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Research Article

# Architectural Vantage Point to Bioplastics in the Circular Economy

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**Abstract:** In a circular economy, bio-based plastics or bioplastics as emerging innovative materials are increasingly being used in many industries, from packaging to building materials and agricultural products to electronic and biomedical devices. Further, there is increasing research on the evaluation of bioplastics in architecture, both as a material or as a design element in interior design. Therefore, this article is a step towards understanding the importance of bioplastic materials in circular economies and in architecture regarding the negative carbon footprint and long-term environmental effects of fossil-based plastics.

***Keywords:*** *bioplastic; biocomposites; architecture; circular economy; material*

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## 0 Introduction

Looking at the recent past, we confront an event that makes us rethink the use of conventional plastics and their major side effects on the environment. In 1992, a cargo ship traveling from Asia to North America and carrying approximately 28,000 plastic floating bathtub toys was hit by a storm in the North Pacific Ocean, causing the toys to be spilled into the sea. Since then, a few of the toys have continued their epic journey, still floating, while some of the others have been sunk or digested by sea mammals. Interestingly, some of the duck toys were found on the British coast, others in Japan, Hawaii and Europe over the years. Thus, the long-term travel of the toys was due to the rotational pattern that drew waste materials along the North Pacific Ocean and as such, the toys were locked in a pattern known as the Pacific Trash Vortex (Great Pacific Garbage Patch)[1] [Figures 1 and 2].

This region, known as the world's largest landfill of 3.5 million tonnes in the middle of the ocean, is located in the North Pacific Ocean between America and Japan. Furthermore, about 80% of the debris in the Great Pacific Garbage Patch, which is trash, comes from North America and Asia[5]. This event later encouraged scientists to study the ocean currents and in turn, hundreds of toys were launched into the sea with sensors to track the currents again. Since the Great Pacific Garbage Patch is far from the coasts of many countries, no country will undertake any responsibility or provide funding to clean it[6]. Therefore, despite this common perception, the plastics stored as waste in landfills also destroy the marine water and freshwater lakes, since they leach chemicals to wildlife and humans[7]. Moreover, recent research on newly established marine bacteria consuming plastics in the ocean does not relieve an escape from pollution.[8]

This event reminds us of the negative and widespread impact of petroleum-based plastics use and its tragic side effects on environmental and marine pollution. Therefore, we need to rethink our over-consumption practices for these materials, which leads us to find more sustainable and environmentally friendly alternatives that can replace them in the long-term. This article is a step in understanding the potential of bioplastics in architecture. Regarding the negative carbon footprint and long-term environmental impacts of fossil-based plastics through landfill and incineration, the search for such a material underlines its importance through sustainability in an architectural perspective.

## 1 The role of bioplastics in the circular economy

Starting after the 1960s, plastics production has been the most valuable thing in our economies because of their low cost and high versatility. Roland Barthes once called the plastics as something in "an infinite transformation; which makes it a miraculous substance: A miracle is always a sudden transformation of nature"[9].

In today's changing world, we see a shift towards a circular economy due to our excessive consumption and production practices related to the use of conventional plastics and other materials. While many countries have developed successful recycling programs and improved waste management, more strategies need to be taken towards benefiting the environment, climate and living being's health.

In a circular economy, nothing is considered as waste. Waste is seen as a "valuable resource". "Materials used for industrial and commercial purposes should safely (re-)enter, re-use, mechanical or biological recycling systems by design or intention"[10]. This model is apart from the traditional linear economy model, which includes "take-make-dispose" "economy"[11] and can change into "make, use, reuse, recycle"[12]. This model "implies reducing waste", keeping resources as long as possible, "re-using, repairing, refurbishing and recycling existing materials and products"[13]. Circular economy consists of "three different components: Preserve and enhance natural capital, optimize resource yields and foster system effectiveness"[14] [Figure 3].

According to statistics "by 2025, at least 55% of municipal waste (from households and businesses) should be recycled.The target will rise to 60% by 2030 and 65% by 2035. 65% of packaging materials will have to be recycled by 2025, and 70% by 2030. Separate targets are set for specific packaging materials, such as paper and cardboard, plastics, glass, metal and wood"[13].

