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# Bioplastics made from upcycled food waste. Prospects for their use in the field of design

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**Abstract:** The negative effects on the environment of the intensive use of synthetic, oil-derived plastics to make products have given renewed impetus to the search for biopolymers derived from vegetable, animal or microbial matter that could prove to be a sound alternative in a number of applications. However, the real challenge is to create new materials from food waste and not from specially grown crops, whose production in any case comes at an environmental cost.

In recent years, the testing of substances made from food waste has increased significantly; the sheer abundance of raw materials that can be used to make them has encouraged institutional research, as well as an approach to project development that has been widely embraced by the many young designers who craft these materials.

This paper considers all aspects of these materials, starting from a historical overview. It presents interesting experiments underway and envisages possible future scenarios.

**Keywords:** Agroindustrial Design, Bioplastics, Upcycled Food Waste, Technological Transfer, Design for Sustainability

## 1. From bioplastics to synthetic plastics – and back again: the future of plastic is written in its past

Synthetic polymers produced from oil are the materials that, over the past 70 years, have changed the world of objects and their consumption times more than any other. They belong to a large family whose members include materials with highly diverse – and in many cases antithetical – characteristics, their identity is changeable, too: they can perfectly mimic any other material, but can also have an unmistakable image, given their ability to be shaped and coloured, in addition to being light and transparent.

This extreme performance, along with their affordability, has made plastics too successful for their own good, leading to their extensive spread. This has not only changed the artificial environment, but has significantly impacted the natural one as well.

The non-renewability of plastics' fossil origin; the problems of pollution caused by the high percentage of improperly disposed-of materials; and growing suspicions towards chemical substances: in the most recent years, these have all given great impetus to studies on biopolymers – bioplastics – made not from oil but from renewable sources.

We are thus beginning to reverse the course begun starting in the mid-nineteenth century, when the near-alchemy of the experiments done by visionary researchers aimed at discovering replacements for natural polymers – ivory, tortoise, rubber – that were expensive, hard to obtain, and poor in performance. Today, however, researchers around the world are busy seeking natural alternatives to synthetic plastics.

Indeed, the synthetic plastics of our own time – which, thanks to the manipulations done on the macro, micro, and nano level, astound us with their surprising performance – spring from countless attempts made in the pre-technological age. These efforts made it possible to produce the first artificial plastics obtained through rudimentary physical and chemical processing starting from molecules present in nature in amorphous form (cellulose, starches, seeds, milk proteins...): Charles Goodyear added sulphur to natural latex to obtain Ebonite (1843); Alexander Parkes developed Parkesine (1862) by mixing together vegetable oils, naphtha, and camphor; John W. Hyatt used nitrocellulose and camphor to obtain Celluloid (1869), the first widespread artificial material.



Figure 1. Title with bas relief, bois durci, an animal-based polymer obtained by mixing cow blood with sawdust. Figure 2. Ink bottle, bois durci. Figure 3. Frame, cellulose nitrate a raw material used to make Celluloid (Plart Foundation, Italy).

The age of laboratory manipulations had thus begun, and subsequent decades saw the blossoming of increasingly high-performance materials. The passage from artificial to synthetic plastics – obtained

from macromolecules not found in nature, through physical and chemical processing – was completed by Leo Baekeland, considered the father of plastics, who invented Bakelite (1907) by chemically processing phenol and formaldehyde.

The history of the synthetic polymer family, although short in comparison with that of natural materials, is one filled with conquests in terms of performance. The hundreds of new molecules patented every year present a virtually unlimited system of possibilities making it possible to satisfy all and even the most extreme needs: one need only consider the possibilities offered by technopolymers and polymer compounds.

But the problem is that synthetic polymers, as pointed out earlier, are also used improperly, with concern only for their low economic cost, and without considering their environmental cost, it is urgent to find alternatives to replace them, particularly for items that do not require considerable mechanical performance. Research is moving in this direction (Cecchini, 2014, 2015).

