Food waste: potential bioresource for the colour of polymers

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ABSTRACT

The paper proposes the results of the research carried out by the authors on the theme of sustainable product design starting from the material component. In this context, there is a significant link between bio-materials and their chromatic value, originated by the pigment of natural origin, which is mainly responsible for the aesthetic characterization of the product. To support this thesis, a methodological approach has been adopted, developed in two phases: the first is critical - analytical (desk) and identifies the framework of the research and the state of the art; the second is applicative - experimental (field) and proposes some original experiments that include both the definition of new polymeric materials, obtained by adding waste coffee and sea urchins, and the characterization of optical and chromatic qualities, also conducted through technical tests instrumental mechanical strength.

The results of the research arrive at hypotheses of mechanical and optical characterization, however the scalability of the results to the industry would require the use of appropriate instrumentation in the preparation phase of the materials (in this phase of study they were composed through an artisanal approach).

KEYWORDS Food waste, Organic colour, Bioresource, Sustainable product design, Digital manufacturing

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1. Introduction

The paper proposes the results of the research carried out by the authors on the theme of sustainable product design starting from the material component (Di Roma et al. 2019). This research was carried out in the Design_Kind research and teaching laboratory, with the collaboration of the company Crea 3D and the mechanical testing laboratory of the DMMM Department of the Politecnico di Bari. In the field of product design, there is a significant link between bio-materials and their chromatic value, originated by the pigment of natural origin, which is mainly responsible for the aesthetic characterization of the product. To support this thesis, a methodological approach has been adopted, developed in two phases: the first is critical - analytical (desk) and identifies the framework of the research and the state of the art; the second is applicative - experimental (field) and proposes some original experiments that include both the definition of new polymeric materials, obtained by adding waste coffee and sea urchins, and the characterization of optical and chromatic qualities, also conducted through technical tests instrumental mechanical strength.

The logical bases of the research are based on the need to offer a critical contribution to the reflection of design, which on the one hand is measured by the theme of environmental pollution associated with the production and use of synthetic dyes, on the other hand defines a new phase of material culture that is based on the (re)acquisition of an aesthetic sensitivity associated with natural materials, with particular reference to those obtained using waste from the food and non-food sectors of the agri-food (Scarcelli 2017).

With reference to the state of the art of the artistic industry, the paper shows how colour has always played a fundamental role in describing the link between the aesthetic sensitivity of a civilization and the technical means at its disposal (Kubler 1976): the culture of colour is the synthesis of scientific and technological innovation and the artistic sense of time. It is argued that in the "chain of time" that links colour to material culture, humanism and the first industrial revolution have impacted with profound changes.

With reference to the current scenario, the development of a new approach to the theme of color as a material that supports the growth of green chemistry through experimentation and self-production of bio-materials is highlighted.

2. Return to the origins of the material colour

In the history of art and artistic manufacture, colour takes on a primary role, since each civilisation, starting with the first representations on the rocky walls of the Lascaux caves, has been characterised by its own culture of colour. Scientific discoveries and technical innovations accompany the evolution of the chromatic world in art, translating into tastes and styles shared by the material culture in the most common objects of use, from pottery to clothing. Coloring the material means knowing how to masterfully manipulate pigments, tints and dyes; it means knowing ancient recipes and procedures to be skilfully adopted on different supports. In the ancient world, this science had a precise name, before becoming chemical: Alchemy.

Until the dawn of the fourteenth century, color was a priority in art, evident in the recognized expertise of the artist in the preparation of colored powders, like the craftsmen: the color was produced in the workshop, with processes of manufacturing of organic and inorganic materials made available by the local land.

"This is the why the grinding of a colored powder may affect its hue - a phenomenon exploited by the artists of the middle ages, who controlled the shade of a pigment by the degree of grinding" (Ball 2003).

Among the Guild of Arts and Crafts of Florence, in the '300 painters chose to join the Art of Medici and Speziali precisely because of the presence of pigments and dyes in their shops.