In this context, new emerging innovative materials in bio-based plastics or bioplastics and bio-composites are being used by an increasing number of industries, from agricultural to biomedical, from the packaging sector to construction sector materials. It is estimated that "bioplastics can play an important role in this transition" as they are "becoming a crucial component in the drive to create a fully sustainable and circular bio-economy"[16]. As such, they can help in transforming a linear economy into a circular economy. Furthermore, they can help in "reducing the carbon footprint" and "landfill waste, utilizing renewable feedstocks, recycling petroleum based plastics and limiting the use of finite resources"[14] [Figure 4].

**Figure 1.** A row of plastic ducks for a scientific mission in the ocean, long after the 1992 ship accident in the Pacific Ocean which later inspired scientists to study ocean currents[2]

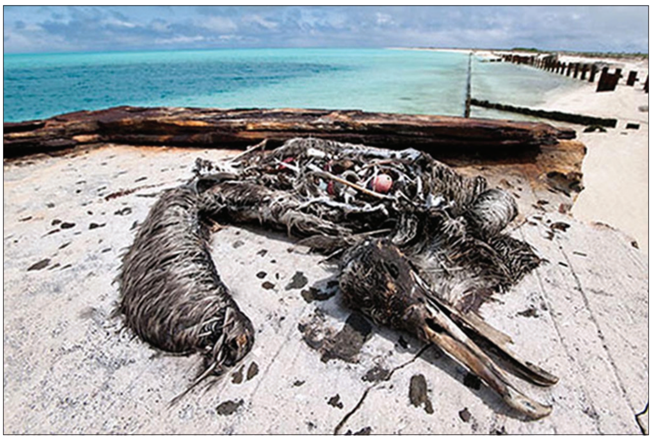

**Figure 2.** An albatross effected by petroleum-based plastics[3]

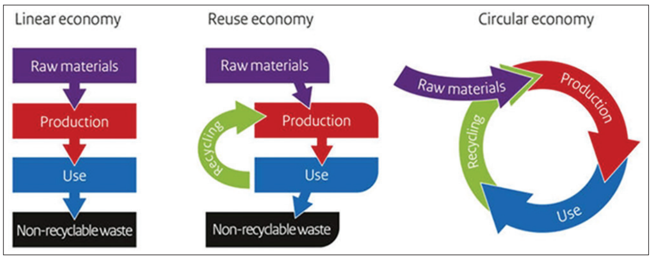


**Figure 3.** Comparison of linear and circular economy models[15]

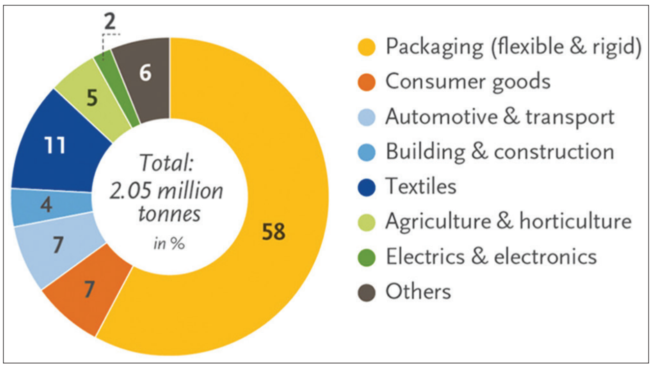


**Figure 4.** Distribution of bioplastic market sector in 2017[17].
Source: European Bioplastics, nava-Institute (2017). More information: www.bio-based.eu/markets and www.european-bioplastics.org/market

“Bioplastics are used in an increasing number of markets, from packaging, catering products, consumer electronics, automotive, agriculture/horticulture and toys to textiles and a number of other segments”. Currently, packaging is one of the biggest and largest expanding areas of production for bioplastics[17].

## 2 What is a bioplastic?

Biobased plastics or bioplastic is biodegradable and biocompatible plastics which come from renewable resources. According to European Bioplastics, bioplastics are “biobased, biodegradable, or both”[18] [Figure 5].

Bioplastic category is mentioned in Figure 6.

