GO!PHA
Global Organization for PHA

ADDRESSING THE PLASTIC POLLUTION CHALLENGE

EXPLORING SUSTAINABLE SUBSTITUTES FOR POSITIVE CHANGE

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RENEWABLE & CIRCULAR
MATERIALS DESIGNED BY **NATURE.**

GO!PHA
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SUSTAINABLE SUBSTITUTES TO FOSSIL-BASED PERSISTENT PLASTICS

LET'S CHAMPION BIO-BASED AND BIODEGRADABLE MATERIALS TO TURN OFF THE TAP ON FOSSIL PLASTICS!

RENEWABLE & BIO-BASED

CLOSING THE CARBON LOOP

- Sustainable alternatives to plastics can be sourced from renewable materials like organic waste streams, biogas, marine biomass, cellulose, sugars, fat-rich plant-based feedstocks, corn, sugarcane, or cellulose from wood.
- A shift to renewable sourcing reduces carbon emissions compared to fossil-based plastics. In many cases, CO2 is even captured from the atmosphere and converted into these feedstocks in nature. The use of bio-based resources reduces dependency on fossil fuels. For example, a variety of microorganisms make PHA biopolymers through bacterial fermentation.
- Bio-based and biodegradable materials can be made from a large variety of renewable feedstocks, and each region will favor different ones based on availability and economics.

BIODEGRADABLE

NO PERSISTENT MICROPLASTICS

- Sustainable alternatives to fossil-based plastics, such as polyhydroxyalkanoates (PHA), naturally break down without leaving persistent micro- and nanoplastics in the environment.
- These materials are consumed by microorganisms and break down quickly into harmless substances. This degradation process takes only a matter of days to weeks for microparticles and stands in stark contrast to persistent microplastics that can endure for centuries. Biodegradation speed is dependent on many factors, such as temperature, biological activity and part thickness.
- This feature is essential for safeguarding ecosystems, including soil health, as it prevents the harmful accumulation of microplastic particles in flora and fauna. PHAs are recognized by authorities as biodegradable alternatives used in various applications.

CIRCULARITY & END-OF-LIFE

REUSABLE, RECYCLABLE & COMPOSTABLE

- Sustainable alternatives can be efficiently reused, recycled or composted, certifications and standards help in getting the waste managed correctly.
- This minimizes waste and supports responsible end-of-life management, including mechanical recycling of the materials and creating plant nutrition and building blocks such as biogas through composting and digestion.
- Recycling options including mechanical methods in the plastics recycling industry and organic methods in the composting industry allow for recirculation of raw materials and building blocks.
- If circular systems fail, nature can recycle biodegradable materials.

BIOCOMPATIBLE

NATURAL PRODUCTS

- Sustainable alternatives, including various biodegradable and bio-based polymers, are biocompatible, which means they are compatible with living organisms.
- These materials do not pose harm to ecosystems or living organisms because they break down naturally without introducing harmful substances into the environment. Harmonized rules help to avoid the use of polluting ingredients and additives.
- Some of these materials are already tested, qualified, and used for medical applications, implants, or are designed to be consumed in ecological restoration projects.
- Examples of such polymers produced via biosynthesis in bacteria, plants, and algae include cellulose, starch, and polyhydroxyalkanoates (PHA)

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01. SOIL HEALTH

Executive summary

Micro- and nanoplastics have spread throughout various environments, posing threats. Among these, soils are crucial because they support over 98% of our food production and other essential functions. Using biodegradable materials can help mitigate the issue of persistent micro- and nanoplastics. Not only mulch film and other agricultural plastics are responsible for the microplastics in our soils; these contaminants also get there via aerial deposition and through water (rain, irrigation). Additionally, additives used in making fossil-based plastics also contribute to negative effects on soil, and more research is needed for a full understanding. Since conventional plastics are found to "shed" micro- and nanoplastics during different life phases, a switch to biodegradable materials can contribute to maintaining healthy soils and preventing micro-plastic accumulation. There exist International standards for biodegradability in different environments, which differ, e.g., in temperature, moisture content, and concentration of microorganisms, which are responsible for mineralizing bioplastic materials. While certain bioplastics have limited biodegradability, the adoption of naturally occurring biopolymers like Polyhydroxyalkanoates (PHA), exhibiting versatile functional properties that can fully biodegrade in all soil conditions, should be promoted.