## 2. The enormous family of materials produced from living organisms

The natural rubber produced from the latex of a tree (*Hevea brasiliensis*) is a natural biopolymer, as is silk from silkworms, the shellac secreted by an insect (*Kerria lacca*), the lacquer that is a resin extracted from a tree (*Rhus verniciflua*), amber, horn, ivory, and a host of other protein- and sugar-based natural substances. But when we speak of artificially produced bioplastics, things grow more complicated.

According to European Bioplastics, “a plastic material is defined as a bioplastic if it is either biobased, biodegradable, or features both properties.” Biodegradation is a chemical process during which microorganisms available in the environment convert materials into natural substances such as water, carbon dioxide, and compost (no artificial additives required). The biodegradation process depends on the surrounding environmental conditions (e.g. location or temperature), on the material, and on the application. But biobased does not equal biodegradable. Indeed, even some oil-based plastics can become oxo-degradable or UV-degradable by introducing special additives; conversely, some polymers of natural origin are not biodegradable. Then there are hybrid polymeric materials, formed in part by natural resources and in part by synthetic polymers. Then, too, there are polymers with the same molecular chain – and thus identical – that can be produced from either oil or from renewable raw materials, such as synthetic polyethylene and natural polyethylene obtained from sugars.

European standards are the point of reference (see in particular: EN 13432/2002, EN 14995/2006; EN4995/2007), both for issues related to the sources with which to make materials classifiable as biopolymers, and for the performance features they must satisfy at the end of their life, with particular regard to biodegradability and compostability – a material’s ability to be transformed into compost, a sort of organic recycling whose end product is a substance that may be used as fertilizer.

Another important factor introduced by the regulations in force in Europe is related to the disposal of these materials (Norma EN 13432/2002). Natural biological degradation can in fact be a very lengthy process, and this requires establishing certain timeframes for a material to be defined as biodegradable and/or compostable.

We shall limit our discussion to bioplastics extracted directly from or produced indirectly by biomass – which is to say from or by animal, plant, or microbotic organisms of recent origin, and not of

geological origin like oil. These may be classified as: starch polymers, which are the most widespread, obtained by chemical, thermal, or mechanical processing from natural starches of corn, potato, wheat, tapioca, rice, sorghum...; *PLA* (polylactic acid) obtained from the fermentation of biomonomers, mainly carbohydrates, which are polymerized by various procedures; *PHA* (Polyhydroxyalkanoate), produced directly by various genera of bacteria through the fermentation of sugars or lipids; and cellulose polymers obtained through the chemical modification of cellulose, a natural polysaccharide, such as Rayon-Viscose, or liquid wood, derived from the lignin extracted from wood pulp.

### 3. Producing bioplastics from waste: the challenge leading to the most interesting prospects

Bioplastics certainly have a lighter environmental load than synthetic ones, but the base material they are made of is of no small importance as regards both the environment and ethical concerns. Today, the material most used for their production is corn; although the quantities at stake pale in comparison with the global production of this cereal, this still raises an important question: is it right to use for other purposes a crop that can be eaten, that provides basic sustenance for a part of the world's population? It is the same question posed for biofuels. Corn prices are soaring; given the repercussions on the world food system, and the hoarding of immense landholdings by rich nations in the poorest countries in order to plant crops for these purposes, the question is not only a legitimate one, but is one that must be asked.



Figure 4. Alkesh Parmar, orange juicer made from orange peel. Figure 5. Raul Lauri, pendant light made of "Decafé" a material made from used coffee grounds.

Some research currents are thus geared towards using as base materials inedible plants that require limited quantities of water to grow, or plants that grow wild, or that can be raised in marginal areas unsuited to intensive farming. But today, the real challenge is to create new materials from food waste and not from specially grown crops, whose production, in any case, comes at an environmental cost. One need only consider the consumption of water – along with land, the Earth's other precious asset. Every year, the agro-food and fishing sectors produce millions of tons of waste potentially useful for the recovery and reuse of valuable carbohydrates and cellulose fibres. Using these precious resources would also help us reduce the problem of disposing of the solid and liquid waste produced by food processing – usually a practical problem involving considerable economic investment.