A bio-based bioplastic means that “some or all of its carbon produced from a renewable plant or animal source”[21]. Application fields for bioplastics are shown below in Figure 7. In the architecture and construction segment, we currently see bioplastic use in interiors and the making of furniture.

“Biodegradable polymers are classified as agro-polymers (starch, chitin, protein) and bio polyesters (polyhydroxy-alkanoates, poly-lactic acid etc)”[23]. “Bioplastics can be made from renewable resources, such as crops and wood, or from waste streams, such as the residues of food processing”[16]. Thus, biodegradation of bioplastics depend on the polymer type used[24].

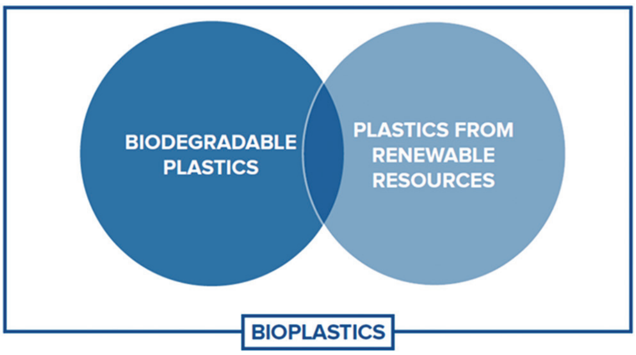


**Figure 5.** Diagram showing European Bioplastics definition of bioplastics[19]

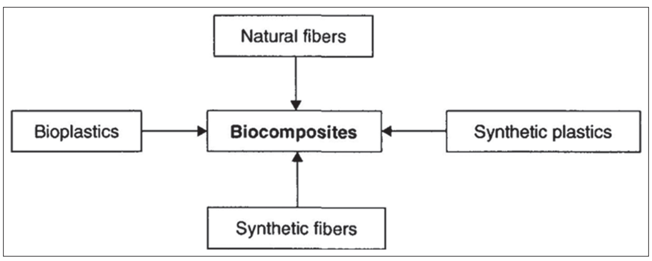


**Figure 6.** Different routes to make bioplastic[20]

There are three different types of bioplastics depending on the feedstock used. These are blended with other polymers and fibers: “(1) Bio-based (or partially bio-based), durable plastics such as bio-based polyethylene (PE), polyethylene terephthalate (PET) (socalled drop-in solutions), bio-based technical performance polymers, such as numerous polyamides(PA), or (partly) bio-based polyurethanes (PUR);(2) bio-based and biodegradable, compostable plastics, such as polylactic acid (PLA), polyhydroxyalkanaoates(PHA), polybutylene succinate(PBS), and starch blends; and (3) plastics that are based on fossil resources and are biodegradable, such as PBAT and PCL, but that may well be produced at least partly bio-based in the future”[25] (Figure 8).

There are different categories of bioplastics depending on the polymers used, including petroleum-based sources. For a broad classification of bioplastics including petroleum and mixed contents[27]. The different types of bioplastic that are not derived from petroleum based polymers are mentioned in Table 1.