Humanism led to a separation of art from technique, of intellectual activity from manual activity, and this led to a greater attention of artists to the role of drawing at the expense of color, which remained an exclusive activity of craftsmen, especially ceramists, glassmakers, goldsmiths and tailors: the pigments were no longer processed by painters but purchased ready by traders, in increasingly wide color ranges. The advent of the Industrial Revolution, in addition to determining new market needs and new quantities to be satisfied in the consumption of goods of use, introduced the chemical industry of colorants into the artistic world, able to produce synthetically in the laboratory products cheaper, in practical tube packaging, and especially available in colors until then unimaginable. The colour naming, previously associated with the material origin, is identified by a number perfectly corresponding to its reproducibility according to artificial processes: red, for example, is no longer cinnabar, carmine or purple but, choosing the colour coordinates in CMYK, becomes 0-80-100-0, 0-75-42-1 and 30-100-100-0. In other colour systems it is possible to obtain other codes which, however, do not tell us anything about the colour or its history (Di Roma and Scarcelli 2017).

Another fundamental aspect of modernity is represented by the affirmation of the solid colour, which underlines the need to standardise and make constant the colour of a material in all its consistency, highlighting the artificial character of the perfect industrial product against the inconstancy of the imperfect handmade product. "*La frequentazione dei linguaggi industriali comporta infatti che del colore oggi predichiamo prevalentemente la tinta… quando diciamo "tinta", diamo per scontato che sia unita. Insieme ai pigmenti sintetici, quest'idea di compattezza è forse la vera e più importante novità del mondo moderno*" (Falcinelli 2017).

3. Research Framework

The theme of colour associated with industrial products is fully integrated into the history of industrialism and identifies the area that has given rise to the development of the contemporary chemical and pharmaceutical industry.

"*Il maggior sforzo della chimica industriale fu quello di produrre tinte derivandole dalle scale coloriche di quelle naturali già selezionate dal gusto e dall'occhio, ma imponendo, infine, quelle prodotte come più convenienti ed eliminando di fatto quelle più rare, care e di difficile produzione*" (Brusatin 1999). As far as the development of the material is concerned, there is a progressive substitution of the raw materials of organic origin with the polymeric materials of fossil matrix and by chemical synthesis.

"*I coloranti sintetici, vengono facilmente inglobati nella massa plastica durante il processo di stampaggio; ciò fa si che il colore diventi il carattere distintivo del design del tempo, che dall'imitazione dei marmi e madreperle passa a sapienti "urli" cromatici che denunziano la loro artificialità, spesso ispirata all'uso ardito dei colori dei Fauves; agli inizi degli anni '30, la Catalin Corporation, la più importante ditta statunitense a produrre oggetti in resine fenoliche fuse, comprendeva 200 tinte, dai colori compatti e pastello a quelli traslucidi e perlati*" (Ferrara 2012).

On the other hand, today, the theme of sustainability applied to materials and products opens up a new phase of reflection in design that goes hand in hand with developments in the so-called green chemistry industry. In this context, the contribution of scientific research on bioplastics is of great importance: these, in fact, give back to the reflection of design the chromatic qualities of the material in its natural meaning. In particular, the "artisan" production of the product from the material defines a new field of experimental research and the self-production of the material (Rognoli et al. 2015) thus becomes an indispensable moment in the definition of the new product. A new dialectic is established between material and product: one influences language, the other influences the technical performance of the product. Below is a selection of case studies identified during the desk phase of the research that defines the framework of the proposed research: the main assumption is the aesthetic value of the bio-based polymer, rather then the technical performance, this in order to define and develop a new sensibility on color.