Moreover, bioplastics produced from waste can create positive synergies between industry and the agro-food sector – two areas generally distant from one another, and that have always had opposing development dynamics in Italy. There are also hopes for the development of production chains

dedicated to individual settings, with small plants built near agricultural production facilities or food processing plants, as in the case of the tomato pulp, fruit juice, and wine industries – processes in which enormous quantities of skins and residual materials are produced and must be disposed of.

There is an enormous variety of vegetable, animal and microbial waste that can be used to create biopolymers: from the orange peels left over from fruit juice production to the grapes used to produce wine; from chocolate production waste to egg and prawn shells. From these materials, we can obtain the starches, cellulose, pectin, chitin, lactic acid, collagen, blood proteins and gelatin that form the basis of bioplastics, either by extracting them directly or by using mechanical or chemical processes. These are genuine treasure troves of substances that can become useful materials thanks to processes of varying complexity.

Materials obtained from waste can also be processed – as takes place for the biopolymers produced from virgin materials – in many ways to improve their performance. They can undergo nanotech treatments and additives may be introduced; in the latter case, shrewd use must be made of additives that do not compromise biodegradability and/or compostability.

In recent years, the testing of substances made from food waste has increased significantly (Matrec, 2015); the sheer abundance of raw materials that can be used to make them has encouraged institutional research, as well as an approach to project development that has been widely embraced by the many young designers who craft these materials. A large amount of research has been done on all scales: by multinationals, costing millions; by small industries that originally produced synthetic plastic materials; by universities; and by independent, enterprising researchers who have built cutting-edge businesses. Then there is the more artisanal work being done by individual designers who, like novice alchemists, are busy crafting new materials from the most diverse waste substances, or by repurposing the natural polymers of the past and reinterpreting their formal and productive possibilities. These new/old materials are sometimes hailed as revolutionary game-changers (Rognoli et al, 2015, 2015, 2016, Humier, 2012, Baud-Berthier et al, 2015).

For example, in the 1930s, the engineer Antonio Ferretti – already the inventor of Cuoital, leather made from the regeneration of scraps – patented a new artificial polymer fibre that saw immediate popularity. Made from the casein in milk, it was called Lanital, its name derived from the Italian word for “wool” to highlight the similarity. Dissolved by an alkaline agent, the casein was transformed into a liquid solution, forced through a spinneret with very small perforations, and passed through a hardening chemical bath to obtain a fibre. And since nothing went to waste at that time, the processing residues were used as pig fodder.

In the 1950s, this fabric was relaunched with the name Merinova, but that was the era of the wide spread of synthetic fabrics, and it thus fell into oblivion. Recent years have seen the introduction of Milky Wear, with the clever slogan “*latte da indossare*” (“milk you can wear”), a fabric derived from milk proteins like Lanital, it has been hailed by the market as a futuristic novelty!

## **4. Straddling the divide between technology and biology: a new bioscience for making objects**

The world of material design is increasingly becoming one of bioscience, the crossroads of diverse disciplines and areas of knowledge. The synergies derived from it are opening new prospects, and have already yielded their first results (Aldor et al, 2003, Bader et al, 2016, Hays et al, 2015). The variety of waste to be drawn from, and production procedures, are among the most diverse, and in some cases highly imaginative. The following is an initial overview, by necessity brief and incomplete.



Figure 6. Jonas Edvard, MYX Mushroom Project.

#### 4.1 Algae, peels, crustacean shells, parsley stems... useful substances derived from what we generally throw away

Among the most interesting experiments are those being done by a research group from Ipcb-Cnr in Pozzuoli (Naples) coordinated by Mario Malinconico, which is making biopolymers from the pectins contained in orange and apple peels, from the alginates obtained from algae, and from the chitosan present in crustacean shells treated with waste vinegar. The idea is to develop short supply chains using local materials: for example fruit peels in Europe, algae in northern Europe, and shellfish processing leftovers in India, China, Mexico, and Canada (Malinconico et al, 2008, 2013).