The importance of soil and soil health

Approximately 30% of the Earth's surface, equivalent to 149 million square kilometers, consists of land. The majority of this land is occupied by glaciers, mountains, deserts, and natural ecosystems like forests. Approximately 50 million km² can be farmed, or 0.2 ha per capita. That farmland is mostly intensively managed to produce high yields of feed and food.

The soil on Earth ("pedosphere") is a mix of minerals, gases, liquids, organic matter, and microorganisms, which support life. Approx. 50% of the soil is solids (45% minerals, 5% organics). The humus fraction (decayed organic matter) is typically on the order of 5%, and yet this is a major determining factor in fertility.

The soil serves four key functions: It acts as a reservoir for water storage and purification, alters the atmosphere, provides a habitat for organisms, and serves as a medium for plant growth. Soil is used in agriculture, and more than 98% of our feed and food are produced on soil [1]. It is also an important carbon sink. Soils have a profile made up of distinctive layers. The upper 10-30 cm of soil is "topsoil", where the concentration of microorganisms and organic matter is highest. From here, plants draw their nutrients.

Soil can be formed naturally (though our rate of use and erosion currently surpass pedogenesis), or artificially.

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Soil contamination by microplastics

Soil health is vital not only for agricultural soil, and soil degradation includes acidification, contamination, desertification, erosion, or salination. Soil conservation and sustainable agriculture have received increased attention due to decreasing soil quality.

Conventional Plastics, particularly micro- and nanoplastics (MNP), are part of current contamination found in soils, and they are persistent. Sources include aerial deposition [2], water, sewage sludge, plastics used in the fields such as mulching film, and litter or items lost from the collection.

Some key findings on the adverse effects of micro and nanoplastics in soil:

- MNP were found to influence soil nutrient cycling negatively [3].
- Many terrestrial plant species can take up and transport MNPs to the above-ground tissues. Plants exposed to MNPs have exhibited multiple adverse effects on plant morphology and physiology. Moreover, MNPs can be further transferred through the food chain and finally may be ingested by humans [4].
- Biodegradable plastics can have temporary latent adverse effects on agroecosystems [5], which should be further studied, however, in the long term such issues are not cumulative.
- "Larger plastics (>1 µm) caused unfavourable changes to plant growth, germination, and oxidative stress, while nanoplastics (NPs; ≤1 µm) only increased oxidative stress. On the contrary, there was a clear trend showing that small plastics adversely affected fauna reproduction, survival, and locomotion greater than large plastics. Plant responses were indifferent to plastic-type" [6].
- MNPs, both biodegradable and non-biodegradable, have adverse effects, serving as vectors for environmental toxins. Nonetheless, biodegradable variants break down faster than fossil-based ones, resulting in overall reduced harm compared to fossil-based plastics [7].

At best, bioplastic materials mineralize completely to CO2 and H2O via aerobic processes. The anaerobic route can lead to CH4 formation, which is useful in a biogas plant but detrimental in nature due to the climate effect of methane. Bioplastics do not yield compost upon decomposition. It needs to be stated that PHAs are also recyclable, which should be the primary end-of-life option for plastics. Biodegradability in the soil is a "fallback" option so that the leaked fraction of materials, amongst that MP and NP, will decompose and not persist.

Conclusion

Our fields, and all other soils, are consistently exposed to a flood of micro- and nanoplastics particles, from various routes, which were shown to be harmful and persistent. Though we lack a full understanding, we clearly know that this burden needs to be reduced and eliminated. A transition from conventional plastics with a move towards biodegradable alternatives can counteract soil deterioration by ensuring any leaked materials do not persist.

Summary

- Conventional plastic micro and nanoparticles pose risks to soil, plants, and human health.
- Additives used in conventional plastics are of concern.
- Microplastics from biodegradable materials may also be harmful since they can pick up toxins from their environment similar to fossil plastics, however, given their shorter life they pose far less risk in the environment.
- More research is needed to help transition to biodegradable plastic alternatives.
- Polyhydroxyalkanoates (PHA) can offer a solution from renewable resources that will not persist in the soil environment.

