



# **OCEAN WISE**

State of the art working  
catalogue/database of  
current available  
alternatives to Expanded  
Polystyrene (EPS) &  
Extruded Polystyrene  
(XPS) products

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## Executive summary

Expanded polystyrene (EPS) and extruded polystyrene (XPS) are two foams of the polymer polystyrene and are abundantly used in manufacturing and construction. Both foams consist mostly of air, which makes them very light weight and good insulators. Their compressive strength also makes them very useful for packaging. EPS can be moulded in any shape and is therefore suitable for uses as different as storage and transport of fish, meat and vegetables, disposable plates and cups, and protective packaging moulded for appliances. As XPS is mostly used as insulation in construction.

Over recent decades, global use of plastics has increased drastically. Polystyrene is recyclable, but polystyrene foams are mostly still being landfilled or incinerated. They are also easily dispersed because of brittleness and lightweight, creating an enduring impact on the environment. EPS and XPS have been banned in several countries in attempt to decrease post-consumer waste. However, the success of the bans depends on the options to reduce single use items and the availability of alternatives material to the consumers.

Alternatives to expanded and extruded polystyrene are available and new ones are being tested. There is not a unique material that can substitute polystyrene foams, but there is an array of different materials that can be used to cover the entire range of applications. Alternative materials can be oil- or bio-based. Oil-based thermoplastics like polyethylene and polypropylene are more easily recycled and can be used to create alternative products that fit better in a circular economy. They can also be foamed to provide protection, insulation, and buoyancy. Natural polymers (wool, cellulose, vegetable fibres) can be also used to protect and transport goods/food, and to maintain constant temperature in boxed during transportation of food and other temperature-sensitive products. Natural molecules can also be polymerised in synthetic biopolymers (e.g., PLA) that have similar characteristics to thermoplastics but that can also be compostable in industrial environment. Other materials can also be used to insulate buildings, sometimes recurring to traditional solutions (e.g., straw bales or mineral wool).

The decision to adopt an alternative to EPS/XPS depends on many factors, but the fate of end-of-life products is important to consider. Biodegradability, compostability or at least widespread recyclability are desirable characteristics, and their certification is necessary to ensure that impact on the environment is reduced. However, there is some confusion about the use of the terminology like 'bio-' or 'compostable' and more stringent standards should be implemented to ensure that only certified claims can be used for marketing.

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## List of abbreviations

ASTM	American Society for Testing and Materials
C	Carbon
CFCs	Chlorofluorocarbons
CO <sub>2</sub>	Carbon dioxide
EN	European Standards / European Norms
EPS	Expanded polystyrene
HCFCs	hydrochlorofluorocarbons
IPREM	Institut des Sciences Analytiques et de Physico-Chimie pour l'Environnement et les Matériaux
ISO	International Organization for Standardization
OECD	Organisation for Economic Co-operation and Development
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PS	Polystyrene
TUV	Technischer Überwachungs-Verein e. V.
UK	United Kingdom
UV	Ultraviolet
XPS	Extruded polystyrene

## 1 Introduction to Expanded Polystyrene (EPS)/ Extruded Polystyrene (XPS)

Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS) are two foams of the polymer polystyrene (PS), a hard, stiff, transparent synthetic resin (thermoplastic) which was discovered in Germany in 1839. PS is a polymer, i.e., a long organic (carbon based) molecule formed by a chain of small molecule units (monomers). The monomer of PS is styrene, which was initially isolated from the resin of the American sweetgum tree (*Liquidambar styraciflua*). PS commercial production started in the 1930s thanks to the German company BASF, while polystyrene foams were invented by the Dow Chemical Company in 1954. Today their trademark name Styrofoam® is sometimes used as a synonym for polystyrene foams.

EPS and XPS production start with the polymerization of styrene monomers into PS beads. More details about the production of PS can be found in the report for action 5.1. The two PS foams, EPS and XPS, are obtained through different manufacturing processes: to produce EPS, batches of beads are expanded within a mould, using heat and pressure to fuse the beads together; XPS is instead the result of an extrusion process that produces sheets of a homogeneous closed-cell cross section.

EPS and XPS are mostly (95-98%) composed of air, which makes them light and provides high thermal insulation qualities. Both foams are waterproof, strong, durable, with high compressive strength and block rigidity. They can also be easily moulded in different shapes and have high design versatility. These characteristics make EPS and XPS a common choice for the packaging, protection and transport of food, goods, and pharmaceutical products. PS foams are used to produce safety equipment, notably helmets and life jackets. The construction sector uses them to provide effective insulation in buildings. Due to their buoyancy, they are also used by fishery, maritime and leisure sectors to create floating devices for many different uses (buoys, surfboards, pontoons etc.).

PS and its foams are presented by the plastic industry as a 'sustainable' plastic because the material is stable and durable; its light weight is advantageous during transportation because it does not increase carbon emission; and the material is theoretically fully recyclable. Furthermore, EPS/XPS production has been innovated to replace harmful chemicals previously used as blowing agents such as CFCs (phased out because of severe environmental damage to ozone layer) or HCFCs (currently being phased out) with more sustainable alternatives such as CO<sub>2</sub>.

Despite the benefits and properties of EPS and XPS, a report from WRAP in 2019 (WRAP, 2019) included PS in the list of challenging plastics that should be eliminated from the UK market. The reason for this strong position is that the use, management and, above all, final disposal of PS, EPS and XPS present several challenges. Despite being fully recyclable, PS is in fact not widely recycled. PS foams are particularly problematic because they are very bulky as they are made out of 98% air. Therefore, the transport of EPS and XPS to recyclers is inefficient because only small amounts of actual plastic can be transferred to the recycler, unless compactors are used. Due to these logistic challenges, often citizens are not offered the service of EPS/XPS collection for recycling directly from their households (i.e. through the kerb waste collection system), and few recyclers are equipped to process this material. When not recycled, EPS and XPS are either incinerated (they have high calorific properties) or end up in landfills. EPS and XPS are also used for single-use products that can be contaminated with food and therefore difficult to recycle.

Another problem of EPS and XPS is their brittleness. PS foams break down easily into small pieces, sometimes releasing single expanded PS beads. Because of their light weight, EPS and XPS fragments are easily dispersed by agents like wind and water runoff and, once in the environment, they are difficult to collect. This fragmentation happens throughout the lifecycle of EPS and XPS products, for example when blocks are cut, handled, or when waste is not covered during transportation.

Fragmentation can also be accelerated in the environment due to weathering of the plastic by UV, temperature, and abrasion.

Mismanagement and fragmentation of EPS and XPS products make them a contributor to marine litter and microplastics, which are accumulating in the world ocean with obvious impacts on marine life, human economy, and health. The EPS and XPS fragments can be very small (meso- and microplastics) and can be easily ingested by small animals, entering the food web. Once in the animals' digestive system, these small fragments can release chemicals and toxins. This is of concern for pieces of EPS and XPS, since several chemicals are added to PS during their production. Flame retardants are used because PS can be highly flammable, making it a potential hazard when used in construction works. Antioxidants are used to protect the material from thermo-oxidative degradation, reducing yellowing, cracking, or more general surface degradation, especially after prolonged exposure to a heat source. Surfactants strengthen the outer coating and eliminate the accumulation of static electricity on the surface. Plasticizers make the plastic more flexible through lowering the glass transition temperature. There are also pigments, that are added to provide the colour to the final product. Carbon black is also sometimes added as an opacifier to screen from infrared radiation and to improve thermal performances. Furthermore, residues from the production process (e.g., precursor compounds, blowing agents and nucleating agents) can be found trapped in the EPS/XPS. The leachate of chemicals from PS, EPS and XPS products, including the release of potential toxins in food, has been shown by several studies (Stubbings & Harrad, 2019., Thaysen et al, 2008).

## 2 Solutions and alternatives to EPS/XPS

Thanks to their durability, low weight and insulation properties, EPS and XPS are nowadays used for several application such as the transportation of fragile or thermally sensitive goods, the production of buoyant devices, or the thermal and sound insulation of buildings. However, the popularity of EPS and XPS and the difficulty to correctly manage their waste, along with the difficulty to remove fragments from the environment, have led some experts and administrators to indicate phasing out EPS/XPS as the way forward. Several private and public stakeholders are therefore looking at adopting solutions to reduce the supply of EPS/XPS thus limiting the rate at which they become waste and their leakage into the environment.

Initiatives to phase-out plastics can be voluntary based, by inviting citizens to use less products (in this case EPS and XPS). However, more radical, and stringent options have been adopted by some cities



and countries which have banned EPS and XPS products in their territories (in particular single use items).

The success of both voluntary and mandatory measures relies on the presence of alternatives that citizens can use instead of the banned items/materials. The market is providing several alternatives that would be useful to phase out EPS and XPS. These alternative materials vary according to the type of application and include other thermoplastics (i.e., oil-derived polymers) and natural or synthetic biopolymers (polymers extracted directly from biomass or polymerised starting from natural precursors). Some oil-derived thermoplastics are considered greener alternatives because they are easier to sort, collect and recycle, i.e., to include in a circular economy system. Polyethylene and polypropylene are two examples of these alternative thermoplastics, since they are easier to transport, already collected from households and commercial activities, and already widely recycled thanks to a well-established network of businesses dedicated to their recycling. However, these alternative thermoplastics are not biodegradable, so if they are not recycled, they will have to be landfilled or incinerated to reduce the chance of spill into the environment. Furthermore, the use of thermoplastics does not reduce the carbon footprint linked to their production, since their precursor rely on oil extraction.

The other class of materials considered as an alternative to EPS and XPS is biopolymers. As the name suggests, these materials are defined by the fact that most of their constituents come from living organisms. Several naturally occurring biopolymers are created by animals (chitin), plants (pectin, cellulose, lignin), fungi (chitosan) and bacteria (PHA or Polyhydroxyalkanoates) and can be extracted directly from living biomass. These natural biopolymers have been used by humans since millennia, both in their natural form (e.g., wood, wool) or after physical treatments (e.g., rubber or paper).

Natural polymers can also be chemically modified, and these processes have been the base of the modern rubber and plastic industry. Three centuries after the import of rubber from America to Europe by Christopher Columbus, Charles Goodyear developed the process of vulcanization that played a major role during the industrial revolution. Another example of chemical modification of natural biopolymers is the Parkésine, which is a derivative of cellulose discovered by Alexander Parkes in 1862 that was at the base of the modern plastic industry. When at the beginning of the twentieth century synthetic oil-based polymers were developed, the use of natural polymers slowed down (except for natural rubber and Polyamide 11 which are still widely used). In the last twenty years biopolymers have again become of interest because of the desire to reduce the use of fossil fuels and reduce plastic pollution. The industry has also developed new polymers using precursors derived from biomass.

Examples of these new biopolymers (e.g., bio-PET, bio-PE, PLA, organic epoxy resins) are today routinely produced around the world (**Erro! A origem da referência não foi encontrada.**). An alternative route to the production of new polymers is the production of monomers and precursors by microbial fermentation, followed by chemical polymerisation (Figure 2).

## FROM BIOMASS TO POLYMERS

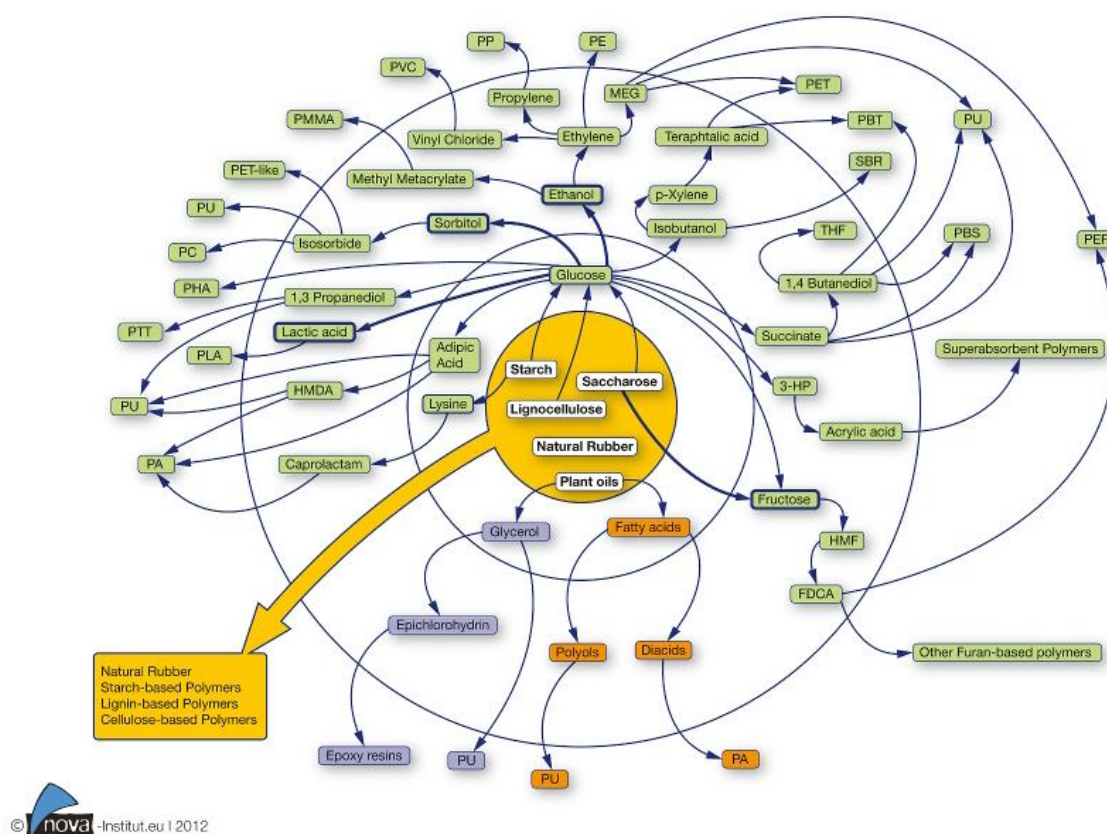


Figure 1 : Polymer based by biomass extraction (source Nova-institute)

Today, synthetic biopolymers have applications in a wide variety of fields, such as packaging, agriculture, automotive, electronics and textiles. However, they currently account for only 0.5 % of global plastics production capacity, which stood at 311 Mt in 2014 (Aeschelmann, 2016). According to current estimates, global production of bioplastics is expected to grow by 30% annually over the next decade, reaching 3.5 million tonnes in 2020 (Aeschelmann, 2016). Sectors like packaging, where lifetime of the products is short, are now adopting bio-based synthetic and natural biopolymers to reduce the use of thermoplastics and plastic pollution.