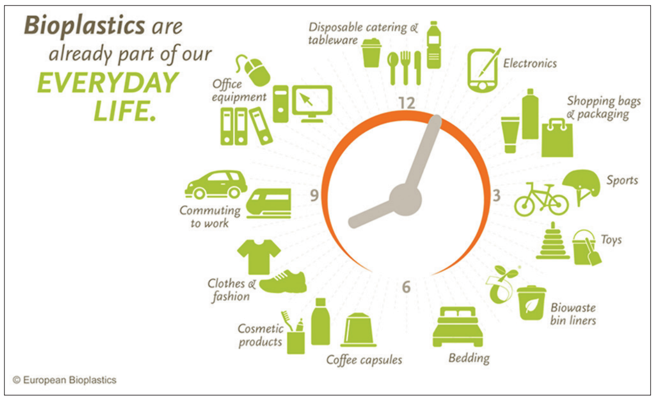


**Figure 7.** Bioplastic production market area[22]

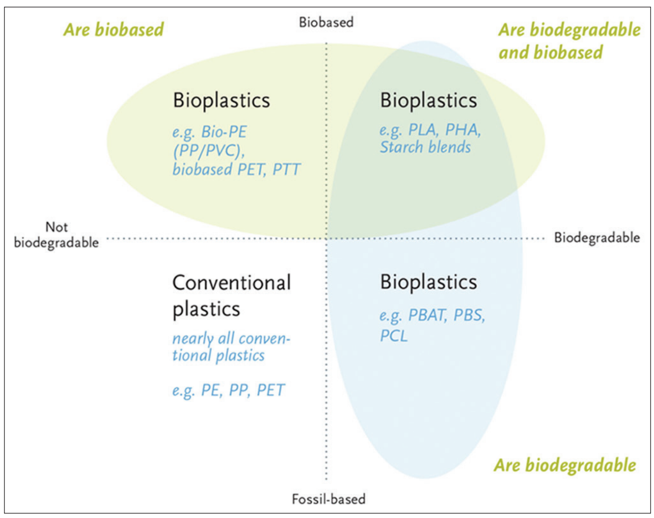


**Figure 8.** Material coordinate system of bioplastics[26]

**Table 1. Bioplastic types based on its natural polymers.**[25,28-31]

| Bioplastic types | Bioplastics and its polymers | Products used | Properties/sources |
|---|---|---|---|
| Bio-based (or partially bio-based), durable plastics | Bio-based PE, PET (so-called drop-in solutions), bio-based technical performance polymers (PA, or (partly) bio-based PUR) | PE: bags, toys, cables, lids/caps…, PET: bottles., PUR: automotive applications (seats, headrests, armrests, door and roof liners, dashboards and instrument panels) | Similar to conventional plastics. These bioplastics are technically equivalent to their fossil counterparts; yet, they help to reduce a product's carbon footprint. |
| Bio-based and biodegradable, compostable plastics | PLA | Packaging (cups, bowls, foils and food storage containers), textiles (t-shirts and furniture textiles), hygiene products (nappies), foils for agriculture and cutlery. | Produced from sugar feedstocks obtained from sugar beets or sugar cane. Polylactides (lactic acid polymers) are made from lactic acid (lactose (or milk sugar) and obtained from sugar beet, potatoes, wheat, maize etc). They are also water resistant. |
| | PHA, (PHA's: PHB, PHBV, etc. | PHA: hardeners in cosmetic products, for hygiene products, packaging products and golf tees. Polyalctides decompose harmlessly in the human body, and are used for medical applications | Polyhydroxybutyrate (from sucrose or starch by a process of bacterial fermentation) is moisture resistance. |
| | PBS | Everyday products (disposable items as coffee cups and capsules). | |
| | Starch blends | Use in water-soluble chips as spacers to protect the contents of packages and other expanded materials as a replacement for polystyrene (styrofoam), shopping bags, bags for the bio-waste storage, food packaging and packaging, hygiene products and cosmetics products. Thermoplastic starch is unsuitable for packaging liquids, and is a good oxygen barrier to properties | Starch is a natural polymer that occurs as granules in plant tissue, from which it can easily be recovered in large quantities (from potatoes, corn, maize, wheat, rye, tapioca, pea, oat, water chestnut, chestnut, banana, etc). |
| Fossil resources and are biodegradable | PBAT, PCL | PBAT: Shopping bags, compost bags etc., PCL: packaging | May well be produced, at least partly, bio-based in the future |

PE: Polyethylene, PET: Polyethylene terephthalate, PCL: Polycaprolactone, PBAT: Polybutylene adipate terephthalate, PBS: Polybutylene succinate, PHA: Polyhydroxyalkanaoates, PA: Polyamides, PUR: Polyurethanes, PLA: Polylactic acid

Bioplastics today are derived from plant-based feedstock, such as starch. The next generation of bioplastics is estimated to be produced from greenhouse gases; carbon dioxide and methane gas by Newlight Technologies,[32] transforming $CO_2$ to PHA and NatureWorks producing PLA bioplastics from methane gas[33] [Figure 9].