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02. HUMAN HEALTH

Executive Summary

Microplastics (MPs) and nanoplastics (NPs) are not only emerging as environmental pollutants but also as a growing biological concern for human health and the health of other living organisms, including marine animals. These small plastic particles can infiltrate into animals and humans through various exposure routes, and their size and chemical composition determine their ecotoxicological risks. Polyhydroxyalkanoates (PHA) are a family of biobased and biodegradable polymers that are naturally produced by an estimated 40% of the world's microorganisms. They comprise a superior alternative to fossil-based plastics in short-term use sectors such as food processing, medical, agriculture, and packaging industries as well as in durable uses. The key advantage of PHAs lies in their ability to fully decompose in all environments where biodegradation takes place, including the human body, without leaving behind MPs/NPs or any ecotoxic products.

Plastic Revolution and Environmental Challenges in the 20th Century

The 20th century witnessed the plastic revolution, with plastic production increasing from 1.7 million tons in the 1950s to over 348 million tons in 2017, owing to its numerous advantages like durability, low weight, resistance to degradation, strength, thermal and electrical insulation, formability, and cost-effectiveness [1]. However, the persistence of plastic in the environment has posed significant challenges and concerns for the health of the environment. A huge number of plastic items, debris, and particles, including MPs with sizes ranging from 1 μm to 5 mm and NPs with sizes between 1 nm and 1 μm, exist in marine waters alone. High concentrations of plastic particles have been found in indoor dust, agricultural farms, surface and ground waters, landfill sites, and, consequently, in the gastrointestinal system of various aquatic animals and humans [1–4]. The presence of microplastics in aquatic animals is a major concern for human health due to their presence in the food chain. In addition, inhalation and dermal contact have also been identified as additional exposure routes, with high concentrations of microplastics found in air and dust, and human intake of microplastics from personal care products through skin absorption [1,5]. Advanced imaging techniques have revealed the presence of synthetic plastics like polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), nylon, polycarbonate (PC), and polyethylene (PE) in human blood, sputum, stool, lung tissue, colectomy samples, and placenta [6]. Moreover, microplastics can absorb environmental chemical contaminants and release toxic plastic additives within the human body, adding to the risks associated with these elements [4.] As recently described, microplastic particles serve as a vector for antibiotic resistance genes and pathogens in new environments [15].

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Exploring Potential Health Implications of Microplastic Exposure through Cellular and Animal Studies

Although direct clinical evidence or epidemiological studies on the effects of microplastics on human health are lacking and more research is needed, scientists have focused on *in vitro* (in the laboratory) cellular and tissue studies and *in vivo* animal experiments in the last decade, indicating potential adverse effects [6]. Studies using human intestinal cells have confirmed that ingested non-biodegradable nanoparticles can pose a health risk by damaging the intestinal membrane's protective barrier over time. Human lung epithelial cells cultured in contact with polystyrene (PS), nylon, and/or polyethylene (PE) showed cytotoxic effects, DNA damage, oxidative stress and immune responses, disruption of the epithelial layer, and decreased cell viability [1]. In a human placental perfusion model, Grafmueller et al. discovered that PS particles accumulated in the syncytiotrophoblasts, a specialised layer of placental epithelial cells in direct contact with maternal blood [7].

PHAs: A Promising Solution to Mitigate Microplastic Health Concerns

PHA biopolymers offer functionalities like popular fossil-based plastics, but their unique advantage lies in their full biodegradation in various environments, including soil, freshwater, and marine settings, without causing microplastic pollution. Additionally, they are not only suitable for industrial composting facilities but can even be composted at home. Moreover, PHAs are fully biocompatible, posing no long-term risk when in contact with or inside the human body. Numerous *in vitro* studies using different human cells and *in vivo*, animal models have demonstrated no toxicity and negligible to no inflammatory response due to the presence of PHAs. Although previous waves of commercial development faced challenges like high cost and scalability issues, the current optimization of production processes and methods has led to a significant trend with over 25 companies and start-ups, along with 30+ brand owners, announcing partnerships for PHA production and utilization. This indicates a strong and serious momentum in the industrial and commercial adoption of PHAs in various fields, making them the most promising solution to combat the threat of plastic pollution to human health [8].