Recent technological innovations have resulted in a substantial improvement in properties, such as heat resistance, of these biopolymers, which are now eligible for a wider range of applications. However, they currently cost 2-4 times more than oil-based polymers. The whole market represents a production capacity of 1.7 million tons (Aeschelmann, 2016). However, these figures are to be taken with caution because the market leader, bio-PET, represents 35 % of the biopolymer market while this bio-PET is manufactured using only 30 % biomass (Figure 3).

Some of the alternatives used to replace EPS and XPS are also foamed polymers, and blowing agents (both physical and chemical) used for EPS and XPS can be used for foaming alternatives biopolymers materials. The use of physical blowing agents (for example, CFCs, HCFCs and hydrocarbons such as pentane, butane, liquid carbon dioxide, etc.) involves an endothermic and irreversible process. During cooling, the blowing agent will condense, making it impossible to return to the initial state. Chemical blowing agents (nitrogen-based materials used in powder or bead form) produces an exothermic reaction and low molecular weight compounds. These solid agents are advantageous for conventional extrusion and injection processes. The choice of blowing agent for the expansion of the alternatives materials depends on the use of the material produced. Fluorocarbon agents will never be used with new alternative materials but pentane and butane have become the most used agents due to their far lower impact on both ozone depletion and global warming. Since 2005, other agents have been studied. Gases such as nitrogen and carbon dioxide are now making their way into the foamed market due to their lower environmental impact. These inert gases are not flammable like pentane and butane, are cheaper, non-toxic and leave no residue in the foamed material. More information about the foaming process is provided in OceanWise report 5.1.

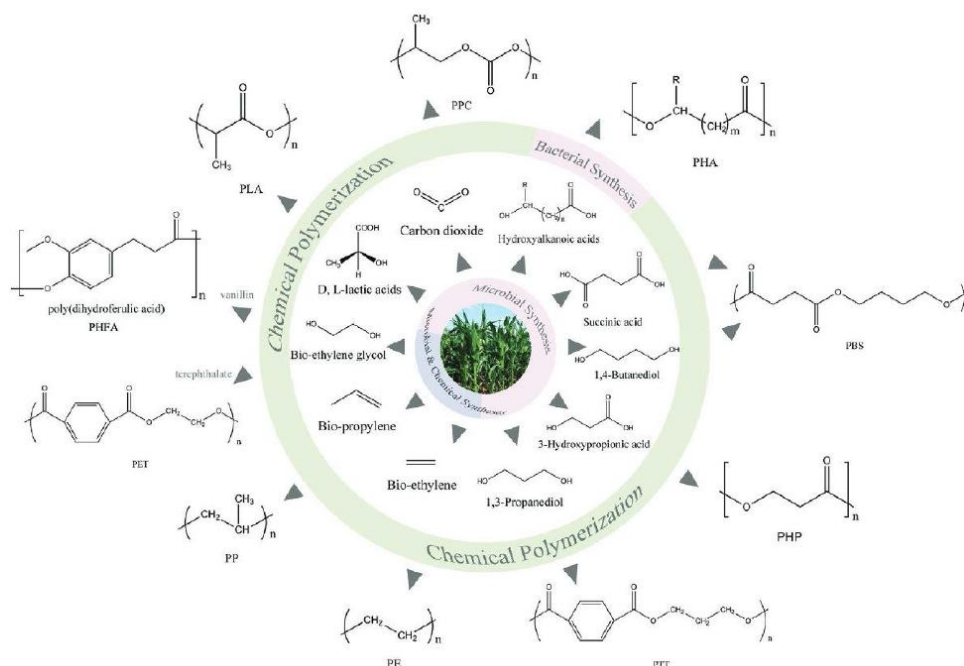


Figure 2 : Monomer and polymer development by microbial fermentation combined with a chemical polymerisation (Aeschelmann, 2016)

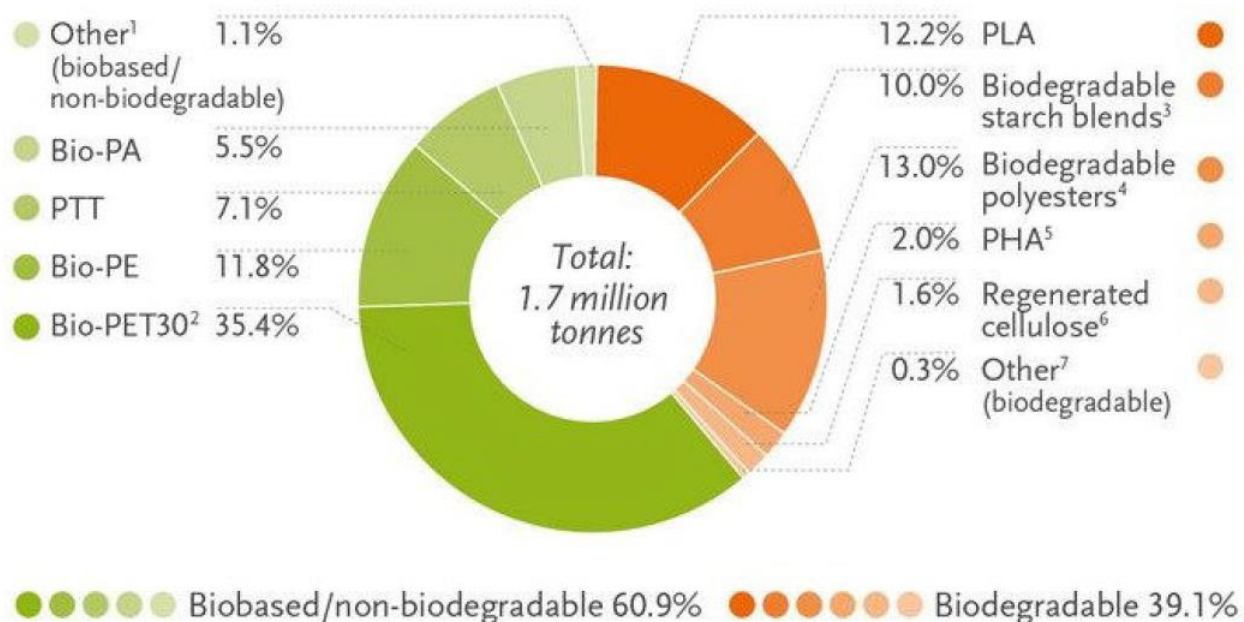


Figure 3 : World production capacity of bioplastics in 2014 (Aeschelmann, 2016)

### 3 End of life

One of the factors that should play a pivotal role in deciding whether to adopt an alternative material instead of EPS and XPS is the capability to divert these materials from landfill, incineration, and dispersion in the environment once they become post-consumer waste. As already discussed above, the fragmentation of EPS and XPS during use and transport, and the difficulties for recycling are some of the main concerns related to these foams. PS is refractory to microbial degradation and the permanence of EPS/XPS in the environment therefore has enduring impacts.

While the circularity of thermoplastics is currently related to their ability to be reused and recycled, natural and synthetic biopolymers present more options since some of them are biodegradable or compostable in home/industrial environments. These advantageous properties have however created confusion, since the 'bio-' denomination has been linked to the wrong perception amongst the general public that all these polymers, once abandoned in the environment, will automatically biodegrade because of their origin. The term compostability of these polymers must also be specified since the use of the term 'compostable' can sometimes hide the need for industrial composting facilities, which have different conditions compared to home composting. The use of home composters to get rid of industrially compostable polymers is linked to partial degradation and fragmentation with the possible production of microplastics instead of mineralisation.

To provide a clear framework allowing producers and consumers to decide on the use of biodegradable plastics, in December 2020 the European Commission gathered scientific advice about biodegradability of plastics in open environment. Following this consultation, the European Commission recommend to:

1. **Limit the use of biodegradable plastics in the open environment to specific applications for which no reduction or reuse or recycling is feasible** – this recommendation aims at prioritising the reduction, reuse and recycling of plastics before considering biodegradation; limiting the use of biodegradable plastics in the environment to specific applications for which collection in the "open environment is not feasible; and not making biodegradable plastics a solution in case of inappropriate waste management or disposal.
2. **Support the development of consistent testing and certification standards for the biodegradation of plastics in the open environment.**




In relation to the second recommendation by the European Commission, clarity over three terms must be considered: 'biodegradability', 'home compostability' and 'industrial compostability'. Table 2



summarizes the measurement conditions that are necessary to certify and label a product as biodegradable or compostable in a specific environment. For this report, we will define:

- Biodegradable: a material that is mineralised in the environment without the need for specific conditions.
- Home compostable: a material that is mineralised in compost bins/heaps in citizen's gardens or households.
- Industrially compostable: a material that is mineralised in stringent environmental conditions that are maintained in dedicated industrial facilities.

*Table 2 : Criteria to certify environmentally friendly end-of-life options of a product (from TÜV Austria)*

		Soil biodegradable	Industrial compost	Home compost
Measures conditions	Temperature	Between 20° and 28°C (25°C)	58°C ± 2°C	25°C ± 5°C
	Environment	Standard soil (real compost matured at least 2 months + minerals)	real compost 2 to 4 months old	real compost 2 to 4 months old
	Standard test	NF EN ISO 17556	NF EN ISO 14855 NF ISO 16929	NF EN ISO 14855 NF ISO 16929
Labelling	Metals	maximum content to be verified	maximum content to be verified	maximum content to be verified
	Aerobic biodegradation (O <sub>2</sub> consumption and/or CO <sub>2</sub> emission)	>90% loss of mass after <b>24 months</b> max	>90% loss of mass after <b>6 months</b> max	>90% loss of mass after <b>12 months</b> max
	Fragmentation	Not required	Max 10% of mass > 2mm after 12 weeks	Max 10% of mass > 2mm after 180 days
	Ecotoxicity	Germination rate and biomass > 90% versus control compost	Germination rate and biomass > 90% versus control compost	Germination rate and biomass > 90% versus control compost
	Standard specification	Does not exist	NF EN 13432 NF EN 14995	NF T 51-800
	TUV Austria labelling			
		SOIL	INDUSTRIAL	HOME

### Biodegradability

Biodegradability is the inherent characteristic of the material to be consumed by microorganisms, meaning that it will not accumulate in nature. It is linked to the chemical composition of a material and represents the % of solid organic C converted to gaseous C under the form of CO<sub>2</sub>. Standard protocols to test biodegradability in different natural substrata are ISO 17556, ISO 11266 and/or ASTM D5988 (in soil), ISO 14851, ISO 9408, EN 29408, ASTM D 5271, OECD 301C, OECD 301F, OECD 302C and/or OECD 302F (in fresh water), OECD 306 and ISO 14851 and/or ASTM D 6691 (in marine water).

### Home compostability

Home compostability refers to the ability of a product to disappear in households' compost bins/hips, whose conditions are usually not controlled and, therefore, less extreme, and more variable. While the first norms on industrial compostability were already published at the turn of the century, it took 10 more years to create a norm on home compostability. Based on AS 4736, the Australian norm on industrial compostability, Australian Standards published in 2010 world's first norm on home compostability: AS 5810.

Nevertheless, several other certification schemes were also created, of which some much sooner:

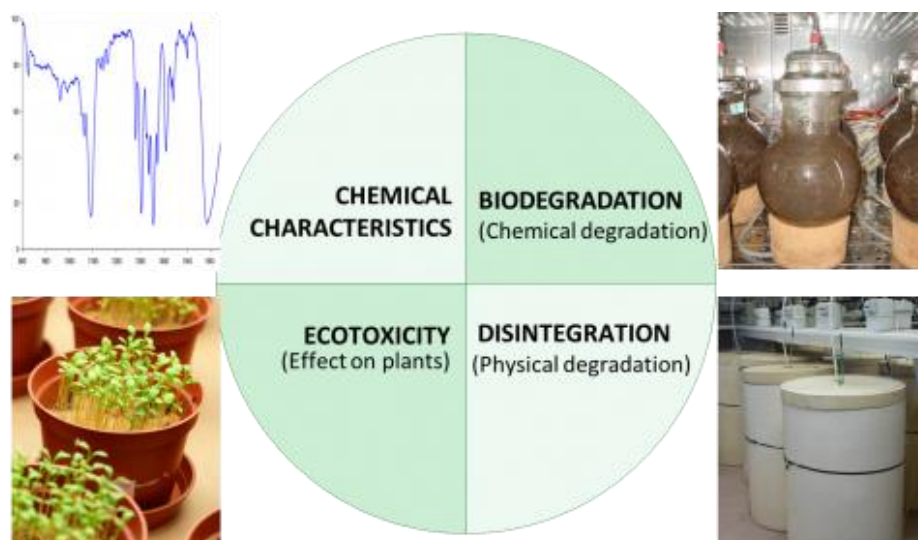
- **Belgium:** OK Compost Home program (TÜV AUSTRIA Belgium)
- **UK:** Home compostable certification scheme (Association for Organics Recycling, in cooperation with TÜV AUSTRIA Belgium)
- **US (general):** BioSpecs for Food Service Ware (Sustainable Biomaterials Collaborative)
- **US (state of California):** Senate Bill No. 567: 'claims on home compostability are only possible if the material is OK Compost Home certified'

To be considered compostable, products must be tested for four parameters (Figure 3):

- **Biodegradability:** as above, but according to certifications ISO 14855, ASTM D 5338 and/or EN 14046 (biodegradability in compost). The certification of biodegradation EN 13432 requires that 90% of the initial mass is converted into CO<sub>2</sub> by aerobic microbes under compost conditions within six months.
- **Capacity to disintegrate:** the ability of the material to break down and falls apart. The disintegration of a material is linked to its physical form and is therefore strongly affected by its thickness, grammage and/or density. Mass balance to measure the exact % of disintegration are used for certification. Reference protocols are ISO 16929 and/or EN 14045. The

certification of biodegradation EN 13432 requires that 90 % of the product disintegrates into pieces smaller than 2 mm after 12 weeks in compost facilities.