According to European Bioplastics, "Bioplastics are driving the evolution of plastics. There are two major advantages to biobased plastic products compared to their conventional versions: They save fossil resources by using biomass, which regenerates (annually), providing the unique potential of carbon neutrality. Furthermore, biodegradability is an add-on property of certain types of bioplastics. It offers additional means of recovery at the end of a product's life"[35]. Bioplastics "can play an important role in the reduction of food waste, a major source of $CO_2$ emissions", and reduce "dependency on fossil feedstock and $CO_2$"[36].

## 3 Bioplastic materials used in nanocomposites

Bioplastics have been used in many different additives to form nanocomposite materials. One of the most important is carbon fiber microelectrode (CFME) materials, which has a diameter of ~7 μm and improves the mechanical properties of nanocomposites. We observe the filose structures from scanning electron microscope images [Figures 10 and 11].

The Fourier transform infrared-attenuated total reflectance image indicates that the peak at 3273 $cm^{-1}$ belongs to O-H bond stretching. The peak at 1416 $cm^{-1}$ refers to C-C bond stretching and the peak at 1151 $cm^{-1}$ shows C-O bond stretching. In addition, the peak at 2931 $cm^{-1}$ has C-H bond stretching [Figure 11].

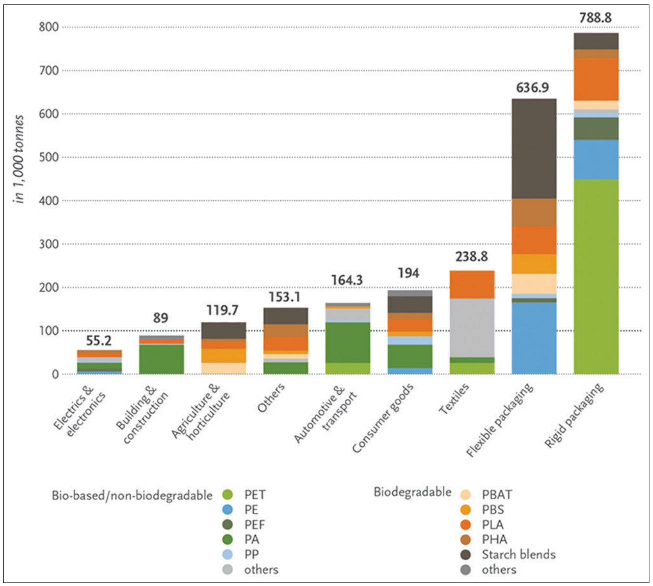


**Figure 9.** Global production capacities of bioplastics in 2022 by market segment[34]. Source: European Bioplastics, nava-Institute (2017). More information: www.bio-based.eu/markets and www.european-bioplastics.org/market

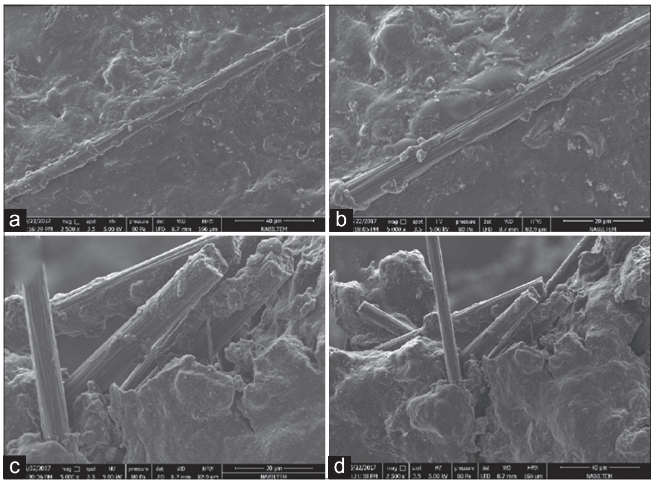


**Figure 10.** Scanning electron microscope images of bioplastic with 0.5% carbon fiber microelectrode nanocomposites. Magnification of nanocomposites; (a) 40 µm, (b) 20 µm, (c) 20 µm, (d) 40 µm

Thermal gravimetric analysis is given in Figure 12. Nanocomposite materials weight decreases to 61.2% at 206.5°C and 9.2% at 354.8°C. Moreover, the material completely loses its weight at 495.5°C

Mechanical properties of nanocomposite improve addition of CFME in the bioplastic materials due to the bonding via CFME and bioplastic materials, as shown in Figure 13. Nanocomposites are used via bioplastics and additives, such as CFME, to improve thermal, electrical and mechanical properties of materials.