IIn addition to addressing micro- and nanoplastic pollution, the biocompatibility and biodegradability of PHAs have made them excellent candidates for various applications in the biomedical field. Over the last few decades, synthetic polymers like poly(lactic acid) (PLA), poly(ε-caprolactone) (PCL), and poly(lactic-co-glycolic acid) (PLGA) have gathered interest for their processability and biocompatibility, making them suitable materials for external medical devices and in vivo tissue engineering implants. However, their degradation profile, characterized by bulk erosion and acidic degradation products, along with incomplete biodegradation, poses challenges such as mechanical instability and strong inflammatory response. In contrast, PHAs have shown enhanced cell proliferation and functionality across a wide range of cell types, along with tuneable and stable mechanical properties and harmless degradation by-products that are natural metabolites. This makes them ideal biomaterials for medical devices and *in vivo* implants to promote tissue regeneration for nerve, cardiac, bone, cartilage, kidney, and pancreatic tissues [9–14], paving the way for improved solutions to treat diseases and enhance human health.

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03. BIODEGRADABLE ALSO MEANS RECYCLABLE

Executive Summary

PHAs are a type of biopolymer with massive potential to replace fossil-derived plastics. Although they are biodegradable, there is potentially more economic value, supply security, and environmental benefit in retaining these materials in the economy for as long as possible, especially if this can be done without creating micro- and nanoplastics and PHA makes this possible. As such, this biodegradability should only be seen as a last resort, when due to contamination or other similar reasons these materials need to be composted. Instead, at the end of their useful life, the material value could be captured using a range of different recycling strategies. These include mechanical and thermal recycling, which are currently used commercially for conventional plastics, through to chemical depolymerisation and biological recycling. Implementation of these techniques at scale will enhance circularity, as both material and carbon are recycled into new, biodegradable products.

Introduction

Within a circular economy, there is no such thing as waste. Every step helps to regenerate the next step. When a material reaches the end of its purpose life, it is used to make a new product. The current use of plastics is, generally, the opposite of this. Virgin petrochemicals are used to make plastics, which are only used a very small number of times or are even of single-use only, before being disposed of in a landfill, incinerated, or regrettably leaked into the environment. To improve their sustainability, biodegradable plastics made from renewable resources are being developed. One such group of biopolymers is called PHA (or PolyHydroxyAlkanoates) which can be made from bacteria and archaea [1]. However, their biodegradability should be seen as a last resort, an eco-friendly safety net for when leakage of plastics into the environment occurs or due to contamination they need to be composted or incinerated. Instead, their value should be retained within a circular economy, as illustrated by Figure 1, with the loops kept as small as possible. As a polyester, PHA is fully recyclable, as well as biodegradable. How they can be recycled is described in this paper.

Commercial Plastic Recycling

To recycle PHAs, the most well-developed recycling technology is mechanical extrusion [2]. This is used commercially to recycle a wide range of plastics. In principle, the washed plastic waste is shredded, fed through a hopper, and into a long, heated tube. A large screw, located inside the tube, rotates, which subsequently propels the plastic towards the end. Doing so also melts and compresses the plastic fragments together to form a single filament which can then be used to make new polymer products. This process often uses less energy than other recycling methods and the polymer chains mostly stay intact. The downside of this treatment is that there is slow degradation of the plastic; properties such as strength and stiffness are reduced over time. A mixture of different polymers recycled together may also lead to the creation of an inferior product which is then itself difficult to recycle. This means that, ultimately, the material is downgraded until it is eventually incinerated or disposed of in a landfill [2].

Chemical & Biological Recycling

As an alternative to mechanical extrusion, plastics can also be broken down by heat in a process called pyrolysis. This is different from incineration as there is no oxygen present, which means that the plastics do not combust. Instead, they form a mixture of gases and oils which can be used as a raw material in other chemical processes [3]. Pyrolysis, however, uses a lot of energy [4], and so, other methods are being developed.