- **Ecotoxicity:** the potential presence of detrimental effects on plant growth or the survival of soil fauna caused by material residuals left behind after composting. Plant toxicity testing is a part of all norms on industrial compostability and prescribes the use of 2 plant species. Earthworm toxicity testing however is only required for AS 4736 certification in Australia. Plant toxicity testing is described in OECD 208 and EN 13432, earthworm toxicity testing is covered by ASTM E 1676, OECD 207, ISO 11268 and/or AS 4736.
- **Chemical characteristics:** Reference maximum contents of heavy metals (Cu, Zn, Ni, Cd, Pb, Hg, Cr, Mo, Se, As) and fluorine and other volatile compounds must not be exceeded. The added product must not have any negative influence on the quality of the compost. Each norm has its own set of heavy metal limits, with EN 13432 and AS 4736 as the most stringent ones.



*Figure 3 : Compostability requirements*

Certification bureaus offering certification for home compostable materials and products include TÜV AUSTRIA Belgium (OK Compost Home), DIN CERTCO (DIN-Geprüft Home compostable), and AfOR (FILM home compostable) in Europe; and ABA (Home compostable) in Australia.





## Industrial compostability

After many years of development and intensive discussions in normalization committees, requirements for industrial compostability have become well established and have been firmly fixed in several norms. Several protocols for quality standards have been developed internationally (Figure 5: International standard protocols for compostability) to certify the compostability of materials and items.

	WORLDWIDE	EUROPE	US	AUSTRALIA
				
PLASTICS	ISO 17088	EN 14995	ASTM D6400	AS 4736
PACKAGING	ISO 18606	EN 13432		
PAPER COATING			ASTM D6868	

Figure 5 : International standard protocols for compostability

To be certified as industrially compostable, items must be tested to match the same four essential requirements as home compostability (biodegradability, capacity to disintegrate as shown in Figure 4, ecotoxicity, chemical characteristics). Heavy metals and plant toxicity requirements are similar to those for home compostability. Biodegradation and disintegration however need to be performed at elevated temperature.



Figure 4 : Evolution of the disintegration of sample

Examples of certification bureaus around the world that certify industrial compostability are:

- **Europe:** TÜV AUSTRIA Belgium (OK Compost), DIN CERTCO (DIN-Geprüft) & European Bioplastics (seedling)
- **USA:** BPI (compostable)
- **Japan:** JBPA (GreenPla)
- **Australia:** ABA (seedling)
- **Rest of the world:** national/regional systems in Italy, Korea, Canada, Catalunya, Finland.



## New composting systems: OKLIN compost machine and SeaClicBox

Oklin composters are self-contained machines that use patented Acidulo™ microbial technology to speed up the organic waste composting process and reduce their volume by up to 90 % in 24 hours. The output is immature compost which can then be matured and used as a soil amendment.

Acidulo™ microorganisms, unlike other microorganisms, can resist and multiply under extreme conditions such as high temperature, high salinity, and high acidity. This guarantees a long service life

and easy maintenance of the machines. Furthermore, Oklin has developed the Nano Deodorization system in addition to the food waste composter. The Nano Deodorization System absorbs and reduces foul odours, providing an odour-controlled environment.

To avoid damaging the machine or contaminating the compost, Oklin bio-waste composter can accept only compostable waste such as all kinds of products food, raw or cooked (vegetables, meat, cat litter, wood chips, soups, seeds, compostable cutlery, and trays). Oil or oil mixtures, shells such as oyster or clam shells, fruit pits like lychee, peach fruit pits, chestnut peels, paper, drugs, cigarettes, batteries and any other or any other non-organic material such as plastic or metal products should instead not be discarded of in the machine.

### Degradation in other environments

In case the product's intended disposal route does not include industrial or home composting, its end-of-life fate might involve the disposal in other environments (soil, fresh water, marine water, anaerobic digestion, or landfill) in which the product will need to degrade after being disposed of.

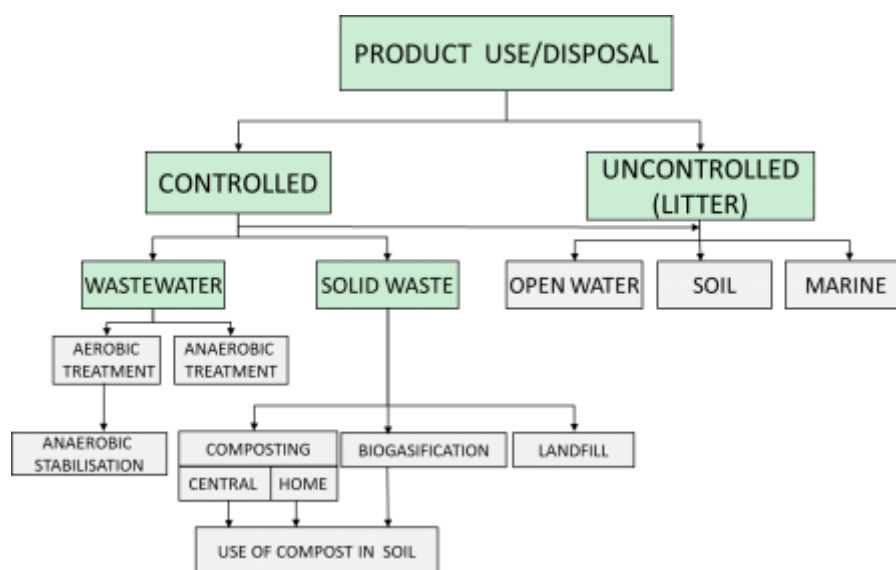
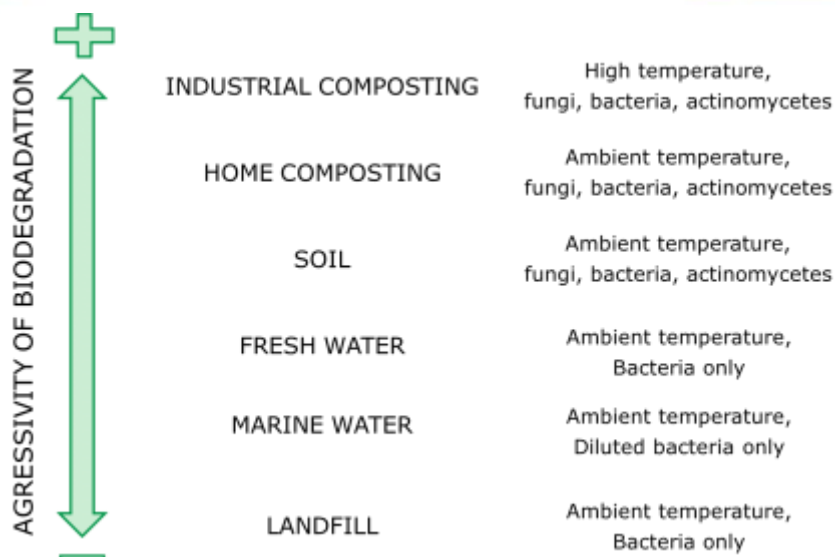


Figure 7 : End of life environment

It must be noted that the biodegradation of a product varies from one environment to another. In most cases it is the temperature and the microbial activity which determines the rate and level of (bio)degradation. Compost is considered as the most aggressive environment, while landfill is considered as the least aggressive environment. It is therefore not possible to extrapolate positive biodegradation results from one environment to another.



*Figure 8 : Aggressivity of biodegradation*

Existing certifications for the environments listed above include:

- Biodegradation in soil (ISO 17556, ISO 11266 and/or ASTM D5988)
- Biodegradation in fresh water (ISO 14851, ISO 9408, EN 29408, ASTM D 5271, OECD 301C, OECD 301F, OECD 302C and/or OECD 302F)
- Biodegradation in marine water (ISO 14851, OECD 306 and/or ASTM D 6691)
- High-solids anaerobic digestion (ISO 15985 and/or ASTM D 5511)
- Accelerated landfill test (ASTM D 5526)



*Figure 9 : OWS biodegradation equipment*

Similar to industrial and home compostability, TÜV AUSTRIA Belgium has created a certification scheme and accompanying logo for products which biodegrade in respectively soil (OK Biodegradable Soil), fresh water (OK Biodegradable Water) and the marine environment (OK Biodegradable Marine).

Certification for biodegradation in soil requires heavy metals, biodegradation (in soil) and plant toxicity testing, while certification for biodegradation in water only requires heavy metals and biodegradation (in water) testing.



Figure 10 : Symbols used by TUV Austria to certify biodegradability in non-compost environments

Even if certifications exist, there is a lot of discussions about the standard use for this certification in Europe. In 2021, pre-normative studies for standards on biodegradation, environmental safety and organic recycling are ongoing. New marine biodegradation tests need to be developed.

Certifications for the marine environment are particularly important to be sure that alternative products help tackling marine litter. Marine biodegradation tests are available (ISO 19679: research for new reference materials; and ISO 23977-1&2: test with reference materials). Marine biodegradation test at lower (realistic) temperature (possibly 10°C) will be performed because ASTM D6691 standards are currently tested at 30°C.

About Marine disintegration tests, a new method for marine disintegration testing ISO/FDIS 23832 (ISO/TC 61/SC 14) will be investigated with test duration for 1 year by the Belgian OWS to check with real-life conditions. Marine solubility/dispersibility currently have standards only applicable to freshwater environments (EN 14987) and it should be tested to examine if it is also valid for marine conditions at lower temperatures. Finally, there is a lack of marine toxicity tests for bioplastics.

Research on organic recycling in anaerobic digestion started in the project OPEN-Bio by the Belgian company OWS, and it will be extended to improve the testing scheme on organic recycling by anaerobic digestion.

#### 4 Alternatives to EPS/XPS (food, packaging, transport, leisure)

Being thermic insulators, EPS and XPS are used to transport and preserve hot and warm food. Examples are the clamshells used for takeaway food, or the fish boxes used to move fresh and frozen seafood. These products are particularly problematic from a circularity point of view because they are usually

designed to be single-use items and because the contamination by food hampers their recyclability. EPS and XPS rigidity and lightweight explain why these two materials are also used for protective packaging and to fill voids in boxes during shipments. The EPS and XPS blocks, and chips used for this purpose are not necessarily designed to be single-use products, but their bulkiness and the absence of household collection led to frequent disposal through general waste in landfilling or incineration, or to mismanagement and dispersal in the environment. The buoyancy of EPS and XPS blocks make them also a popular option for the creation of floating devices like pontoons, buoys, and boards. The EPS and XPS in these devices tend to be screened by protective layers. However, weathering, damage or faulty design can expose EPS and XPS to the environment, with high risk of fragmentation and consequent pollution of freshwater and marine environment,

This section explores the possible alternative materials that can be used instead of EPS and XPS for packaging, protection, and production of floating devices. The different materials are listed and described with a list of benefits and applications. A list of products is also presented in the final table with relevant links and considerations about their end of life. The reader should be aware that the list is no meant to be exhaustive due to the high number of possible products. However, the table provides several options already on the market for several material alternative to EPS and XPS.

## 4.1 Polyethylene, Polypropylene and their foams

**Material:** Polyethylene and polypropylene are two polymers with similar properties. Several companies are able to foam these polymers.

**Production:** Polyethylene and polypropylene are the first and second most produced plastic polymers and are widely recyclable. They can be produced as virgin plastics from oil or from biomass. Sometimes virgin plastic is also mixed with pellets deriving from mechanical recycling.

SealedAir® can produce Polyethylene foam from sugarcane biomass, which they brand as 'EcoPure'. Both the biopolymer and the oil-derived polyethylene can also be mixed with recycled polyethylene (eg., Ethafoam® HRC and Stratocell® have 65 % recycled resin content).

CIPASI produces polypropylene boxes (FreshBox®) using polypropylene sheets produced melting virgin polypropylene and feeding it to a series of co-extruders. The material flows through the extruders into a cast to obtain the desired shape of the alveolar lamina. Auxiliary units can add colours, and treat the material with different additives, such as protection against UV radiation. It can also be printed by a flexographic processes. CIPASI packaging solutions come with the UNIQ Agricultural Quality Seal.



TriPack is also producing polypropylene boxes, including pop-up boxes to reduce transport space and costs; drainage boxes, for draining meltwater while on the move; and leakproof boxes, which are ideal for air freight transportation.

High-density polyethylene is also used to produce floating devices that can be used instead of EPS blocks to provide buoyancy to pontoons/bridges. Companies like Cubisystem®, Deep Dive Systems or Work on Water LTD produce these types of floats that can be assembled to create floating platforms resistant to up to 1000-2000 kg per square meter (often as result of more layers of floats).

Polyethylene and polypropylene can also be foamed through an extrusion process. Foams with different porosity, strength and resistance can be produced according to the necessity of the final users.

**Benefits:** Polyethylene and polypropylene are recyclable. The bio-based polymer from sugarcane biomass has a lower impact than oil-based products. Customisable products (densities, colors, thicknesses). It is flame-resistant and anti-static. Planks can be laminated to obtain high strength-to-weight ratio, reducing the amount of material needed. Resistance is enough for military-grade packaging (resistance to explosion). Fine cell foams also have low-abrasivity.

The polypropylene boxes are lightweight, highly customisable (available in different sizes, printable and treatable to be anti-UV, coronavirus-free, antistatic, conductive, fire retardant) and reusable. They work in a wide range of temperatures (-40 °C up to 70 °C) and have high cold transmission in chamber. Polypropylene fish boxes have proven to keep products cooler for longer with faster cool down times from the very start of the cold chain than similar polystyrene products. They are watertight and provide thermal insulation. They are also suitable for hydrocooling, washing and disinfection tunnels. They are suitable for contact with food but it is not clear whether this involves a coating of polyethylene or if the box keeps being monomaterial (so easily recyclable).