A renewable-based polymer used in bioplastics can decrease the use of "fossil fuels." As Šprajcar, Horvat, and Kržan put it, "Bioplastics from renewable resources represent a new generation of plastics that reduce the impact on the environment, both in terms of energy consumption and the amount of greenhouse gas emissions"[37].

## 4 Bioplastic in future architecture

In today's world, along with the knowledge gained by many experts in the field, architects are not alone in the decision-making of building materials and components. The environmental long-term effects of the materials should be considered holistically, as a one-way information resource shared by a specialized firm may not be sufficient in the future's multi-layered and layered design processes and productions. We see that bioplastics are mainly used in packaging and textile production. In architecture, bioplastic application is relatively young when compared to other commonly used sustainable materials.

As Pilla puts it, "Civil engineering, especially building and construction materials, utilize about 23% of the world's total plastic usage. Also, many of these materials are energy intensive to produce. Besides packaging, the construction and demolition debris

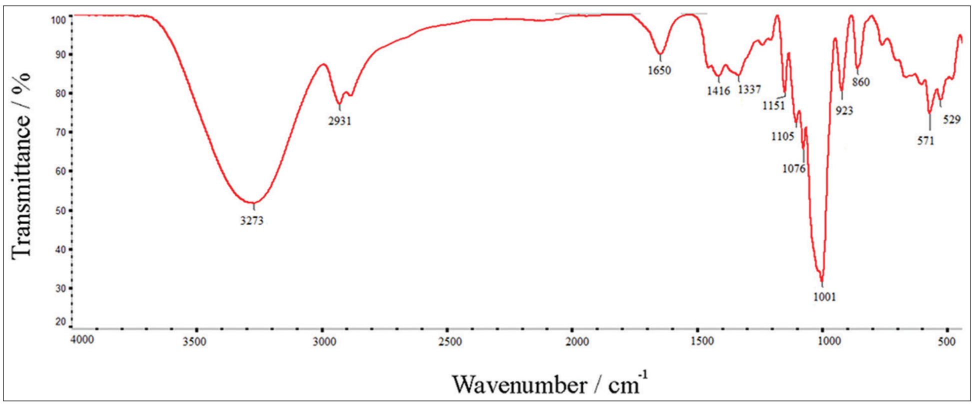


**Figure 11.** Fourier transform infrared-attenuated total reflectance image of bioplastic with 0.5% carbon fiber microelectrode nanocomposites

constitute a large percentage of landfill waste. Thus, biocomposites, in addition to being environment-friendly, offer many advantages, such as light-weight, low material costs, high specific properties.. Some of the building and construction applications where biocomposites are potentially applied include formwork, scaffolding, decking, railing, fencing, framing, walls and wallboard, window frames, doors, flooring, decorative paneling, cubicle walls and ceiling panels. Additionally, foamed biocomposites are investigated for housing insulation applications"[38].

As Datta mentions, "the construction industry is becoming a major field of use for biopolymers"[39]. "In the construction industry, starch and starch derivatives, usually starch ethers, based on a variety of raw materials, are used as additives for hydraulic binders," such as cement, lime, and gypsum. "Starch or starch derivatives have a strong effect on the rheology of aqueous systems. In particular, they act as efficient thickening agents, rheology enhancers as a means of improving water retention, and as processing additives." Fields of application in the construction industry include "machine/hand plasters, adhesives for tiles,