The biopolymers obtained in this way were successfully trialled in the replacement of films for agricultural soil mulching: when sprayed directly on the ground, they form a weed-killing film that in a few months, once its protective function is done, becomes an excellent plant fertilizer. The films generally used for this purpose today are made with polyethylene (PE) and ethylene-vinylacetate copolymers (EVA). Such films, contaminated by chemical fertilizers and herbicides, are left on the soil or to burn unsupervised by farmers, with a consequent emission of severe pollutants into the air and soil.

These same biopolymers, joined by reinforcement fibres made with the waste from the processing of tomatoes, olives, and hemp, may be used to make containers (trays or nursery pots) to transport the small plants widely used in agriculture. Made today using polyethylene (PE) or expanded polystyrene, these containers, if produced with bioplastics, can be placed in the earth along with the plants, and in fact transform themselves into compost.

Gelatinous mixtures obtained from polysaccharides derived from fruit and vegetable waste have been trialled in gel form for food packaging as well, in particular to wrap Italy's famous mozzarella cheese, thus maintaining its quality and nutritional characteristics for 30 days!

Genoa's IIT – Istituto Italiano di Tecnologia, as part of the Smart Materials Group led by Athanassia Athanassiou, is conducting interesting experiments with biopolymers obtained from a variety of plant scraps, such as coffee, cinnamon, and parsley treated with biocompatible solvents. Depending on the plant used and on the nanoparticles they can be enriched with, bioplastics may be obtained that are antioxidant, antibacterial, magnetic, or able to change colour. Also of particular interest are the studies on bioplastics capable of absorbing heavy metals dispersed in water: these promising materials may come in handy in environmental disasters.

## 4.2. Fermentation and bacteria

Many research efforts of different kinds are being done to obtain bioplastics thanks to the fermentation of bacteria nourished with food waste. Some are still being trialled, while others have already resulted in patented materials. This is the case of the Italian firm Bio-on, which makes PHAs (Polyhydroxyalkanoates) – a bioplastic belonging to the family of linear polyesters, produced in nature by the bacterial fermentation of sugars – thanks to bacteria fed with brown molasses, a by-product of sugar beet processing. The bacteria reproduce rapidly and accumulate their energy stores in the form of polymer chains, just as fat is stored by human beings. After growth is completed in fermenters, the recovery process begins: extraction of the microscopic white polymer granules the bacteria have inside them, that are then processed without using organic solvents, and dried. The organic residues of this process are entirely reused to feed new bacterial colonies. The bioplastic made in this way (MINERV-PHA) is completely biodegradable in the ground, and in about 10 days dissolves in water without a trace. The first item made with the material produced in this way, in 2012, is the Miss Sissi lamp, designed in 1991 by Philippe Starck, and manufactured in polycarbonate by Flos.

Moreover, combining PHAs with different monomers allows bioplastics with very different properties to be obtained: thermoplastic or elastomeric materials, with melting points ranging from 40 to over 180°C.



Fig.7. Cecilia Cecchini, *eco-leather made with the fermentation of bacteria.*

Other companies are also studying how to obtain plant-based polyester. These include the Japanese multinational Toray, which is experimenting with a polyester fibre starting from refinery molasses plants located in India and Brazil. Given the strong impact of the textile industry of synthetic polymers, a fibre made of waste-derived biopolymer might therefore have a major positive effect on the environment.

Another particularly interesting research effort in the development phase is being carried out by the Thore Rohwerder group at Duisberg-Essen University (Germany) to make Plexiglas, known as acrylic glass, thanks to a bacterial enzyme, fed with sugar, alcohol, or fatty acids, that produces 2-HIBA: after



a series of biological and chemical reactions, this enzyme can be transformed into biosynthetic Plexiglas.

A different experiment, also using bacteria, is being carried out by Ginger Krieg Dosier who, in 2012, founded bioMASON after winning *Metropolis* magazine's Next Generation "The Big Fix" international design award. The award submission was a proposal for a brick that was "grown" as opposed to being "fired." The idea of growing bricks emerged from a study of coral's structure: a very hard cementitious material created by nature in ambient sea temperatures with low energy and material inputs. The process has since been refined and continually optimized for increased performance and reduced production costs; bioMASON employs bacteria to "grow" a durable cement in ambient temperatures between loose grains of aggregate.



