olveira et al. (2024) the transition towards bioeconomy requires to evaluate environmental, social and economic impact assessments of supply chains and processes adopted to provide goods and services. In the framework of Material Design, the Life Cycle Assessment (LCA) is suggested as methodology useful to identify and compare trade-offs of bio-based and fossil-based plastics. LCA performed adopting comprehensive and system-level approach will be essential to outline environmental profile of new bio-based polymers especially during the transition from laboratory towards industrial scale. Concerning biodegradability, further investigations should focus on defining bio-based composites' biodegradation profile in different environments (soil, compost, or aquatic systems) and conditions (controlled and natural) (van der Zee, 2020). These studies must take into account European standards, national guidelines, and laboratory methodologies already adopted to assess if polymers are fully biodegradable or compostable of if they release hazardous compounds during degradation (Pires et al., 2022).

## 5. Conclusions

This study shows potentialities offered by the DIY approach to valorise freshwater vegetation biomass as filler for reinforced bio-based composites. Using handcraft tools and low-tech procedures and only natural and biodegradable ingredients, the DIY approach allows to explore opportunities and criticalities of bio-based composites obtained from this study as substitute of elastomeric materials. This study demonstrates how the DIY approach can be adopted as framework to foster innovation and creativity in the field of material science. On the other hand, the MT performed in this investigation was a useful tool to identify a single formulation (of the prototype n° 25) among others as the most promising one to produce a *rubber-like* material. In the framework of DIY materials, the MT performed using the *9-point hedonic scale* allowed to compare varied prototypes related to specific sensorial properties. Even if the most prototypes presented some limitations and criticalities such as the resistance to wettability, they can inspire further experimentation involving the same filler or other natural fibres as bio-composite reinforcements. Moreover, results obtained from mechanical and thermal characterisation are promising and suggest adjustments and changes in the formulation itself to improve mechanical and thermal properties. Moreover, this approach is in line with principles of the circular economy, as it reduces the generation of waste and supports resource efficiency, thus promoting sustainability. Indeed, the reuse of organic waste and by-products as secondary raw materials in the field of bio-plastic industry can reduce the demand for new resources, consequently reducing the environmental impacts related to their extraction or synthesis and promoting the transition towards a *zero-waste* economy.

## CRediT authorship contribution statement

**Laura Dominici:** Writing – original draft, Visualization, Supervision, Methodology, Conceptualization. **Anna Fornaseri:** Visualization, Investigation, Formal analysis, Data curation. **Martina Grassi:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Dumitru Moraru:** Writing – review & editing, Validation, Investigation, Data curation. **Marco Sangermano:** Validation, Resources. **Raffaella Sesana:** Writing – review & editing, Validation, Resources. **Elena Comino:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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