3.1. *Shellworks*

This is a project carried out by Ed Jones, Insiya Jafferjee, Amir Afshar and Andrew Edwards of the Royal College of Art and Imperial College of London that develops a system of machines and instrumentation suitable for the extraction of chitin from the exoskeleton of crustaceans. The aim is to produce biodegradable and recyclable disposable packaging from crustacean waste (Fig. 1). Chitin is a biological polymer that, when mixed with vinegar, produces a bio-plastic. The chromatic gradient obtained is the result of the different type of vinegar used and the different dosage of the components, which is also associated with a gradient referred to the optical clarity of the material and the different specific thickness.

Fig. 1. Shellworks (2019) at the Royal College of Art and Imperial College London by E. Jones, I. Jafferjee, A. Afshar and A. Edwards. Bioplastic based on vinegar and chitin extracted from the shell of crustaceans. Image courtesy: www.dezeen.com/2019/02/22/shellworks-bioplastic-lobster-shell-design)

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From scientific literature it is evident the wide interest in chitin and its main derivatives (chitosan), because this new family of biological macromolecules shows excellent proprieties such as non – toxicity, ability to form film, biodegradability, biocompatibility. All this aspect as defined a wide field application: in the field of medicine, food, biotechnology, agriculture and cosmetic industry (Alabaraoye E. et al. 2017).

3.2. *AlgaeLab*

This is a laboratory that consists of a structure for the cultivation, harvesting and drying of algae for the production of starch suitable for the production of bioplastics (Fig. 2).

Fig. 2. AlgaeLab (2017) at the Luma Atelier in Arles by Erik Klarenbeek and Maartje Dros. Algae bioplastics and container production through rapid printing. (www.dezeen.com/2017/12/04/dutch-designers-eric-klarenbeek-maartje-dros-convert-algae-biopolymer-3d-printing-good-design-bad-world)

The project Algae Lab won the New Material Award in 2018. Klarenbeek & Dros have set up the Algae Lab in collaboration with Atelier Luma. Their project is based on the collaboration of a wide number of experts from various discipline that includes scientist of materials and designer. The definition of the new polymer is suitable to be used in the FDM technology systems, and actually the project is shifting from the small size to largest one trough a specific technological research on 3d printing system. This line of research aim at rising up the local economy and employment, giving evidenc about social inclusiveness potentiality of the project.

3.3. *That's It*

Austeja Platukyte, a student at the Vilnius Academy of Arts, developed the project for a bioplastic produced by the addition of agar, extracted from algae, with calcium carbonate, reinforced with an emulsifying wax (Fig. 3).

Fig. 3. That's It (2016) at the Academy of Arts in Vilnius of Arles by Austeja Platukyte. Bioplastic based on algar and calcium carbonate reinforced with emulsifying wax. (www.austejaplatukyte.com/project-15)

The produced material is lightweight and whaterproof, suitable both for packaging solution and product design, as well. After the primary use of the material it could be composted or used as fertilizer.

4. Coloring the material: Caffil and Echinmat

This section summarizes the results of the original research outcomes, conducted in the Design_Kind Laboratory at the Politecnico di Bari, which led to the development of physical samples, characterized by a double composition, as they consist of the basic polymer added with food waste: it is precisely the waste that gives new perceptive qualities to the plastic material, first of all the inhomogeneity of color. The chromatic characteristics of the inclusion powders mainly affect formal variations, based on the detection of the natural colour of the organic compound used, which can be distinguished in the various samples produced.

4.1. *Caffil*

In the first case, the material produced is the result of an experiment started in the didactic and research laboratory Design_Kind of the Politecnico di Bari coordinated by the authors together with the students Antonello Monitillo and Ivan Saccotelli of the CdL in Industrial Design, in collaboration with CREA 3D, a company specialized in 3D printing machines located in Ruvo di Puglia.