PHAs are made by microbes, and there is potential for them to be reused by microbes. Enzymes generated by certain bacteria may be able to break down PHA into chemicals that can be used to make new bioplastics [6]. This approach may, therefore, be able to fully close the loop within a new, circular economy for PHAs.

Because PHAs are naturally occurring, they are biodegradable under all conditions where biodegradation takes place, making PHAs a unique polyester chain. They can be used to make all manner of food packaging products and may be biologically recycled via microbes in compost, soils, freshwater, marine environments, and anaerobic digesters.

Tightening the Loop in a Circular Economy

Composting or incinerating PHAs ultimately leads to their degradation into CO2 and water. To maximise circularity, reduce resource consumption, and improve sustainability, we should aim to tighten the loop within a circular economy as much as possible. Doing so retains economic value within our existing materials and ultimately reduces our environmental impact. We should rely on the biodegradability of PHA as a preferred recycling methodology, while also considering effective reuse and recycling strategies.

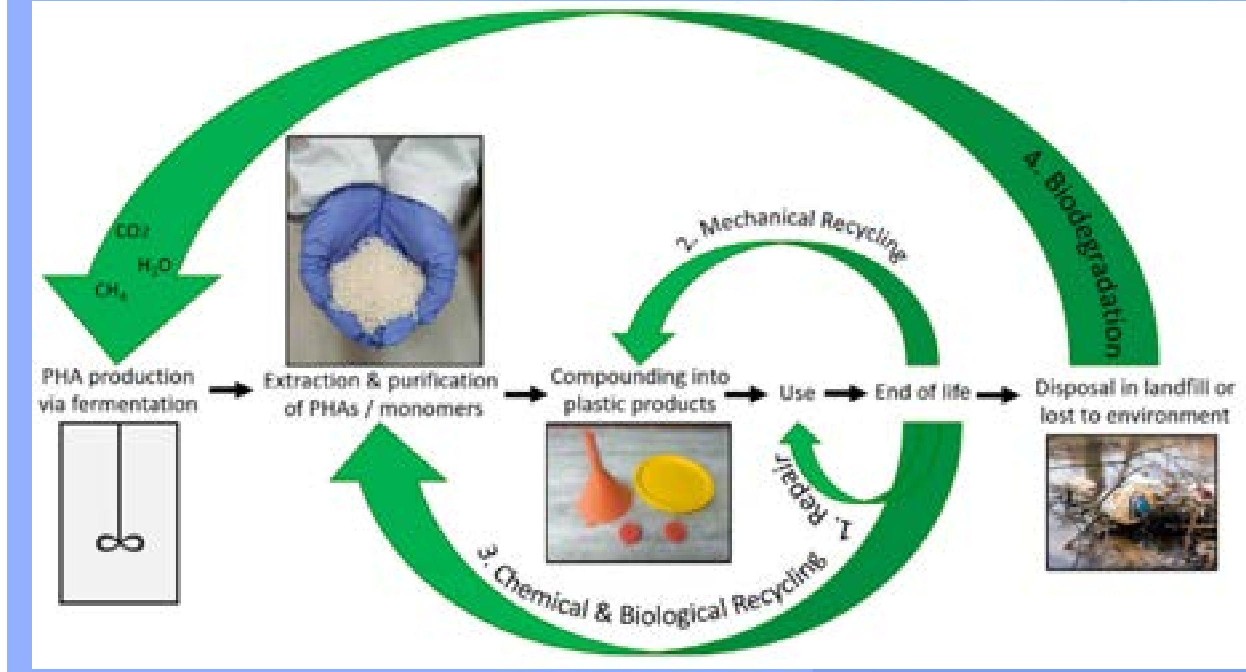

Figure 1: SEQ Figure * ARABIC 1. A Circular Economy for PHAs

Aerobic and Anaerobic Biodegradation – Nature's Strategy towards Recycling!