Polyethylene floats are modular, which gives high flexibility to build many different structures. Blocks can be easily transported, and do not break down in small particles in water. They are resistant, to chemicals, water and UV. Some products like Cubisystem® are also more stable thanks to a concave bottom.

Floating properties of polyethylene and polypropylene foams are also used for leisure purposes directly related to marine pollution risk. Bodyboards can have a core in EPS, polyethylene foam and polypropylene foam. The three foams are different in their use, with EPS and polyethylene being more indicated for beginners for their stability. Polypropylene bodyboards are also more suitable for hot

climates and polyethylene bodyboards for colder weather. A mix of the two non-EPS foams is also available on the market.

**Applications:** Polypropylene boxes can be used to store, freeze and transport fish and seafood, crops such as asparagus with wet foam, wet aromatic herbs or vegetables with ice or ice water; and it facilitates the processes of washing and disinfecting food. Foamed polyethylene can be used for packaging, cushioning, case inserts and to provide buoyancy. It can be used to transport dangerous goods (e.g., military grade explosives) and can be also used for acoustic insulation thanks to sound-absorbing properties.

**End of life:** Polyethylene and polypropylene can be recycled and producers claim that foam polyethylene can be recycled in the same waste stream (#4, low density polyethylene or LDPE). Foamed bio-based polyethylene can be recycled with normal polyethylene. The issues for recycling foamed polystyrene in terms of density will be true here too. Polypropylene FreshBox® by CIPASI are made from polypropylene which is 100% recyclable (ISO 18604:2013).

**Sources:** <https://pontoonprovider.co.uk/products/cubisystem>,  
<http://www.cubisystem.fr/en/floating-docks-product#prettyPhoto/0/>, <https://deep-dive-systems.com/pontoon-systems-hdpe/>, <https://www.boardshop.co.uk/blog/Bodyboard-Buyers-Guide/>

## 4.2 Polyurethanes

**Material:** Polyurethanes are a class of polymers created by different types of monomers: alcohols with two or more reactive hydroxyl (-OH) groups per molecule (diols, triols, polyols); and isocyanates that have more than one reactive isocyanate group (-NCO) per molecule (diisocyanates, polyisocyanates). These molecules form a 'urethane linkage', which is the essential part of the polyurethane molecule. Polyurethanes can be presented in solid forms or as spray foams.

**Production:** While thermoplastics such as polyethylene and polypropylene are produced in granules, powders or films that are subsequently moulded, polyurethanes, usually made directly into the final product. Liquid polyisocyanate and polyol are mixed in a mould, reacting within seconds/minutes and solidifying into a ready-to-use product. Much of the polyurethanes produced are in the form of large blocks of foam, which are cut up for use in cushions, or for thermal insulation. Liquid reactants can also be sprayed into a building surface or coated on a fabric.



The manufacture of polyurethanes needs a variety of other chemicals such as catalysts to speed up the reaction between polyol and polyisocyanate; cross-linking and chain-extending agents for reinforcement to improve physical properties; blowing agents and surfactants to create the foam; pigments; fillers to improve stiffness; flame retardants and smoke suppressants; and plasticisers to reduce the hardness of the final product.

Foamed polyurethane can be produced chemically or physically. Chemical blowing uses water that reacts with some of the polyisocyanate to create carbon dioxide; physical blowing is based on the effects of liquids with a low boiling point that vaporise during the reaction, creating the bubbles that expand the polymer.

Annual production of polyurethanes is expected to be 26.4 million tonnes in 2021.

**Benefits:** The physical and chemical properties of the polyurethanes, and their use, depend on the structure of the original reactants. Foams can be flexible or rigid, resistant to cold or particularly kind to skin. Closed-cell polyurethane is also highly resistant to water and can be used to effectively waterproof many surfaces. Polyurethanes can be bonded to surface materials without the introduction of separate glues because they have adhesive properties during their the forming reaction.

Polyurethane spray foam are very good insulators. Once sprayed, expands in voids, bonding tightly to adjoining surfaces sealing the surface.

**Applications:** The ability to control polyurethanes properties (e.g. flexibility, density, bubble presence and size) during production allow for a wide range of possible uses. Polyurethane is used to create foams that can be used instead of EPS or XPS for cushioning fragile goods.

When rigid foamed polyurethanes are attached to rigid sheet building materials (e.g. plasterboard, steel sheet, plywood), composite building insulation panel can be produced. In this case, thermal insulation properties are dictated by the gas trapped in the cells. The polyurethane can also be provided in liquid form that is sprayed in cavities of on surfaces, solidifying to provide an effective insulation layer.

Foams can also be used for providing buoyancy to pontoons, hulls and floating devices.

Polyurethanes are also used for cushioning, clothes (e.g. shoe soles), medical devices (artificial heart valves) and electrical equipment.

**End of life:** Polyurethanes are recyclable through chemical and physical recycling.

**Sources:** <https://www.sciencedirect.com/science/article/pii/B9780128040393000142>,  
<https://www.essentialchemicalindustry.org/polymers/polyurethane.html>,  
<https://www.europur.org/sustainability/recycling>, <https://www.edu-chem.co.uk/polyurethane-systems/contracting-applications/marine-applications/buoyancy-for-pontoons/>,  
<https://www.ibpportland.com/blog/polystyrene-vs-polyurethaneinsulation#:~:text=Polyurethane%20foam%20is%20more%20costly%20and%20harder%20to,during%20operation%20and%20creating%20a%20tight%20air%20seal.>

## 4.3 Polylactic acid (PLA)

### 4.3.1 Un-foamed PLA

**Material:** Polylactic acid or polylactide (PLA) is a polymer composed of lactic acid molecules chained together. It is a thermoplastic polyester discovered by Wallace Carothers in 1932.

**Production:** Wallace Carothers first produced PLA heating lactic acid under vacuum while removing condensed water. Higher density was subsequently developed by using lactide (a dimer consisting of a small chain of two molecules of lactic acid) and a ring-opening polymerization process. Lactic acid is produced by biomass of plants like corn or cassava. PLA is currently the second most produced and consumed bioplastic in the world in terms of volume. NatureWorks, the leading producer of PLA, has a world capacity of 150 000 T/year, Total Corbion have an Asian capacity of 75 000 T/y and will develop a new capacity production of 100 000 T/year more in France in 2024. For Ecovio® (mixed of PBAT and PLA), BASF have an European capacity of 74 000 T/year and will develop a new capacity production of 60 000 T/year in collaboration with Red Avenue New Materials Group in China.

PLA can also be distributed in granules to produce foams, with comparable storage times to EPS. These granules can be used, with some parameters modifications, in conventional pre-expansion and molding process steps already used for EPS.

**Benefits:** PLA is biodegradable and compostable. PLA is manufactured from renewable sources.

Foamed PLA can be expanded using natural foaming agents such as CO<sub>2</sub> and using machineries already in use to expand PS into EPS. Foamed PLA is durable, resistant (more than other biopolymers such as starch-based ones) and lightweight.

**Applications:** Early applications of high-density PLA were mostly limited to biomedical areas due to its ability to be safely absorbed biologically. Over the past decades, the development of economical

production methods and a rising environmental consciousness in consumers lead to the widespread use of PLA as packaging material for consumer goods.

Foamed PLA has been approved for food contact, has good thermal insulation properties and multishock resistance. It is also light weight and moisture-resistant. These characteristics make PLA a valid alternative to EPS and XPS for several applications. Currently PLA products are used to produce beans for filling space in boxes or bigbags, ZealaFoam (Biopolymer Network Foamed), fish boxes (SEAclic Box by STOROpak produced by BASF Ecovio® EA (mixed of PLA+PBAT).

Non-foamed PLA can also be used to produce cups and trays. Some of these products (such as BioCup by BioPak) are to be used only with cold food drinks.

**End of life:** PLA can be composted, recycled and safely burned. Its ability to biodegrade has been used since the early days of PLA for biomedical products.

The biodegradability is also advantageous for waste management of non-medical applications of PLA since the products can be composted under industrial composting conditions (58 °C). This means that PLA products do not have to be landfilled even after contamination with food. Composting involves a chemical hydrolysis process, followed by microbial digestion. PLA can partly (about half) decompose into water and carbon dioxide in 60 days, after which the remainder decomposes much more slowly (actual rate depending on the material's degree of crystallinity). For example, BioPak products use Ingeo™ PLA and their products are certified to European Compost Standards EN13432.

PLA is also recyclable. On top of mechanical recycling, there are attempts to carry out chemical (cradle-to-cradle) recycling depolymerising post-use PLA to produce lactic acid molecules to create new virgin PLA (e.g., the company Galactic is developing this protocol).

Mismanaged waste is still dangerous because without the correct conditions, PLA decomposes very slowly, similar to oil-based polymers. Even though PLA decomposing bacteria have been isolated in soil (Bubpach et al., 2018), Bagheri et al., (2017) found that PLA did not show any sign of decomposition (no decrease in mass) in sea- and freshwater conditions (at 25 °C) throughout a one year long experiment. Nazareth et al., (2019) also did not find any sign of decomposition of PLA products in seawater. This is also a problem in home composters, where PLA will not disappear. PLA incineration does not release any toxic chemicals because it contains only carbon, oxygen, and hydrogen atoms, without chlorine atoms that would produce dioxins during burning. Also, traditionally, bioplastics like PLA do not have heavy-metal additives.

In the natural environment, PLA also undergoes thermal and photodegradation by UV light. PLA can also be degraded by some bacteria, such as *Amycolatopsis* and *Saccharothrix*. A purified protease from *Amycolatopsis* sp., PLA depolymerase, can also degrade PLA. Enzymes such as pronase and most effectively proteinase K from *Tritirachium album* degrade PLA.

Carbiolice, a french company, have invented and patented Evanesto® additive that increases the kinetic biodegradation of PLA. With 5 % of this additive, PLA can be home compostable.

#### 4.3.2 Foamed Polylactic acid (PLA)

**Material:** Some companies are focused on the production of foamed plastic based on PLA. Some products are already available, while new options are being currently developed.

**Production:** The existing solution (produced by Bewi) uses biomass such as corn starch and sugarcane to produce PLA. No VOC's are emitted during production. Without addition of a flame retardant it meets the Euro class E fire standard. Bewi produce beads that can then be treated to produce finalised products. CO<sub>2</sub> is used to impregnated and foam up the beads with hot air or a mixture of steam with air. A coating is also applied to improve the fusion between the beads. Prior to moulding, the blowing agent is removed from inside the foamed beads (using air or pressure filling with saturated steam with a maximum pressure of about 2 bar). After moulding, hot wires (oscillating or stationary wires at 200–300 °C) can be used for cutting.

In Ricoh's new technology, PLA is foamed in a process utilizing Ricoh's "CO<sub>2</sub> fine foam technology" to produce foam sheets. At high temperatures, CO<sub>2</sub> acts as a foaming agent and is dissolved in the polymer until, at saturation, it starts a process of nucleation creating CO<sub>2</sub> bubbles. Bubbles expand increasing the volume of polymer. After a stage of coalescence, the matrix is stabilised by cooling the structure and diffusing CO<sub>2</sub> outwards. A continuous super critical CO<sub>2</sub> (CO<sub>2</sub>-SC) foaming process (CO<sub>2</sub>-SC extrusion) is also available and to produce polymer foams in the form of cylindrical rods or more complex profiles. A "conventional" extruder is coupled with a pressurization and CO<sub>2</sub> injection system directly into the sheath of the extruder. The polymer is introduced into the extruder through the hopper, it begins to melt in the first section and rise in pressure. Then, the CO<sub>2</sub> is introduced at the same pressure as the polymer. Then the mixture is forced through the die where the drop in pressure and temperature causes the passage of CO<sub>2</sub> in the gaseous state and therefore triggers the foaming. CO<sub>2</sub>-SC has made it possible to limit or even eliminate the use of organic solvent for the development of new, more "green" processes.

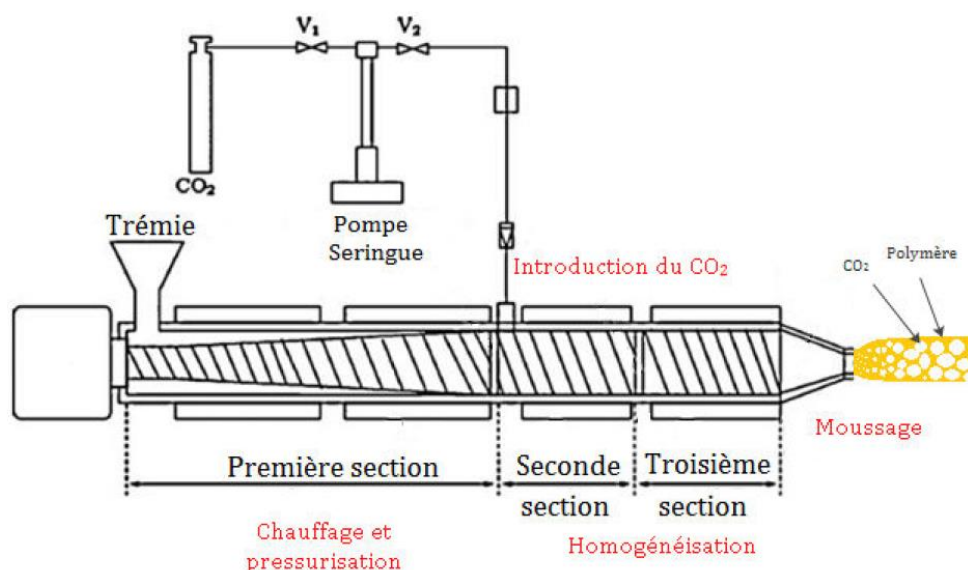


Figure 11 : Equipment used for the extrusion of polymer per CO<sub>2</sub>-SC

Ricoh's supercritical CO<sub>2</sub> technology produces uniform bubbles only tens of microns in diameter, while in conventional foaming methods bubble sizes are difficult to control and of large diameter, resulting in brittle and often uneven sheets. Making PLA foam requires that it be blended with other materials, such as fossil-derived resins. Beyond that is an inevitable tradeoff, adding fossil-derived resins compromises the carbon-neutrality and biodegradability of PLA. Through the kneading process, fillers (foam nucleating agents) are evenly distributed in PLA, and the foaming takes place with the fillers as nuclei. PLA can be made into very thin sheets while its flexibility and strength are maintained because of the bubble uniformity.