The result is Caffil, a PLA filament for rapid prototyping, characterized by an internal composition with a percentage of coffee powder, resulting from the post-production poses of bars and restaurants. The material is

100% biodegradable and compostable. The choice of the material comes from the reflection on the great quantity of food waste deriving from the bottom of coffee produced by every gastronomic activity, bar, restaurant in the Italian territory, which generally does not undergo a differentiation in the waste cycle, nor a diversification for recycling. The hypothesis of reuse of this waste has been supported by the state of the art verification of other experiences of material experimentation starting from the coffee waste, including Kaffeeform, Decafè, C2C coffee cup, NAT2 vegan, and others (Fig. 4).

Fig. 4. Examples of products made from coffee waste material. From left: Kaffeeform, Decafè, C2C coffee cup, NAT2 vegan.

What distinguishes Caffil from other experimented materials is the desire to define a new material class, rather than a defined and finished product, able to open infinite creative possibilities and to generate classes of products from new material qualities.

In general, coffee powder is obtained by grinding the seeds of some tropical tree species belonging to the Coffea genus: although it is not a typical dyeing plant, coffee is part of the Rubiacee botanical family, to which belongs, among others, the Robbia, a spontaneous plant from whose roots the famous garanza lacquer was extracted.

For the extrusion of the Caffil filament, an Italian experimental machine was used, the Felfil Evo, a plastic extruder capable of producing personalized filaments with a recycled base for 3D printers, starting from industrial pellets or plastic waste.

The preparation of the materials involved a drying process, in an electric oven for several hours at a constant temperature of 60°C, both for the coffee grounds and for the PLA pellets, in order to remove any water and humidity present. In addition, the coffee has been sieved to uniform the grain size of the compound.

To extrude a filament with PLA, the machine must reach a temperature of 187 °C, and then set a printing speed of 50-120 mm/s; once the temperature has been reached, the materials can be inserted in the upper pocket.

The extrusion temperature affects the color and strength of the material. When the temperature exceeds 190°C, the material enters a glassy phase, which increases its fragility: with the same dosage, the material tends to behave differently between 190°C and 200°C, passing from a plastic to a glassy state, before starting to carbonize at around 210°C. Even the coffee must remain roasted and must not carbonize, to avoid giving a dark color and increase the fragility of the material.

In the first phase, to understand the behaviour of the composite material, different doses of the elements, different temperatures and different times were tested in order to define a stable and repeatable recipe. In fact, following some preliminary tests, to optimize the production process the machine underwent some changes, including a track with side pockets equipped with cooling fans, so as to guide the wire quickly on the winding coil. In the end, a filament with a diameter of 1.75 mm was chosen, with three different percentages of coffee compared to the PLA, 8%, 10% and 20%; with this dosage different filament reels were made (Fig. 5).

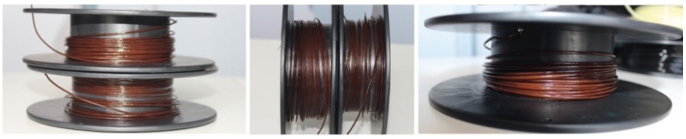

Fig. 5. Caffil Filament Reels, 8%, 10% and 20%.

The experimentation continued with the technical verification of the material following 3D printing.

4.1.1. *Mechanical test*

For the mechanical stress test, 20 dog-bone test pieces were produced (Fig. 6), printed with the three different percentages of compound, according to three different extrusion directions, 0°, 45° and 90°, and different thicknesses.

Fig. 6. Samples of 3d -printed Caffil for the stress tests.

Mechanical analysis of the test pieces was carried out in accordance with the international ASTM D638-14 standard, which specifies the test conditions for determining the strength properties of unfilled and reinforced plastics. These properties include rupture, deformation at rupture and modulus of elasticity. The mechanical properties of plastics can change dramatically when some additives are incorporated into the formula, in particular strength and ductility. Tensile strength tests were carried out in the optical test laboratory of the Politecnico di Bari, using an INSTROM uniaxial loading machine with a maximum load cell of 1 k/N. The samples were analysed maintaining a constant traction speed, corresponding to 5 mm/min, to evaluate the variation of the load supported. Tensile tests have shown that the organic compound added to the PLA causes a decrease in the original elasticity of the material and therefore an increase in brittleness, with acceptable values up to a maximum percentage of dust of 20% (Fig. 7).