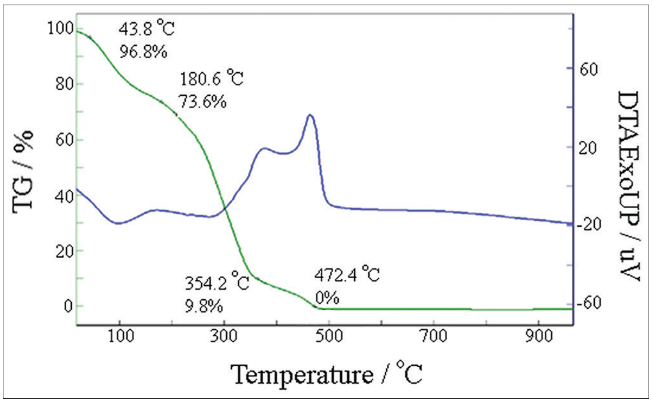


**Figure 12.** Thermogravimetric analysis-Differential thermal analysis of bioplastic with 0.5% carbon fiber microelectrode nanocomposites

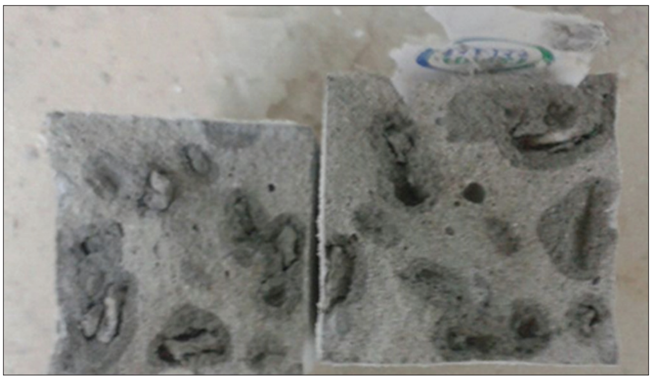

**Figure 13.** Concrete pattern of bioplastic with 0.5% carbon fiber microelectrode nanocomposites

fillers, plaster boards, concrete applications, emulsion paints and synthetics"[40].

The results obtained from numerous experiments show that bioplastics can be used as building materials in the form of three-dimensional elements under available conditions[41]. Nevertheless, this technology is not economically sustainable. Besides, bioplastics also have a complex design, as they "create difficulties in collection and recycling processes" and they combine with petroleum-based plastics, which all end up in landfills, incinerators or cause marine pollution[42].

In recent years, we have seen an increase in bioplastic technology being applied in architecture, design and construction. Their use in design extends from the artistic experience to the work of Meredith Miller, Marilu Valente, Thomas Vailly, Juliette Pepin, Johan Viladrich, and Zalán Szakács, as well as to a variety of consumer products with a long life span of toys and kitchenware. These are made by designers such as; Formafantasma and Jean Louis Iratzoki, with some examples in product design including the Alki chair, a plant-based polymer that can be recycled and is biodegradable.

In architecture, we see less research and practice applied with bioplastic technology. Some of the bioplastic architecture has been created by ITKE, including the Arboskin pavilion building, as the fire-exit of a building

**Figure 14.** Arboskin pavilion by ITKE, Stuttgart, 2016[43]

**Figure 15.** Decaying architecture: A biodegradable pavilion, bio-plastic with hydro-soluble polymer from agriculture and casted in cellulose nanocrystals molds[44]

and derived from biodegradable feedstock, such as lignin and cellulose [Figure 14][43].

Another experimental and biodegradable pavilion that is a responsive surface combined with a three-dimensional printing technology and free form experiments is "Things which necrose," by François Roche and Stéphanie Lavaux. This transient performative surface-wall was featured in an exhibition in Denmark. Visitors witnessed the decaying of the surface with time and its degradation was controlled by the humidity within the room. Thus, the surface slowly necroses with the mist nozzles, which changes the humidity in the atmosphere [Figure 15][44].

## 5 Conclusion

First, we need to change our consumption practices and consumer behaviour to draw attention to the market for bioplastics. This can be done by replacing fossil-based products into greener ones that may be biodegradable or biocompatible. Second, this should be done by creating awareness, starting with our environment. The replacement of bioplastics or bio-based materials does not help the environment, as all plastic consumption should be decreased.

However, there is a million-dollar industry within the green market. Yet, the effects of a large-sector and a greener world remain a controversial issue in today's society.

## 6 Acknowledgement

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## 7 Conflict of interest

No conflict of interest was reported by all authors.

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