**Benefits:** Foamed PLA is meant to be flexible, lightweight and strong. Producers say it has similar properties to EPS/XPS. Bewi's beads shall be stored for up to one year at below 30 °C, protected from direct sunlight and other weather conditions (rain, wind, frost etc.).

Ricoh claims it shall provide excellent insulation, high shock absorption, freedom of design and more resistance thanks to small-size bubbles. The material is also designed to be insensitive to moisture, hygienic, not hazardous to health and durable (rot free, fungal proof, resistant to UV radiation).

**Applications:** The PLA foam from Bewi is suitable for filling hollow spaces, beanbags, pillows and for the production of light and heavy products by shape moulding. Some foams are also approved for food contact and could be used for trays and bowls. Bewi Group (former Synbra) includes companies (IsoBouw, Synprodo, Plastimar, Styropack) that produce insulation and packaging, but it is not clear if

those companies use their foamed PLA as material. A practical application is BioFoamPearls® for wall insulation.

Ricoh intends to deliver the PLA foam sheets in the near future..

**End of life:** Just like normal PLA, foamed PLA is supposed to be composted, recycled and safely burned. However, the Bewi solution is branded to be recyclable and industrial compostable but the company do not present any certification. Ricoh highlights that foamed PLA is usually not a monomaterial, so the actual compostability shall be assessed once the final material is released on the market.

**Sources:** [https://www.ricoh.com/technology/tech/091\\_PLAiR](https://www.ricoh.com/technology/tech/091_PLAiR), <https://bewi.com/wp-content/uploads/2021/01/Technical-data-sheet-BioFoam.pdf>,  
<https://www.termokomfort.nl/isolatieparels/biofoampearls>

## 4.4 Kaneka Biodegradable Polymer Green Planet PHBH™

**Material:** Kaneka Biodegradable Polymer Green Planet PHBH™ is designed to have key characteristics of polyethylene and polypropylene materials.

**Production:** Kaneka Biodegradable Polymer Green Planet PHBH™ is 100 % biobased and biodegradable polymer produced via a bio-fermentation process using renewable plant oils as feedstock but there are also prospects to establish a manufacturing technology based on biomasses not used for food as primary ingredients. Polymers are accumulated in the bodies of microorganisms through strain development and fermentation technology. Kaneka Corporation (Headquarters: Minato-ku, Tokyo) invested approximately 2.5 billion yen to increase production capacity of Kaneka Biodegradable Polymer PHBH™ (then Kaneka Biodegradable Polymer Green Planet PHBH™) at the Takasago Manufacturing Site (Hyogo Prefecture in Japan) aiming at a five-fold increase in the production to around 5,000 tons per annum. A construction completion ceremony was held on December 17<sup>th</sup>, 2019.

**Benefits:** Kaneka Biodegradable Polymer Green Planet PHBH™ is resistant to heat and hydrolysis, is an effective barrier to water vapour, is flexible and can be dyed.

**Applications:** Kaneka Biodegradable Polymer Green Planet PHBH™ is stable under every day usage conditions. It is used mainly for packaging films, bags, bottles, containers, auto interiors and electrical equipment. Kaneka is refining resin mixes and moulding processes in a bid to further improve the strength and tear resistance of packaging films, especially agricultural mulch films and composting bags.



**End of life:** Kaneka Biodegradable Polymer Green Planet PHBH™ resin is biodegradable in either anaerobic, aerobic or marine conditions in the natural environment, ultimately being converted into carbon dioxide and water. It is home and industrial compostable as certified according the following standards: ASTM D6400 and TUV Home Compost OK Certification. Compostability depend on shape, thickness, weight, and the presence of additives in the final products. Kaneka Biodegradable Polymer Green Planet PHBH™ is also biodegradable in soil and aerobically digestible under ASTM D6400, and anaerobically digestible under ISO 15985 standards. Degradability in marine environment has also been certified under TUV Marine Biodegradable OK Certification. However, the resins are not considered soil, marine or landfill degradable in California

**More information:**

<https://kanekabiopolymers.com/certifications/>

<http://www.kaneka.be/new-business/kaneka-biodegradable-polymer-green-planet>

<https://www.kaneka.co.jp/topics/uploads/2019/12/%E3%80%90Kaneka%E3%80%91Completion-of-Kaneka-Biodegradable-Polymer-PHBH%E2%84%A2-Plant-with-annual-production-of-5000-tons.pdf>

## 4.5 Bagasse

**Material:** Bagasse is the dry fibrous residue by-product of the extraction of sugar from sugarcanes.

**Production:** Sugarcane residues are treated with high-heat and high-pressure to press and shape the fibres into a compact matrix.

**Benefits:** Bagasse production has a very low environmental impact since it is produced from the waste of sugar production. When used in food packaging, bagasse doesn't trap condensation unlike EPS/ XPS so the food stays hot and crisp. Bagasse products can be used for both hot and cold food. Bagasse products are safe to use in microwaves, conventional ovens (some companies sell products resistant to ~200 °C) and for fridge storage.

**Applications:** Bagasse has been used to produce biofuel, since it produced enough heat. It is also used to produce ethanol. Fibres in the sugarcane pulp showed durability and malleability: it can be used to produce paper (a process developed in 1937 in Peru by Clarence Birdseye at the W.R. Grace Company) that can be printed and used for notebooks, tissues, boxes, and newspapers. Bagasse can also be used to create boards similar to plywood (bagasse boards) for furniture. Thanks to these properties, bagasse is nowadays used as an alternative to EPS in the production of food packaging for hot and cold food (takeaway containers, plates and bowls).

**End of life:** Bagasse is home and industrially compostable. Examples of companies that received certifications for compostability for their bagasse products include Biopak (for industrial compost: AS4736; and for home compost: AS5810) and Vegware (European EN13432 and American ASTM D6400). Takeaway Packaging products are branded as home compostable and 90 % of a product is supposed to disappear in 120 days at 25 °C.

**Sources:** Rainey and Covey, 2016. Pulp and paper production from sugarcane bagasse. In book: Sugarcane-Based Biofuels and Bioproducts. Chapter 10. Publisher: John Wiley & Sons.

DOI: 10.1002/9781118719862.ch10, <https://takeawaypackaging.co.uk/product/850ml-pulp-oval-lid-bagasse-food-packaging-qty-500/>

## 4.6 Palm leaves

**Material:** Palm leaves naturally fallen from Areca palm trees (*Areca catechu*).

**Production:** Areca palms (also known as ‘betel nut palm’, is cultivated in South Asia, China, South East Asia, South Pacific and West Indies. Producers use these naturally fallen palm leaves. Leaves are gathered and cleansed with high pressure water jets. Once dried, they are shaped under heated moulds and retain shape.

**Benefits:** There are no coatings, additives or chemicals, the product is just made from the natural leaf.

**Applications:** Palm leaves are used to produce tableware suitable for hot and cold food (plates, platters, and bowls). They are microwave friendly.

**End of life:** Palm leaves products are branded as biodegradable and compostable. In particular, Vegware claims that all their products are commercially compostable according to European EN13432 and the American ASTM D6400 standards.

**Sources:** [https://www.vegware.com/uk/catalogue/palm\\_leaf\\_tableware/](https://www.vegware.com/uk/catalogue/palm_leaf_tableware/), [https://en.wikipedia.org/wiki/Areca\\_catechu#cite\\_note-9](https://en.wikipedia.org/wiki/Areca_catechu#cite_note-9), <https://disposablegreen.com/product-features>, <https://foogogreen.com/shop-all/>

## 4.7 Pelaspan-Bio (Storopack) – starch

**Material:** STOROpack is producing packing peanuts that are completely soluble in water that are produced from starch.



**Production:** The Pelaspan-bio is completely made from starch. No more information available on the actual production.

**Benefits:** Pelaspan-bio peanuts are tear-resistant, antistatic (do not attract dust), odorless and their use is easy to integrate in existing packing processes.

**Applications:** fill padding material (packing peanuts). Comes in S-shaped pieces that interlock to create a coherent cushion that blocks, braces, and stabilizes goods and prevents them from knocking against each other. They keep products safe even when exposed to heavy strain.

**End of life:** home and garden compostable and certified in accordance with NF T51-800 in Germany, France, Spain, and UK. Compostable and certified in accordance with DIN EN 13432 (Europe) and ASTM D6400 (USA). Claimed to be entirely biodegradable (no residue) and water-soluble, but no certification is provided.

**Source:** <https://www.storopack.com/products/flexible-protective-packaging/loose-fill/pelaspanr-bio>

## 4.8 Paper / cardboard

**Material:** Paper is a thin layer of interwoven natural fibres. Paper been used for millennia and is manufactured from a pulp of natural fibers (usually from wood). Thicker, stronger paper is referred to as cardboard, which can be layered and corrugated to create stiffer boards.

**Production:** Handmade production of paper has been known in China since eight century BCE. Over the millennia, paper has been produced from a wide variety of natural fibers (hemp, cotton, linen among the others). However, today the main source of fiber is wood.

In manual papermaking, a pulp of vegetal fibres suspended in water (furnish) is created. The useful fibres are separate from waste material and then beaten to create the pulp, which is then adjusted through the addition of several chemicals to obtain specific properties (colour, mechanical resistance, etc). The pulp is then filtered through a fine mesh of non-corroding and inert material (brass, stainless steel, synthetic fibres), where fibers accumulate creating a mat that coats the mesh. The water of the pulp is then moved through draining, through damp cloths, pressing and drying (vacuum drying or simply air drying). These sheets are then flattened, hardened, refined in the surface and cut to the desired shape/size.

In industrial papermaking, which started in the 19<sup>th</sup> century, the process is automated. Pulps are refined creating a slurry that is then distributed to a moving mesh/screen where the pulp is dried in preparation for rolling. Instead of producing individual sheets, industrial paper making produces big rolls.

Cardboards are stiffer and thicker paper sheets.

Corrugated cardboards are produced layering several sheets of cardboard. There are two external layers that are always smooth boards, and there are one or more undulated layers (corrugated) in between them.

**Benefits:** Paper and cardboard are lightweight and resistant. Cardboard provides vibration, dampening and cushioning properties, it's recyclable, static neutral, insulating and can bear substantial loads.

Paper and cardboard are widely recycled and therefore recycled items lower the impact. Paper and cardboard are often monomaterial (non-coated paper), which contributes to their recyclability. Products are also easy to reuse. Paper and cardboards products are very customisable (different shapes and paper types). Paper and cardboard are also appealing to the final customers because they pose less problems for correct disposal (recycling).

Some of the cushioning solutions (e.g., folded paper) can be integrated into existing packing facilities and work streams. The in-situ production also avoids the need to pre-order material. The padding with thermic insulation properties is less bulky than EPS ensuring the use of smaller boxes.

**Applications:** Paper and cardboards products are currently used as an alternative to EPS/XPS for food packaging, insulation and transport of goods. The way in which paper and cardboard are used varies greatly and many companies have produced machines that can fold paper and cardboard to add new mechanical properties to the natural properties of the material.

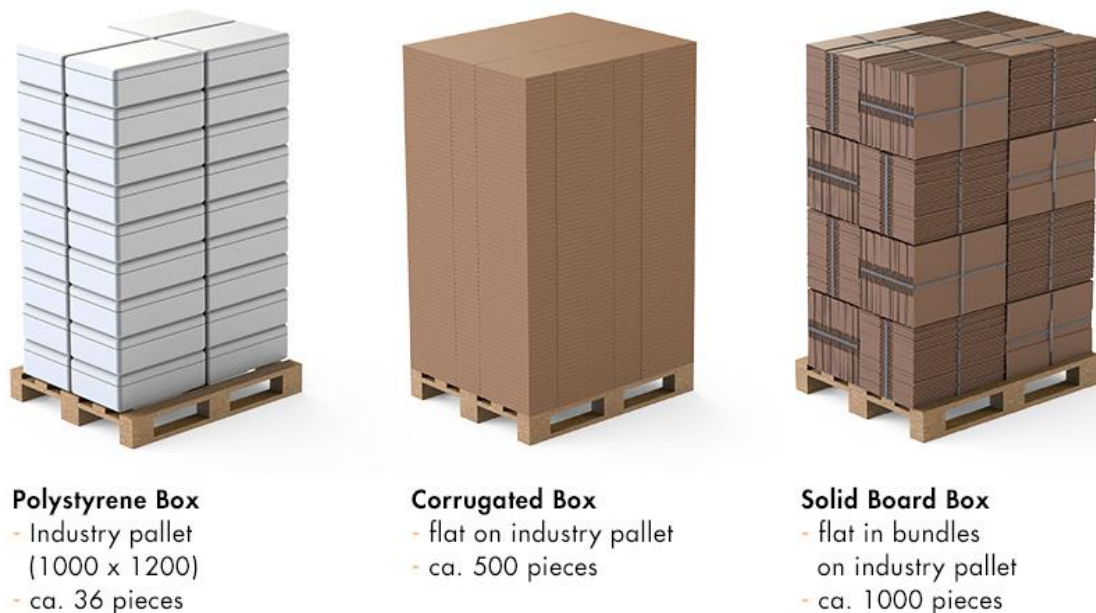
Paper and cardboards can be used to fill the void in boxes and provide cushioning to goods during transportation. Paper can be folded to decrease the amount of material used to fill a box. PAPERplus® by STOROpac and FasFil™ / ProPad™ by Sealed Air® are examples of how different machines can be used to fold paper in a different way to adapt to packaging needs (for example, producing sturdier cushions for heavier goods). These machines can also use different types of papers, including recycled paper, with increasing stiffness and protection properties.

Corrugated cardboard can also be folded for protective purposes. For example, the Corrispring products by GWPGroup, which are folded boards shaped into small 'concertinas' that can be used to

fill the void in packaging. The structure of the corrugated layer in these cardboards can also help provide protection, as in the case of the Hexacomb packaging by Smurfit Kappa.