20%	E[MPa]	σrott
B1	1410,6	11,44
B2	113,3	13,94
B3	1360,2	8,90
B4	1171	8,04
B5	1321	7,95
B6	1069	8,56
B7	1220,3	9,77
B8	1120,9	7,71

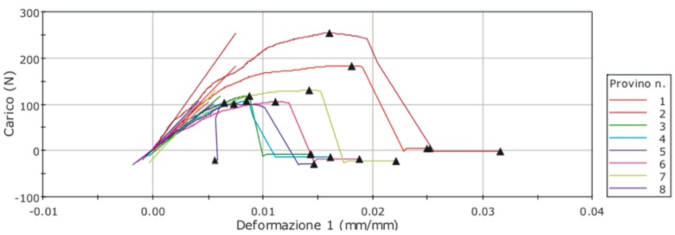

Fig. 7. Samples dog-bone at 20%. Data table: transition point from elastic to plastic deformation and breaking point. Stress/strain graph tensile test.

4.1.2. *Optical test*

For the optical test, 9 square 70x70mm demonstrators were produced, printed with the three different percentages of compound and three progressive extrusion heights. In fact, to evaluate the yield of the printed filament in relation to light, the samples have a variation in thickness, one layer (0.3mm), two layers (0.6mm) and three layers (0.9mm). The test, of a subjective type, evaluated the chromatic qualities and the qualities of transparency of the material, lit directly from a natural and backlit source (Fig. 8).

The coffee powder is not soluble in PLA, and consequently does not "dye" the plastic compound, but has a significant effect on its colour rendering. The density of the inclusion material affects the degree of brightness of the sample, which has a darker shade as the percentage of coffee powder increases and as the layer thickness increases.

The particular mixture of the material gives each print a different texture, determined by an uneven distribution of the coffee in the PLA and therefore in the filament.

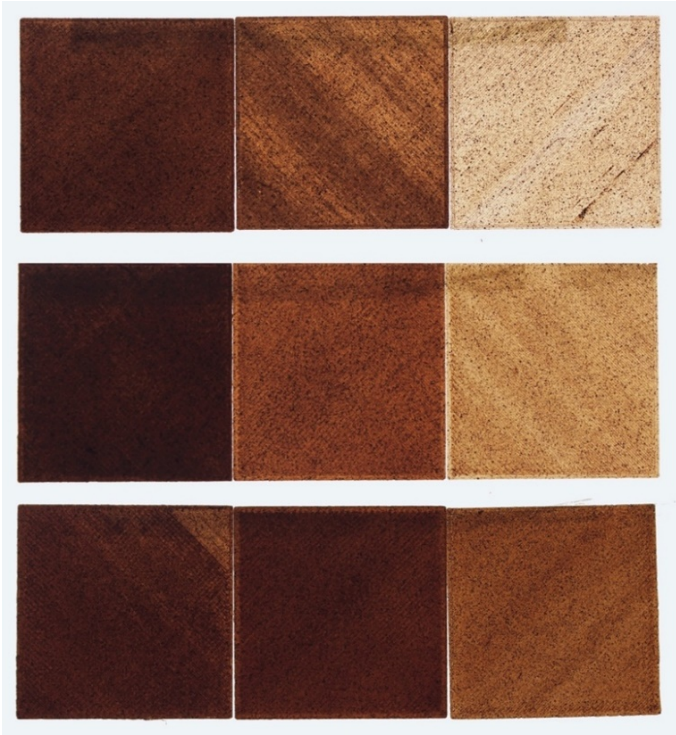

Fig. 8. Backlit Caffil samples for optical performance. From above, proceeding in rows: Coffee 8% (3 layers, 2 layers, 1 layer); Coffee 10% (3 layers, 2 layers, 1 layer); Coffee 20% (3 layers, 2 layers, 1 layer).