Fig.8. Cecilia Cecchini, materials made with the fermentation of bacteria.

On the other hand, Suzanne Lee, founder of BioCouture, uses a symbiotic mix of yeast and bacteria to grow fabrics similar to vegetable leather. With it, she makes apparel and shoes. It is a material that is not only biodegradable, but is compostable as well. She believes that in the future, clothing materials themselves might be living organisms that could work symbiotically with the body to nourish it and even monitor it for signs of disease.



Figure 9 . Suzanne Lee, BioCouture made of a symbiotic mix of yeast and bacteria.

#### 4.3. Do-It-Yourself Materials: the designer's experiments

Many designers are trying their hand at bioplastics obtained from waste: Raul Lauri took home first prize at the 2012 edition of Milan's SaloneSatellite with a material based on coffee grounds, which he used to make lamps; Francesco Faccin uses rice husks mixed with natural resins to make disposable

cutlery; Alkesh Parmar closes the cycle with a citrus juicer made using orange-peel-based bioplastic; Nikolaj Steenfatt's graduation project from The Royal Danish Academy of Fine Arts, called "Impasto," is a self-invented biodegradable natural fibre composite made of leftovers from wood, coffee and skin production; the raw materials are mixed with pigment into a dough, and then pressed, rolled and folded into flat sheets. Afterwards, the sheet can be shaped by vacuum forming.

Along with Jonas Edvard, Nikolaj Steenfatt also carried out the "Terroir" project: lamps and chairs made utilizing the viscous and adhesive effect of alginate – the natural polymer from brown algae – harvested along Denmark's beaches, combined with paper.



Figure 10. Nikolaj Steenfatt, "Impasto" a biodegradable natural fibre composite made of leftovers from wood, coffee and skin production.



Figure 11 . Jonas Edvard, Nikolaj Steenfatt, "Terroir" a material developed from seaweed and paper.

Dutch designer Aagje Hoekstra has developed "Coleoptera", a bioplastic made of pressed insect shells, which contains chitin. Aagje peels the insects, so she is left with just the armour; in a chemical lab, she transforms this armour into pure chitin and then into chitosan which, although virtually the

same polymer, bonds better due to the variation in its molecular composition. She then presses the chitosan together to make the “insect plastic” Coleoptera. Thin layers of this material are used to make small items and jewellery.



Figure 12 . Aagje Hoekstra, “Coleoptera,” made of pressed insect shells.

Perhaps the most bizarre experiment is the one by Dutch designer Lieske Schreuder, which causes snails to produce colourful excrement that may be likened to biopolymers, thanks to the coloured paper she feeds them. The snails’ faeces can be pressed into a mould using a spatula to create a delicate thread with a five-millimetre diameter, with which she crafts a sort of multi-hued woven fabric.



Figure 13 . Lieske Schreuder, threads and titles made of snail excrement.

Thomas Vailly uses keratin from hair mixed with glycerine and sodium sulphite to make items that age as the human body does: a metaphor for the passage of time.

In the Technologies and Design course I teach towards the university degree in Industrial Design, each student is asked to produce a material starting from food waste, and to introduce additives and/or process it in 9 different ways, in order to explore their perceptive and sensory features by working with pigments, texturing, mechanical operations, cooking, and aromatization. Each operation must be described in detail.



Figure 14. Examples of materials made of food waste, students of Technologies and Design - "Sapienza" University of Rome, professor Cecilia Cecchini.

#### 4.4. Growing design: cultivating objects

In his research, Maurizio Montalti, founder of Officina Corpuscoli, went further: he grows objects directly in moulds, by means of a natural process that uses fungi nourished with waste. This project required the use of a species of fungus, easily found in nature, to bond agricultural scraps, fibres and organic materials of various kinds, in order to build base blocks with different properties – mechanical, acoustic, thermal – for use in the field of architecture and design. The fungi, which consume the nutritional substances in the materials, develop an intricate network of filaments – mycelia – that act as a bonding agent, creating different materials according to the ingredients present and the growing conditions.