While PHA can be mechanically and chemically recycled, they have the added advantage of biodegrading in nature – marine, freshwater, and soil. This ensures that in current waste management systems, they can be collected with organic waste and converted into compost or biodegraded during anaerobic digestion. Therefore, the most convenient way to recycle PHA is not via mechanical or chemical recycling, but through their biodegradation along with organic matter: It keeps the components of PHA within nature´s closed-loop carbon cycle! Single-use packaging and thin films of PHA-based items, when spent, can therefore undergo end-of-life scenarios fundamentally different from the fate of spent fossil plastics: In the organic waste management system and under aerobic conditions, they mineralize via diverse organisms into CO_2 and water as the final products of their oxidative breakdown. These, in turn, are the starting material for regeneration of the raw materials for PHA production by phototrophic organisms. Hence, the carbon flux is circular, CO_2 is in balance in nature! During anaerobic treatment of spent PHA, e.g., in biogas plants, CH_4 is also generated, which serves as a valuable component in biogas and is accepted by a number of microbes as substrate for PHA and other bio-based material/chemical biosynthesis; ensuring again that the carbon flux is a closed loop cycle! This contrasts with fossil-based plastics: The time frame for this closed loop carbon cycle in PHA is short, from a few weeks to a few years depending on the part size and thickness in nature and various certifications show that in organic waste management systems, they would compost or anaerobically biodegrade under current waste management conditions [7]. This again contrasts with spent fossil plastics which would take a very long time to go back into their original storage form (fossil feedstock).

Therefore, PHA-based packaging and products can improve and increase the collection of organic waste within the current management systems. If left accidentally in nature, they will biodegrade into CO_2, CH_4, and water just like other natural materials like cellulose. Using materials like PHA in packaging and products with all end-of-life options – recycle, compost, and biodegrade would go a long way in reducing and even eliminating pollution from fossil plastics, and help increase organic waste collection and therefore increase organic fertilizer use and reduced landfilling.

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04. BIODEGRDABLE POLYMERS WITHIN MARINE ECOSYSTEMS

Research and data highlight the need for safe, and environmentally safe, alternatives to replace fossil-based materials. This shift towards biobased and biodegradable alternatives is driven by environmental concerns and a growing body of evidence demonstrating their potential to mitigate ecological damage and reduce the burden of plastic pollution. In alignment with this, the UNEP's 2015 report titled "Biodegradable Plastics and Marine Litter: Misconceptions, Concerns, and Marine Environmental Impacts" [1] highlights that commonly used plastics are not inherently biodegradable, particularly in marine settings. Recent research has shed light on the viability of biodegradable polymers for diverse applications, revealing their ability to break down in open environments, even under varying conditions and deep-sea settings.

(Ready) biodegradability of biobased and biodegradable polymers in aqueous environments has been proven and is considered not to create persistent microplastics.

OECD 301 [2] test guidelines provide a crucial method for assessing the readiness of biodegradability in various chemicals under aerobic aqueous conditions. This approach not only aids in evaluating the exclusion of synthetic microplastics, as stipulated by the European REACH regulation but has also been used by Ryosuke Nabeoka et al.[3] to assess specific plastic materials. These guidelines play a vital role in advancing our understanding of the biodegradability of materials, aligning with the imperative shift toward sustainable alternatives. Within this study, seven biobased polymers *(i.e. polyamide 4, poly(3-hydroxybutyrate-co-3-hydroxyhexanoate), poly(ε-caprolactone), and poly(butylene succinate adipate, poly(3-hydroxybutyrate, poly(3-hydroxybutyrate-co-3-hydroxyvalerate), and poly(butylene succinate)* show biodegradability in an aerobic aqueous medium within 28 days. Four of these *(polyamide 4, poly(3-hydroxybutyrate-co-3-hydroxyhexanoate), poly(ε-caprolactone), and poly(butylene succinate adipate)* even reached the criteria of ready biodegradability (>60% by day 28).

For the seven mentioned plastics, the percentage of biodegradation on day 60 was larger than that on day 28, confirming that a longer test period of OECD 301 is useful for evaluating the environmental persistence of plastics, which is embedded in the criteria for exclusion as synthetic microplastic within the European REACH regulation on intentionally added microplastics (i.e., modified ready biodegradation)[4].