In order to obtain a correspondence of the colour value of the new material with conventional colour spaces, a colour measurement was carried out on the test specimens using an NCS reader.

Different colour variants were detected in each sample, determined by the variegated texture of the material. Therefore, it was not possible to assign a unique colour, but a palette of at least 4 different chromes. The figure 10 shows the matches of NCS values for each piece.

4.2. *Echinmat*

Again, the material produced is the result of a recent experimentation carried out by the authors in the Design_Kind Laboratory, in collaboration with some students of the CdL in Industrial Design, Federica Cardanobile and Flora Dell'Acqua.

Caffil 8% 3 layer	S6020 Y90R	S7010 R10B	S7010 Y50R	S8010 Y50R
Caffil 8% 2 layer	S3030 Y40R	S4020 Y60R	S5020 Y40R	S6020 Y70R
Caffil 8% 1 layer	S1505 Y30R	S2010 Y10R	S3010 Y40R	S3020 Y30R
Caffil 10% 3 layer	S8005 G80Y	S8010 Y50R	S8005 R20B	S8505 Y20R
Caffil 10% 2 layer	S5020 Y30R	S5030 Y70R	S6020 Y30R	S7010 Y50R
Caffil 10% 1 layer	S1515 G90Y	S2020 Y20R	S3020 Y60R	S4020 Y30R
Caffil 20% 3 layer	S7010 Y70R	S7010 R10B	S8010 Y50R	S8505 Y20R
Caffil 20% 2 layer	S7010 R10B	S8010 Y50R	S8505 Y20R	S8505 G80Y
Caffil 20% 1 layer	S5020 Y70R	S5030 Y50R	S6020 Y20R	S7010 Y50R

Fig. 9. Table of NCS colour palettes corresponding to the Caffil samples.

The food waste adopted in this experience was chosen by evaluating the traditional consumption of fish products in the Apulian territory. In particular, the sea urchin was selected for the formal quality of its shell and for its properties of reflection and chromatic variation when subjected to light radiation (Fig. 10).

Fig. 10. Sea urchin shells, chromatic variations obtained from exposure to light

An analysis of the data of the Coastal Conservatory shows that in Italian waters alone there is an annual withdrawal of about 32 million sea urchins, with an induced of about 9 million euros. However, although their shells are food waste, they are not differentiated and recovered, since the calcareous composition of calcium carbonate makes them waste of an inorganic nature, incompatible with the accelerated composting process. This aspect has encouraged the "ecological" aim of the project, which is to partially reduce waste for disposal and to return a material to the world for a second life.

The sea urchin is part of the species Paracentrotus lividus. The rigidity of the dermaskeleton is determined by the union of a series of limestone plates, externally characterized by a black or greenish color and purplish shades. The spines are also composed of calcite and organic matter, and have a pigment, the "chrome spine", which gives them a very intense and dark color ranging from purple to olive green, from brown to red, from yellow to black: these shades depend on the type of nutrition of the hedgehog.

With the rejection of the curl, reduced to powder of different granulometry (Fig. 11), polymeric binders of the epoxy and polyester types were tested to evaluate their technical and aesthetic characteristics.

The use of plastic resins for the development of material samples represents a starting phase of the study, justified by practical requirements of binder availability. The choice of a variable grain size, in any case greater than 0.5 mm, has led to mould casting processes, for which a resin is used as binder (in this case PLA is not suitable, because it requires a melting phase of the material at high temperatures). In a subsequent phase of experimentation, the use of bio-based matrix resins is expected, which will have a positive impact on the environmental sustainability of the new material. To date, in fact, the efforts of academic and industrial research are focused on the production of 'bio-based' polymeric materials, but currently there is little commercial availability. The bio-based nature of these materials derives from their origin from renewable and environmentally compatible raw materials, the most important of which are: starch, cellulose, lignin, furans, terpenes, natural rubber, waxes, vegetable oils, proteins.