Cardboard can also be cut into specific shapes that line the silhouette of products, blocking them in their position and avoiding damage during transportation that might be caused by a shift within the box (e.g. Korrvu® by GWPGroup). This last solutions avoids the need for protective material during packaging.

Paper and cardboard products can also be used for transport of food and other temperature-sensitive goods. For example, paper-based padding TempGuard™ by SealedAir® are box liners (made from 100% paper) that promise to maintain the temperature of the contents over 1-2 days. Fish boxes of different sizes (to accommodate from shrimps up to salmons) are produced by Solidus Solutions and are marketed as alternatives to EPS fish boxes. These boxes are approved for food contact, are moisture resistance and ensure fast freezing of the fish. Thanks to design, these boxes are easy to flatten for palletisation and transport, reducing costs and carbon emitted during transport. A coating of polyethylene can also be added to improve performances. They can be also filled with ice and some design are leak-proof. Another option is offered by Smurfit Kappa, that produces 'ThermoBox', a insulated box made of paper which can maintain food temperature constant. The producers claim that ThermoBox can perform better than EPS equivalent products.



*Figure 12 : Logistics advantages of Solidus Solutions*

Paper pulp can also be used to produce thicker layers with insulating properties. The company Igloo for example mixes paper pulp with alkene ketene dimer (or AKD) that makes it more stable and waterproof. They produce a cooler called RECOOL that can contain ice for 12 hours and water for 12 hours. It can be reused once dried. The company UFP technologies also offer protective solutions made of 100 % recycled paper.

**End of life:** Paper and cartons are widely collected for recycling. Paper fibers shorten during every manufacturing cycle, so paper can be recycled into other paper only 5 to 7 times. However, short fibers can still be used to produce a pulp that can be used for other applications. Paper and carton can also be composted, but possible plastic components/coating should be removed.

**Sources:** <https://www.smurfitkappa.com/us/products-and-services/packaging/thermobox>,  
<https://www.moldedfiber.com/eps-alternative.html>, <https://www.gwp.co.uk/guides/corrugated-board-grades-explained/>

## 4.9 Mushroom biomass

**Material:** This material is a matrix of vegetable waste (hemp hurds) held together by fungi biomass (mycelium). It is branded as MycoComposite™, a biomaterial developed by Ecovative design New-York based biotech company and now commercialised by its subsidiary Mushroom® Packaging. The french company Embelium also produced a similar product.

**Production:** The technology of using mushrooms to create a new insulating material (initially called Greensulate) was patented by Ecovative, which was awarded \$16,000 in 2007 from the National Collegiate Inventors and Innovators Alliance. Today the material is registered as MycoComposite™ and is marketed by Muchroom® Packaging. Several companies around the world have got the license to manufacture products using MycoComposite™.

During the process, agricultural non-food waste product such as hemp and cotton hulls are cleaned, heated and inoculated with fungi. For 4 days, the fungal mycelia grows (in a dark place) and the network binds the mixture. The foam also grow for an additional 2 days outside its mold. Finally, heat is used to make the fungus inert. During growth, the material's shape can be molded into various packaging products.

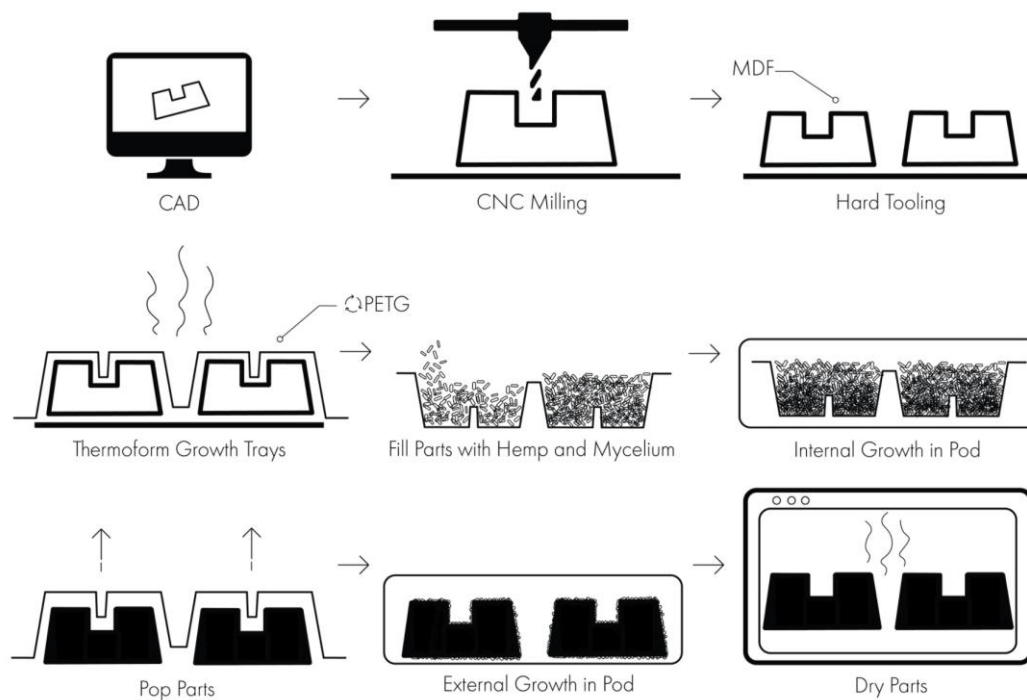


Figure 13 : Process development of Ecovative Mushroom

The company Embelium in France is also producing a similar product using similar production technology. They do not have a specific name branded for their material.

**Benefits:** Mushroom-derived products are water resistant, cost effective to produce and thermally insulating. MycoComposyte™ is certified 'Cradle-to-cradle Gold', it is a Class A fire retardant, it is certified by the Biodegradable Product Institute Certified. It is also VOC and aldehyde free. It is flexible since the material can be grown in any shape. The environmental footprint of the product is minimized through the use of agricultural waste, reliance on natural and non-controlled growth environments, and home compostable final products.

**Applications:** The biomaterials developed by Ecovative design can be used to produce many products for building industry, thermal insulation panels ready for installation, or protective packaging (renewable and compostable replacement for polystyrene packaging, that is also referred to as 'EcoCradle'). Products are used by (IKEA, Dell, Puma SE, and Steelcase).

The same concept was used in the past to test an insulation foam for buildings branded as Greensulate, which was not fully developed.

**End of life:** The product is 100 % home compostable and is supposed to degrade in home compost (30 days, certified ASTM D6400) and also in the marine environment (180 days). The manufacturer suggest to break products into small pieces and place outside in the soil. No industrial composting required.

**Sources:** <https://ecovatedesign.com/mycocomposite>, <https://mushroompackaging.com/>,  
<https://www.magicalmushroom.com/bioprocess>

## 4.10 Wool

**Material:** Wool is an abundant natural material, as a by-product of rearing sheep. Wool is made up of crimped keratin fibres which form a matrix with little air pockets that create a strong thermal barrier.

**Production:** Wool insulated food delivery boxes usually consist of a strong, robust outer cardboard box, containing liners/padding with liners filled with wool. Wool is washed and scoured (some products are certified in accordance with PPC regulations and ISO14001 environmental management systems). Producers claim that the wool is treated without the use of extreme temperatures, chemical treatments, or additives. Beneficial by-products of the washing and scouring process include a nitrate and mineral rich sludge which is used as natural fertiliser or made into biodegradable slug pellets. Some padding solutions have a layer of plastic (e.g., MPDE) to isolate the wool from the goods/food. Pads are produced in pre-defined sizes, but producers offer the possibility to customize.

**Benefits:** Thanks to the air pockets in the structure formed by fibres, wool can minimise humidity and condensation in transit and companies claim that content remains at a stable temperature for 24-72 hours (depends on the specific padding used, some companies are able to provide data from tests). Some of the packaging is strong enough to hold up to 30 kg of produce. Pads can be produced in many ways, giving flexibility to the customers. Wool is less bulky than EPS/XPS, taking up less space in the boxes and making transport more efficient (lower carbon footprint).

**Applications:** Insulated food delivery box sets are a flexible and practical packaging solution to the delivery all chilled food such as meats, cheeses, and chocolate, as well as fruit and vegetables. They are also suitable for shipping chilled fluid products such as detox juices, cream, and raw milk. The remarkable insulation properties make them perfect for chilled items like ice cream.

**End of life:** Wool fibres are biodegradable. Wool is totally compostable and fully biodegradable, and releases valuable nitrates back into the soil. Wool fibres are broken down by seawater much faster than the manmade micro fibres (Collie et al, 2019). Other components of commercially available packaging based on wool are made of cardboard, which is biodegradable. Some pads are lined with



plastics (e.g., MDPE), which is claimed to be recyclable but must be separated from the wool for composting.

**Sources:** <https://www.learnaboutwool.com/globalassets/law/resources/posters/wool-is-100-per-cent-biodegradable-131217.pdf>

## 4.11 Denim

**Material:** Denim is industrially treated cotton, used for the production of jeans.

**Production:** The denim used for insulation is produced using the scraps from the industrial production or post-consumer recycled contents.

**Benefits:** These products are vegan friendly, re-use scrap products, can be re-used and keep produce at a constant temperature during transport.

The denim building insulation is cheap and free from VOC and formaldehyde. Some companies use boron-based chemicals to increase fire resistance and impede the growth of fungi/mold. It has high Environmental standards (e.g. Environmental Specification 1350 Indoor Air Pollutant used for California Public Schools and it is a Class-A Building material that meets or exceeds ASTM testing for both commercial and residential batt insulation).

The installation is easy and does not require a specialist since it does not contain fiberglass.

**Applications:** Some companies that are using wools for packaging insulation (e.g., Puffin Packaging) are offering vegan-friendly pads filled with denim. Denim can be used to insulate buildings instead of EPS/XPS boards. Denim provides sound and thermal insulation (high R-value and Noise Reduction Coefficient).

**End of life:** companies such as ULtraTouch claim that their products are monomaterial (100 % natural denim and cotton fibers) and therefore fully recyclable.

**Sources:** <https://ecofriend.com/green-alternatives-styrofoam-insulation.html>,  
<https://www.bondedlogic.com/ultratouch-denim-insulation/>

## 4.12 Foamed nanocellulose

**Material:** Prototype of foam made of nanocrystals of cellulose. Still at concept stage.

**Production:** This foam is the result of research carried out at the Washington State University ('School of Mechanical and Materials Engineering' and 'Gene and Linda School of Chemical Engineering and Bioengineering'). The work was published in the journal Carbohydrate Polymers. According to the paper, researchers have developed an environmentally friendly, plant-based material that works better than EPS for insulation. The foam is mostly made from nanocrystals of cellulose, the most abundant plant material on earth. The material that is made of about 75 percent cellulose nanocrystals from wood pulp. The researchers also developed an environmentally friendly and simple manufacturing process to make the foam, using water as a solvent instead of other harmful solvents. To make cellulose nanocrystals, researchers use acid hydrolysis, in which acid is used to cleave chemical bonds. They added polyvinyl alcohol, another polymer that bonds with the nanocellulose crystals and makes the resultant foams more elastic. The material that they created contains a uniform cellular structure.

**Benefits:** This foam should be lightweight, strong (able to support 200 times its weight without changing shape) and should have good insulation properties.

**Applications:** Once developed, the product could be used for insulation purposes.

**End of life:** The product should be biodegradable.

**Sources:** Strong ultralight foams based on nanocrystalline cellulose for high-performance insulation. Peipei Wang, Nahal Aliheidari, Xiao Zhang, Amir Ameli. Carbohydrate Polymers, Volume 218, 15 August 2019, Pages 103-111., [https://www.technologynetworks.com/tn/news/styrofoam-alternative-developed-thats-environmentally-friendly-319383?utm\\_content=92074730&utm\\_medium=social&utm\\_source=facebook&hss\\_channel=fbp-372481492827910&fbclid=IwAR3x0fCWVUY3XecsJpCteCgzVvnMtSSN7elopteHEfZYB3bIF6zmR3tgGO](https://www.technologynetworks.com/tn/news/styrofoam-alternative-developed-thats-environmentally-friendly-319383?utm_content=92074730&utm_medium=social&utm_source=facebook&hss_channel=fbp-372481492827910&fbclid=IwAR3x0fCWVUY3XecsJpCteCgzVvnMtSSN7elopteHEfZYB3bIF6zmR3tgGO).

## 4.13 MOTALI - Mousse TAnins Llgine

**Material:** Prototype of foam made of nanocrystals of cellulose. Still at concept stage.

**Production:** The MOTALI "MOusses TAnins Llgine" project MOTALI is part of a research and development programme in France, led by a researcher from the Polymer Physics and Chemistry team at IPREM. The project aims to produce new bio-based porous materials from tannins extracted from trees (mimosa, oak, chestnut) and lignin, the main by-product of the paper industry. Well known for treating leather, tannins are extractables chemically close to phenolic molecules (expensive synthetic molecules, non-renewable and toxic, but of major importance in chemistry). Ecological, chemically

active, and inexpensive, since they are most often extracted from bark by hot water, tannins are proving to be interesting substitutes for homologous petroleum products. Lignin is used in the form of black liquor. The combination with the tannins allows the formation of a three-dimensional network with long chains which ensures the good mechanical resistance of the foam obtained. Currently available in very large quantities and mainly used as liquid fuel to supply energy to paper mills, black liquor has great potential for recovery. The maturation program funded by Aquitaine Science Transfert aims to develop a high-performance rigid foam (formulation, processes) which can be transposed to the pre-industrial scale. This project, in collaboration with the Landes General Council, is part of a strong environmental partnership. The commitment of a world-class building manufacturer in the co-development of the product also offers an additional guarantee for a successful technology transfer.

**Benefits:** This foam should have good mechanical resistance, be ecological (95% biobased) and non-toxic. It should also have infusibility and very low thermal conductivity.