This process was then extended to products. The goal is to "cultivate" products through the use of local resources derived from agricultural scraps. This process may be interpreted by some as a sort of slow 3D printing, in which the printing process takes place at the speed of the organism's growth.



Figure 15. Maurizio Montalti, "Mielium Material" composite organic material cultivated using fungal mycelium.

The MYX lamp by Jonas Edvard, consists of plant fibre and mushroom-mycelium. The lamps are grown into their shape over a 3-week period during which the mushroom eats and grows along with the plant fibres into a flexible and soft living textile. After the edible mushrooms are harvested, the waste can be used as a dry and lightweight material that is organic, compostable and sustainable.



Figure 16. Jonas Edvard, MYX Mushroom textile Project, plant fibre and mushroom-mycelium.

The mushroom mycelium stabilizes the construction by physically growing the material together, behaving as a glue between the fibres. During the production period, each lamp produces 500-600 g of Oyster mushrooms that are both nutritious and healthy. The mushroom's mycelium uses waste to grow fruits, and stabilizes the material in a matrix of mycelium roots, which creates an optimized end-waste product with a nutritious food product during the growing cycle.

The road of using fungi to produce more or less complex objects and structures is a highly promising one being travelled by numerous designers, as also shown by the works presented at the recent "Fungal Futures 02" exhibition at Museum TwentseWelle in Enschede. On display there were fabrics, jewels, containers, modular components for building small structures, and even shoes that grow.

Of particular interest was Gianluca Tabellini's thesis project "Mycelium Tectonis," (Tibellini, 2015) which investigates the construction of natural structures and in particular how mycelium growth can be influenced and guided to evaluate its role as construction, decomposition or re-assimilation material, and the potential of a hybrid system that integrates organic and inorganic material.

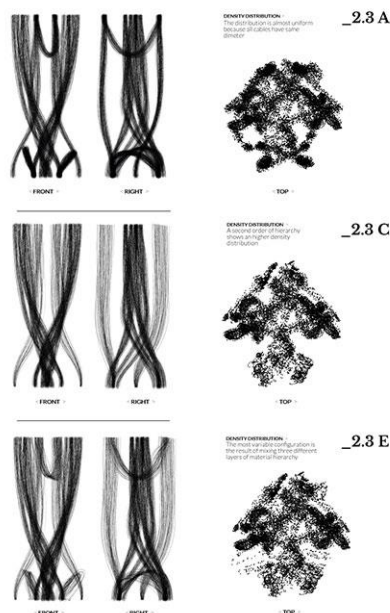


Figure 17. Gianluca Tabellini, "Mycelium Tectonis", research about mycelia and architecture.

## 5. Conclusions

In comparison with traditional plastics, the potential of the replacement of biopolymers, including those produced from waste, increases as their performance improves and with the possibility of processing them with the machines used for synthetic plastics, such as 3D printers. Moreover, highly advanced experiments are aimed at turning certain biopolymers into electrical conductors, by combining them with graphene nanotubes. This opens major applicative possibilities in the electronics market as well, from e-paper to flexible smart phones: by using biodegradable microprocessors to manufacture them, the enormous and continuously worsening problem of electronic waste would be solved.

Bioplastics are spreading rapidly; in a matter of just a few years, they will become a highly varied family, capable of meeting the most diverse performance requirements. This can be a positive factor, a highly positive one, or a real revolution, depending on how they are produced (and here, the use of non-virgin resources has enormous weight with respect to their sustainability) and on how they are used. This goes beyond the facile enthusiasm dictated by considering what is “natural” to be always, and no matter what, better than what is “artificial” – a conviction based on a now obsolete distinction between nature and artifice. The hope is that these materials won’t be considered mere substitutes for synthetic plastics. This would enable indispensable reflection on human beings and their artefacts, today governed at our latitudes by a *hic et nunc* overconsumption, by the culture of the eternal present that consumes everything in great haste. But Nature is not in a hurry. Nature consumes what it needs, and does not even produce waste, because waste becomes raw material for others.

And that’s certainly a good model to take as a reference.

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