Before each trial operation, the waste was carefully washed with water and ethyl alcohol to remove any organic residues and eliminate the characteristic odour: immersion in the compound for 24 hours was followed by a natural drying phase for another 24 hours.

Fig. 11. Sea urchin shells, different particle size variations adopted in the project

In order to obtain material samples, it was necessary to make moulds in which to pour the composite of curl and resin. Two series of square specimens of the size 50x50x10mm were made, obtained by varying exclusively the granulometry of the compound and the type of aggregating agent: the first series was obtained by mixing an epoxy resin, the second a polyester resin, both transparent (Figs. 12-13).

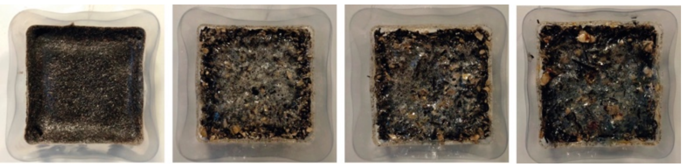

Fig. 12. Echimat: samples with epoxy resin based on different grain sizes of the sea urchin shells.

The same procedure was adopted for the production of the samples in the two series. After mixing the elements together and adding the catalyst, the compound was poured into the moulds. The main difference concerns the curing times, which are very short in the case of the polyester resin series.

Fig. 13. Echimat: samples with polyester resin based on different grain sizes of the sea urchin shells.

The tests carried out on the samples concerned the mechanical technical verification (drop test), in which the polyester samples showed greater resistance to impact, and the optical verification, through the microscopic vision of the different compounds, with a zoom of up to 10x. In this case, the polyester samples proved to be more compact and less porous than those with epoxy resin, where numerous air bubbles were visible. Moreover, the composition of the polyester resin highlights more the texture obtained from the different granulometric gradients, enhancing the chromatic variations present in it.

The tests therefore allowed the identification of the most suitable mixture for the final objective, the polyester resin compound, with which small demonstrators were made (Fig. 14), for the final verification on moulds with more complex geometries and more dimensionally consistent.

Fig. 14. Echimat: demonstrator

5. Conclusion

The paper proposes a concept referring to the color of the material through some experiments to verify the correctness of the theoretical assumptions.

The scalability of the research to the industrial fields of application is open, and in this the proposed study has the limits of an experimentation conducted 'by hand'. However, on the methodological level, a description of the steps has been offered, from experimentation to technical and performance verification, in order to enable scholars in the field to replicate the process. Among the expected effects, the project aims to enhance the socio-cultural context in which the history of color and the material culture to which it is associated is inserted, aiming at a redefinition of the aesthetic value "imperfect and inconsistent" of the chromatic quality of the pigment originating from the waste produced in the food and non-food sectors of the food industry.

6. Conflict of interest declaration

The authors declare that nothing affected their objectivity or independence and original work. Therefore, no conflict of interest exists.

7. Funding source declaration

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The contribution is the result of a common reflection of the Authors; nevertheless, paragraphs 3 and 4.2 are to be attributed to A. Di Roma, while paragraphs 2 and 4.1 are to be attributed to A. Scarcelli.

9. Short biography of the authors

Annalisa Di Roma - Architect and PhD, she is As- sociate Professor in Industrial Design at the Polytechnic of Bari (Italy), specializing in Design and Digital Manufacturing. At the centre of her research interests is the contemporary material culture of design, focused on product innovation in the context of advanced industrial standards, with a focus on the sustainability of processes, products and materials. She is the Scientific Coordinator of the Design_Kind Laboratory.

Alessandra Scarcelli - Architect and PhD, she is a research fellow and adjunct Professor of Industrial Design at the Polytechnic of Bari (Italy). She is specialized in Lighting Design. The current research area combines the transversal areas of product design and information design, with particular reference to the socio-cultural aspects.

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