**Applications:** There are no applications yet, this is a research and development programme.

**End of life:** Not known.

**Sources:** <http://www.formule-verte.com/isolation-une-mousse-rigide-issue-de-ressources-naturelles-renouvelables/>

## 4.14 Wood-based foams – Aalto University

**Material:** Wood-based foams have been developed thanks to artificial intelligence by the Aalto University (Complex Systems and Materials (CSM) group, FinnCERES competence centre and University and VTT Technical Research Centre of Finland on the bioeconomy of materials) under the Smart Foams research project. The materials use wood as a raw material and some combinations (such as a mixture of lignin, wood fibre, and laponite) can produce a foam that resists shock and humidity and can be used to replace plastic.

**Production:** These foams can be produced using different technologies. The correct thickness of the foam can be achieved by web formation (like in paper manufacturing, which is slow for drying). Processes like extrusion, or 3D printing, produce stick-like strong foams with hard and long bubbles.

**Benefits:** The material was designed to have wood-like features, such as strength, flexibility, and heat resistance. Researchers indeed obtained a material that is light, strong, resistant to humidity, fire safe and that can act as a heat insulator. These foams are similar to cork, but tens of times lighter. According

to the researchers, foam can be produced from carrot, lingonberry, cranberry, or beetroot powder, which make some foams of these edible.

**Applications:** The researchers are looking for commercial applications and markets for the new material. It can be used for insulation in buildings.

**End of life:** The researchers claim that the packaging material is fully bio-based, it biodegrades in natural conditions and it is easily recyclable with cardboard.

**Sources:** <https://www.aalto.fi/en/news/edible-shock-and-heat-resistant-wood-foam-could-replace-plastic-packaging>

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of producer	Use	Availability	Link	Comments	End of life
Polypropylene	CoolSeal	Tri-pack	Fishbox	Available on the market	<a href="https://tri-pack.co.uk/">https://tri-pack.co.uk/</a>	Monomaterial	Polypropylene is widely recycled (contamination from food must be avoided)
Polypropylene	FreshBox®	CIPASI/GRUP O Hinojosa	Fish boxes		<a href="https://news.wsu.edu/2019/05/09/researchers-develop-viable-environmentally-friendly-alternative-styrofoam/">styrofoam-alternative-Freshbox</a> <a href="https://news.wsu.edu/2019/05/09/researchers-develop-viable-environmentally-friendly-alternative-styrofoam/">https://news.wsu.edu/2019/05/09/researchers-develop-viable-environmentally-friendly-alternative-styrofoam/</a>	Monomaterial (but website also says they are lined with polyethylene for food contact)	Recyclable certified to ISO 18604:2013
Polyethylene (HDPE)	Cubisystem ©	Pontoon Provider	Floating pontoons	Available on the market	<a href="https://pontoonprovider.co.uk/products/cubisystem">https://pontoonprovider.co.uk/products/cubisystem</a>  <a href="http://www.cubisystem.fr/en/floating-docks-product#prettyPhoto/0/">http://www.cubisystem.fr/en/floating-docks-product#prettyPhoto/0/</a>	Monomaterial	Polyethylene is recyclable. However, after permanence in water for prolonged period, weathering might affect recyclability.
Polyethylene (HDPE)		Deep dive systems	Floating pontoons	Available on the market	<a href="https://deep-dive-systems.com/pontoon-systems-hdpe/">https://deep-dive-systems.com/pontoon-systems-hdpe/</a>	Monomaterial	Polyethylene is recyclable. However, after permanence in water for prolonged period, weathering might affect recyclability.
Polyethylene (HDPE)	HDPE modular pontoon	Work on Water Ltd	Floating pontoons	Available on the market	<a href="https://workonwater.co.uk/">https://workonwater.co.uk/</a>	Monomaterial	Polyethylene is recyclable. However, after permanence in water for prolonged period, weathering

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of product	Use	Availability	Link	Comments	End of life
							might affect recyclability.
Polyethylene foam	EcoPure	SealedAir®	Packaging	Available on the market	<a href="https://sealedair.co.uk/en-gb/node/269341">https://sealedair.co.uk/en-gb/node/269341</a> <a href="https://sealedair.co.uk/sites/default/files/EcoPure%20Brochure%20D-235_032019.pdf">https://sealedair.co.uk/sites/default/files/EcoPure%20Brochure%20D-235_032019.pdf</a>	Monomaterial (but mix of virgin, bio-based and recycled material)	Polyethylene is recyclable
Polyethylene foam	Ethafoam® and Stratocell® (portfolio with different products)	SealedAir®	Packaging	Available on the market	<a href="https://www.sealedair.com/content/dam/protective-materials/foam/polyethylene_fabricated_foams_capabilities.pdf">https://www.sealedair.com/content/dam/protective-materials/foam/polyethylene_fabricated_foams_capabilities.pdf</a>	Monomaterial (but mix of virgin and recycled material)	Polyethylene is recyclable
Polyethylene foam	Several products available	Several producers	Bodyboards and surfboards	Available on the market	<a href="https://www.sortedsurfshop.co.uk/boards/surfing/foam-surfboards.html">https://www.sortedsurfshop.co.uk/boards/surfing/foam-surfboards.html</a> <a href="https://bodyboardking.com/c/4564547/1/pe-polyethylene-core.html">https://bodyboardking.com/c/4564547/1/pe-polyethylene-core.html</a> <a href="https://bodyboardking.com/c/4564548/1/pp-polypro-core.html">https://bodyboardking.com/c/4564548/1/pp-polypro-core.html</a> <a href="https://www.surfdome.com/Bodyboards/sddsl14378.htm">https://www.surfdome.com/Bodyboards/sddsl14378.htm</a> <a href="https://www.decathlon.co.uk/search?Ntt=polypropylene+bodyboard">https://www.decathlon.co.uk/search?Ntt=polypropylene+bodyboard</a>	Only the core is made of Polyethylene or polypropylene foam	Polyethylene and polypropylene are recyclable, but they need to be separated from the rest of the board
Polyurethane	Polyurethane Foam Packaging	Wessex Packaging	Protective padding	Available on the market	<a href="http://www.wessex-packaging-/our-products/polyurethane-foam">www.wessex-packaging-/our-products/polyurethane-foam</a>		Manufacturer does not claim recyclability,



Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of product	Use	Availability	Link	Comments	End of life
							but options for recycling exist
Polyurethane		Edu-chem	Buoyancy Insulation	Available on the market	<a href="https://www.edu-chem.co.uk/polyurethane-systems/contracting-applications/marine-applications/buoyancy-for-pontoons/">https://www.edu-chem.co.uk/polyurethane-systems/contracting-applications/marine-applications/buoyancy-for-pontoons/</a>		Manufacturer does not claim recyclability, but options for recycling exist
PLA	ZealaFoam	Biopolymer Network	Peanut, helmets, fish boxes	Peanuts already available, few helmets produced, fish boxes in prototype stage	<a href="https://www.scionresearch.com//a-natural-alternative-to-a-fishy-problem">https://www.scionresearch.com//a-natural-alternative-to-a-fishy-problem</a> <a href="http://www.biopolymernetwork.com/content/Zealafoam/90.aspx">http://www.biopolymernetwork.com/content/Zealafoam/90.aspx</a>		
PLA+PBAT	Seaclic BIOBASED	STOROpak	Expanded foam fish box		<a href="http://storopack.com/seaclic-boxes">storopack.com/seaclic-boxes</a> <a href="https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecovio.html">https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecovio.html</a>		
PLA	BioCup / BioBowl	BioPak	Food plates, bowls and cups	Available on the market	<a href="https://www.biopak.com.au/other-s/downloads/4185943582_m-flyer-clear-cups-july2018.pdf">https://www.biopak.com.au/other-s/downloads/4185943582_m-flyer-clear-cups-july2018.pdf</a> <a href="https://www.biopak.com/uk/products/cold-cups/pla_bioplastic?p=1">https://www.biopak.com/uk/products/cold-cups/pla_bioplastic?p=1</a>	Monomaterial (not clearly stated)  Produced by Ingeo™ PLA by	AS4736: Australian Commercial Compostable  NatureWorksLLC Compost Certification

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of producer	Use	Availability	Link	Comments	End of life
						Natureworks (USA)	Ingeo™ PLA is certified to European Compost Standards EN13432
PLA	PLAiR	Ricoh	Food packaging, protective packaging	In development	<a href="https://industry.ricoh.com/en/plair/">https://industry.ricoh.com/en/plair/</a>	Not clear whether the final product will be monomaterial	Manufacturer claims that the product will be compostable
PLA	BioFoam®	Bewi (Synbra)	Packaging, protection	Available on the market	<a href="https://bewi.com/products/biofoam/">https://bewi.com/products/biofoam/</a>	The correct management of the waste from products made of this biopolymer will depend on manufacturing process	The resin is branded to be 100 % recyclable (mechanic recycling) and industrially compostable. However, there is no certification available  Cradle-to-Cradle™ certified
PLA	BioFoam Pearls®	Termokomfort	Insulation	Available on the market	<a href="https://www.termokomfort.nl/isolatieparels/biofoampearls">https://www.termokomfort.nl/isolatieparels/biofoampearls</a>	Not clear if they are made up of 100% BioFoam®	No indication about the fate of end-of-life products
Kaneka Biodegradable Polymer Green Planet PHBH™	Biodegradable Polymer Green Planet PHBH™	Kaneka	Potentially used for packaging and industrial equipment (electric, cars)	Resin available on the market, not clear if final products are available.	<a href="https://www.kaneka.co.jp/topics/uploads/2019/12/%E3%80%90Kaneka%E3%80%91Completion-of-Kaneka-Biodegradable-Polymer-PHBH%E2%84%A2-Plant-with-annual-production-of-5000-tons.pdf">https://www.kaneka.co.jp/topics/uploads/2019/12/%E3%80%90Kaneka%E3%80%91Completion-of-Kaneka-Biodegradable-Polymer-PHBH%E2%84%A2-Plant-with-annual-production-of-5000-tons.pdf</a>	The correct management of the waste from products made of this biopolymer will depend on	All certification relate to the resin and not to the final products  home and industrial compostable certified to ASTM D6400 and

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of product	Use	Availability	Link	Comments	End of life
					<a href="https://kanekabiopolymers.com/certifications/">https://kanekabiopolymers.com/certifications/</a> <a href="http://www.kaneka.be/new-business/kaneka-biodegradable-polymer-green-planet">http://www.kaneka.be/new-business/kaneka-biodegradable-polymer-green-planet</a>	manufacturing process	<p>TUV Home Compost OK Certification.</p> <p>Compostable in soil and aerobically digestible certified to ASTM D6400.</p> <p>Anaerobically digestible certified to ISO 15985.</p> <p>Marine degradable certified to TUV Marine Biodegradable OK Certification.</p> <p>Not considered soil, marine or landfill degradable in California.</p>
Bagasse		Vegware	Takeaway food containers (clamshells)	Available on the market	<a href="https://www.vegware.com/uk/catalogue/takeaway_boxes/">https://www.vegware.com/uk/catalogue/takeaway_boxes/</a>		Vegware claims that all their products are certified to the following standards: European EN13432 American ASTM D6400

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of product	Use	Availability	Link	Comments	End of life
							S0137 TUV Austria (Industrially compostable) Certification 2122186 by BPI®
Bagasse		Ecopack	Takeaway food containers (clamshells, trays)	Available on the market	<a href="https://ecopack.co.za/product-category/ecoware-takeaway-containers/">https://ecopack.co.za/product-category/ecoware-takeaway-containers/</a>		
Bagasse		Biopak	Takeaway food containers (clamshells, trays)	Available on the market	<a href="https://www.biopak.com.au/products/takeaway-containers">https://www.biopak.com.au/products/takeaway-containers</a>	Monomaterial	AS4736: Australian Commercial Compostable AS5810: Australian Home Compostable EN13432: European Commercial Compostable NF T51-800: European Industrially compostable:
Bagasse		Takeaway Packaging	Takeaway food containers	Available on the market	<a href="https://takeawaypackaging.co.uk/">https://takeawaypackaging.co.uk/</a>		

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of product	Use	Availability	Link	Comments	End of life
Palm leaves		Vegware	Trays and plates	Available on the market	<a href="https://www.vegware.com/uk/catalogue/palm_leaf_tableware/">https://www.vegware.com/uk/catalogue/palm_leaf_tableware/</a>	Monomaterial and not treated	Vegware claims that all their products are certified to the following standards: European EN13432 American ASTM D6400 S0137 TUV Austria (Industrially compostable) Certification 2122186 by BPI®
Palm leaves	Areca Leaf Plates	Disposable Green®	Trays and plates	Available on the market	<a href="https://disposablegreen.com/product-category/plates-range/areca-leaf-plates/">https://disposablegreen.com/product-category/plates-range/areca-leaf-plates/</a>	Monomaterial and not treated	Claimed to be home-compostable and biodegradable, but no certification is provided
Palm leaves		Foogo green®	Trays and plates	Available on the market	<a href="https://foogogreen.com/shop-all/">https://foogogreen.com/shop-all/</a>	Monomaterial and not treated	Claimed to be home-compostable and biodegradable, but no certification is provided
Starch	PELASPAN® BIO	STOROPack	Packaging, cushioning	Available on the market	<a href="https://www.storopack.com/products/flexible-protective-packaging/loose-fill/pelaspnr-bio">https://www.storopack.com/products/flexible-protective-packaging/loose-fill/pelaspnr-bio</a>	Monomaterial	Garden compostable (certified to NF T51-800 in Germany, France, Spain and UK)

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of producer	Use	Availability	Link	Comments	End of life
							Compostable certified to DIN EN 13432 (Europe) and ASTM D6400 (USA)  Entirely biodegradable (no residue) and water-soluble (claimed by company, no certification)
Paper	PAPERplus®	STOROpack	Packaging	Available on the market	<a href="https://www.storopack.com/fileadmin/02_Produnkte/Flexible_Schutzverpackung/Papierpolster/CP_EN-DE_PP_General_web_01.pdf">https://www.storopack.com/fileadmin/02_Produnkte/Flexible_Schutzverpackung/Papierpolster/CP_EN-DE_PP_General_web_01.pdf</a>	Monomaterial	Paper is widely recycled
Paper	FasFil™ / ProPad™	Sealed Air®	Packaging	Available on the market	<a href="https://sealedair.co.uk/en-gb/node/269806">https://sealedair.co.uk/en-gb/node/269806</a> <a href="https://sealedair.co.uk/en-gb/node/270136">https://sealedair.co.uk/en-gb/node/270136</a> <a href="https://www.sealedair.com/products/protective-packaging/paper-cushioning-system">https://www.sealedair.com/products/protective-packaging/paper-cushioning-system</a>	Monomaterial (recycled paper from post-industrial and post-consumer waste)	Paper is widely recycled
Paper	Molded Fiber Packaging	UFP Technologies	Packaging	Available on the market	<a href="https://www.moldedfiber.com/eps-alternative.html">https://www.moldedfiber.com/eps-alternative.html</a>	100% paper from recycled newspapers	Producer says it is fully recyclable and biodegradable certified to ISO 14000 and European Green Dot standards.



Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of producer	Use	Availability	Link	Comments	End of life
Paper	TempGuard™	SealedAir®	Packaging, insulation	Available on the market	<a href="https://sealedair.co.uk/en-gb/product-care/product-care-products/sealed-air-brand-tempguard">https://sealedair.co.uk/en-gb/product-care/product-care-products/sealed-air-brand-tempguard</a>		
Paper pulp	RECOOL	Igloo	Insulation, cooler	Available on the market	<a href="https://www.igloocoolers.com/pages/recool">https://www.igloocoolers.com/pages/recool</a> , <a href="https://www.rei.com/product/154999/igloo-recool-cooler">https://www.rei.com/product/154999/igloo-recool-cooler</a>		
Cardboard	Korvvuu®	GWPgroup	Packaging	Available on the market	<a href="https://www.gwp.co.uk/packaging/korvvu/">https://www.gwp.co.uk/packaging/korvvu/</a>	Some versions are monomaterial, some products have plastic sheeting	Cardboard is widely recycled
Cardboard	Hexacomb Packaging (Honeycomb)	Smurfit Kappa	Packaging, goods protection	Available on the market	<a href="https://www.smurfitkappa.com/products-and-services/packaging/hexacomb-packaging">https://www.smurfitkappa.com/products-and-services/packaging/hexacomb-packaging</a>	Monomaterial	Cardboard is widely recycled
Cardboard	ThermoBox	Smurfit Kappa	Packaging, insulation	Available on the market	<a href="https://www.smurfitkappa.com/innovation/success-stories/thermobox-eps-alternative">https://www.smurfitkappa.com/innovation/success-stories/thermobox-eps-alternative</a>	Monomaterial	Cardboard is widely recycled
Cardboard	PACKLINE	Solidus Solutions	Food Packaging, trays and plates	Available on the market	<a href="https://solidus-solutions.com/en/packaging/food/fish/">https://solidus-solutions.com/en/packaging/food/fish/</a>	Despite claims that these are 100% recyclable, some products in this line are not	The producer claims it is 100% recyclable

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of producer	Use	Availability	Link	Comments	End of life
						monomaterial (coating of polyethylene)	
Corrugated cardboard	Corrispring	GWPgroup	Packaging	Available on the market	<a href="https://www.gwp.co.uk/packaging/inserts/foam-alternative/">https://www.gwp.co.uk/packaging/inserts/foam-alternative/</a>		Cardboard is widely recycled
Mushroom biomass	Mushroom® Packaging	Ecoative and Mushroom® Packaging and local licensed companies (e.g. Magic Mushrooms in the UK, Grown.bio in Europe)	Packaging,	Available on the market	<a href="https://ecovatedesign.com/myco-composite">https://ecovatedesign.com/myco-composite</a> <a href="https://mushroompackaging.com/">https://mushroompackaging.com/</a> <a href="https://www.magicalmushroom.com/bioprocess">https://www.magicalmushroom.com/bioprocess</a>	Monomaterial  Produced using Myco Composites™	Compostability in 30 days certified to ASTM D6400
Mushroom biomass		Embelium	Packaging,	Available on the market	<a href="https://www.embelium.fr/nos-produits/">https://www.embelium.fr/nos-produits/</a>	Monomaterial  Produced using Myco Composites™	The company claim it is compostable, but there is no clarification on whether it is home or industrially compostable. No certification provided.
Denim	UltraTouch®	Bonded Logic Inc.	Building insulation	Available on the market	<a href="https://www.bondedlogic.com/ultra-touch-denim-insulation/">https://www.bondedlogic.com/ultra-touch-denim-insulation/</a>		Manufacturer claims the material is 100 % recyclable but no certification provided

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of producer	Use	Availability	Link	Comments	End of life
Cellulose	Foamed cellulose	Washington State University	Insulation	In development	<a href="https://doi.org/10.1016/j.carbpol.2019.04.059">https://doi.org/10.1016/j.carbpol.2019.04.059</a> .	The correct management of the waste from products made out of this biopolymer will depend on manufacturing process	The final product should be biodegradable, but not certifications yet
Wool		Woolcool	Packaging insulation	Available on the market	<a href="https://www.woolcool.com/">https://www.woolcool.com/</a>		Wool is biodegradable, home and industrially compostable (peer-reviewed papers available)
Wool		Puffin Packaging	Packaging insulation	Available on the market	<a href="https://www.puffinpackaging.co.uk/">https://www.puffinpackaging.co.uk/</a>		Wool is biodegradable, home and industrially compostable (peer-reviewed papers available)
Denim	UltraTouch®	Bonded Logic Inc.	Building insulation	Available on the market	<a href="https://www.bondedlogic.com/ultra-touch-denim-insulation/">https://www.bondedlogic.com/ultra-touch-denim-insulation/</a>		Manufacturer claims the material is 100 % recyclable but no certification provided
Cellulose	Foamed cellulose	Washington State University	Insulation	In development	<a href="https://doi.org/10.1016/j.carbpol.2019.04.059">https://doi.org/10.1016/j.carbpol.2019.04.059</a> .	The correct management of the waste	The final product should be

Table 2: Showing examples of alternatives of EPS and EPS

	Name of product	Name of product	Use	Availability	Link	Comments	End of life
						from products made out of this biopolymer will depend on manufacturing process	biodegradable, but no certifications yet
Tannins and lignine	MOusses TAnins Llgine	IPREM	Not known	In development	<a href="http://www.formule-verte.com/isolation-une-mousse-rigide-issue-de-ressources-naturelles-renouvelables/">http://www.formule-verte.com/isolation-une-mousse-rigide-issue-de-ressources-naturelles-renouvelables/</a>	The correct management of the waste from products made out of this biopolymer will depend on manufacturing process	Not known

## 5 Alternative to EPS/XPS (insulation)

Thanks to their thermic properties, EPS and XPS boards are used to insulate buildings. When used for this purpose, the material remains in the buildings for long time and, therefore, do not create waste until the demolition or renovation of the building itself. In this case the management of the EPS and XPS boards at the end of their life might be complicated by the contaminations (e.g., glues) and by mixing with other type of waste, particularly after demolition. However, EPS and XPS can also create problems when they are incorrectly handled during construction work. The boards are in facts brittle, and they can break down during transportation, cutting or final positioning.

Some materials already listed in Section 4 (polyurethane, denim) can be also used to produce insulation panels.

### 5.1 Straw bale

**Material:** Straw is an agricultural by-product, usually derived from rice, wheat oat and rye.

**Production:** Straw bales are used in the traditional building systems.

**Benefits:** The production has very low carbon emission and productions costs because is a byproduct. It is fire-resistant (better performance than timber frame constructions) and is also sound-insulating. It is a good thermal insulator, but not in very cold climates. It is cost-effective and can be very durable.

**Applications:** Straw bales can be used as an insulator for buildings. Bales are lined in rows on raised footings/ foundations. A capillary break or moisture barrier is inserted between the supporting platform and the bales. The walls are ties together with wire mesh or pins (bamboo or timber). Stucco or plaster made of lime or clay is then applied. Straw bales can also bear structural loads and support buildings, offering shear resistance to wind and seismic loads. They can make an insulation substrate within a timber structural frame. Bale walls must be protected during construction to avoid water damage.

**End of life:** Straw bales are 100% biodegradable .

**Sources:**

[https://www.designingbuildings.co.uk/wiki/Straw\\_bale\\_construction#:~:text=Some%20of%20the%20advantages%20of%20straw%20bale%20construction,a%20low%20embodied%20energy%20.%20More%20items...%20](https://www.designingbuildings.co.uk/wiki/Straw_bale_construction#:~:text=Some%20of%20the%20advantages%20of%20straw%20bale%20construction,a%20low%20embodied%20energy%20.%20More%20items...%20)

## 5.2 Mineral and glass wool

**Material:** Mineral and glass wool are insulation materials that use pockets of air trapped into a matrix of mineral fibers. Mineral wool is produced working on volcanic rock and glass wool can be manufactured from either sand or recycled glass.

**Production:** Mineral wool is made from volcanic rock or slag (industrial waste) that gets heated in a furnace and spun to create a cotton candy-like texture. It is then flattened into dual density insulation boards. Panels consist of a rock mineral wool slab with a water-repellent additive.

It is extremely flexible, and holds in place between timber, metal frames and rafters without the need for additional fixings. This means it's easy to install and work with. The mixture is characterised by its consistent density and high strength, which make it a good choice for lots of applications. Thanks to its intrinsic properties, the mixture is malleable, very easy to handle and can be installed to any substrate including timber, metal frames and rafters.

Glass wool is produced using natural sand and recycled glass, limestone, and soda ash. Materials are heated up to 1,450 °C and the glass-paste is forced through a fine mesh by centrifugal force, cooling on contact with the air. Binder drops between fiberglass is also used for cohesion and mechanical strength. Heating the mat up to around 200 °C polymerizes the resin and can be cut and packed in rolls or panels. Glass wool can also be sprayed in cavities or under sheets and panels.

**Benefits:** Mineral wool is flexible, malleable, and has consistent density, It is easy to install on timber, metal and rafters and can be reused. It is more breathable than EPS, has excellent acoustic insulation, has superior fire resistance properties without fire stops requirements and is UV resistant (provides sun protection, preventing overheating in the summer).

**Applications:** Mineral and wool insulations are used for providing building with thermal and sound insulation. They are used in some external wall insulation systems.

**End of life:** Mineral wool can be completely recycled.

**Sources:** [https://en.wikipedia.org/wiki/Glass\\_wool](https://en.wikipedia.org/wiki/Glass_wool), <https://ewistore.co.uk/mineral-wool-insulation-vs-expanded-polystyrene/>, <https://www.eurima.org/about-mineral-wool>



## 5.3 Cork

**Material:** Cork is the treated thick bark of a species of oak tree usually growing in Southern Europe (major production is located in Portugal) and North Africa. The bark can be harvested every nine years without damaging the tree (oaks can grow bark again and live for centuries). The cork used for insulation is called ‘expanded cork’ or ‘black cork’ and is produced using the bark whose quality is too poor for making natural wine corks.

**Production:** Oak tree branches pruned from cork trees, damaged by fire, and ‘virgin’ cork (first harvest of a cork tree, whose bark is not dense enough for wine corks).

Lower quality bark contains high levels of suberin, a natural resin. It is granulated, sorted from wood and dirt and placed in moulds. The bark is then placed in an autoclave where it is steam heated to 400°C, a process that releases suberin and expands the granules. After two hours, the granules are bonded together by the suberin and fill out the moulds. The cork is then cooled down to stabilize and is then processed/cut. No chemicals or artificial additives are used in the production process of cork.

**Benefits:** Cork is resistant to water, fire, damp, and rot. It is an overall hard-wearing material. It repels termites and mice. It provides very good thermal and sound insulation to buildings. It is easily applicable (e.g. no protective equipment is required during installation). It is very sustainable coming from renewable sources.

**Applications:** Cork comes in boards and granules. Boards have different characteristics based on thickness and are useful for insulating roofs or to be glued onto a concrete subfloor (particularly good under carpeted floors). Cork granules (between 1 and 10 millimetre) can fill gaps in the ceiling, floors or to insulate cavity walls.

**End of life:** Cork is natural and is biodegradable, but the presence of glues might prevent its compostability. Cork can be efficiently reused/recycled.

**Sources:** <https://www.insulation-info.co.uk/insulation-material/cork-insulation>,  
<https://www.corklink.com/index.php/expanded-cork-how-it-is-made/>,  
<https://www.amorimcork.com/en/sustainability/sustainability-and-the-cork-oak-forest/>

## 6 Conclusions

This report presents a list of materials that can be used as an alternative to EPS. Many of these products are available on the market already, and new materials are in the development stage. While there is not a unique material that can substitute EPS and XPS in all their uses, there are available alternatives that can work towards a substantial reduction of the use of PS foams.

Many of the alternatives have a lower carbon footprint than EPS/XPS. The reduction of the carbon footprint starts from the production of these materials since they are created using agricultural by-products (e.g., bagasse, mushroom biomass), or vegetable parts (e.g., palm leaves or cork). However, the production of some materials like paper and cardboard, or the polymerisation of some PLAs use many chemicals and are very energy consuming, reducing their efficacy in lowering the carbon footprint of the products. The production of thermoplastics like polyethylene and polypropylene, which are oil-based like EPS/XPS, is also not more environmentally friendly than PS foams unless recycled material is used.

The fate of post-consumer products that are alternatives to EPS/XPS products is generally easier to fit into a circular economy model. Many products are branded as home or industrially compostable. Some of the thermoplastics like polyethylene and polypropylene are more easily recycled and their collection is commonly included in the management of household waste. However, there is lack of clarity about how to correctly dispose of some of these products. Many of them are labelled as compostable or biodegradable. However, only a few producers hold quality certification to confirm their claims. Sometimes the compostability/biodegradability/recyclability claims refer to the materials and not the actual final products, which might include glues, additives, coatings or might have undergone other manipulations that could affect the way in which they should be properly disposed of. There should be therefore more clarity in labelling and more stringent standards about the use of terms like 'compostable' or 'bio' in order not to confuse users and to reduce involuntary mismanagement.

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