The presence of polymer-degrading bacteria in seawater has been identified

The existence of microorganisms in a specific environment (such as marine, soil, compost, etc.), will determine the surrounding environment in which biodegradable polymers will fully biodegrade. Related to marine ecosystems, the presence of such bacteria has also been demonstrated. Even more specifically, bacteria isolated from deep-sea environments have been proven to possess the ability to biodegrade films made of polymers such as PCL or PHBH under pressure and low-temperature conditions [5-9].

While the biodegradation rate in the marine environment varies depending on the material, habitat, and climate zone, statistical modelling on lab and field tests can be used to estimate the persistence of plastic objects should they end up in the marine environments.

The variability in the rate of decomposition of biodegradable plastics changes with environmental parameters, such as temperature, habitat, pH-value, or oxygen levels. In order to get an estimation of the environmental persistence of biodegradable plastics in the sea, the performance of such polymers has been studied under different marine environmental conditions [10]. Biodegradation lab tests (20°C) were complemented by mesocosm tests (20 °C) with natural sand and seawater and by field tests in the warm-temperate Mediterranean Sea (12–30 °C) and in tropical Southeast Asia (29 °C) in three typical coastal scenarios. Plastic film samples have been exposed in the eulittoral beach, the pelagic open water, and the benthic seafloor, and their disintegration monitored over time. Statistical modelling has been used to predict the half-life for each of the materials under the different environmental conditions to render the experimental results numerically comparable across all experimental conditions applied. The biodegradation performance of the materials differed by orders of magnitude depending on climate, habitat, and material. Biodegradation as such is also a function of the thickness, shape or size of the material specimen. For example, leaves in the forest biodegrade much faster than thicker logs. Similarly flexible packaging of thin films would biodegrade closer to the 54 days referred to in the study while a thick part would take longer. Important here is the contrast with LDPE which showed no degradation at all while PHA did.

A meta-study on the rate of biodegradation of PHA bioplastics in the marine environment has been worked out by L. Dilkens-Hoffman, by reviewing[11] scientific papers that focussed on the biodegradation of PHA in a natural setting. The key result is the determination of the mean rate of biodegradation of PHA in the marine environment as 0.04–0.09 mg • day-1 • cm-2 (p=0.05). This value was further used to estimate the average lifetime of various PHA products in the marine environment. For example, using the calculated biodegradation rate a PHA bottle could be expected to take approximately one and a half to three and a half years to completely biodegrade. For a PHA straw, this is calculated between 0.3 to 0.7 years.

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05. TRANSITION TO A CIRCULAR ECONOMY

Introduction

Linear life cycles have historically been the foundation of the plastics industry, with the use of under-the-ground fossil resources to make polymers like conventional plastics. Over the years, the majority of these plastics have been disposed of in landfills and oceans causing alarming environmental, social, and economic consequences. As per the United Nations, 19-23 million tonnes of plastic waste leaks into water bodies globally every year [1]. In a minority of cases, plastics are incinerated or mechanically recycled into lower-grade products that release microplastics. Shifting from this linear material life cycle to a framework that eliminates problematic substances, maximizes resource reuse, and revitalizes the natural environment is seen as a potent strategy to combat plastic pollution - a concept encapsulated in the idea of a circular economy. The more recent understanding, and practices of circular economy reveal that a systemic transformation that gives equal importance to innovating the "beginning-of-life" options along with end-of-life considerations (like reuse, and recycling) is essential for a transition to a circular economy. The Ellen MacArthur UNEP Global Commitment Report [2] also emphasizes the RRC (Re-use, Recycle, and Compostable) benchmark to make a successful leap toward the system change enabling truly circular alternatives. Here, in addition to reducing the use of new fossil plastics by recycling and reuse, they suggest making use of alternate materials to replace conventional plastics in a regulated and sustainable way. This paper explores what these alternatives are, their role in a circular economy, and policy considerations to transition towards a circular economy using such alternatives.

Biobased and Circular Materials

Biobased materials are produced using renewable carbon feedstocks, meaning they prevent the emission of additional (fossil) carbon into the environment. Several properties of biobased materials include compostability, biodegradability, and renewability. Alternate materials that can replace plastics are manufactured from novel virgin polymers generated from sustainable feedstock, which can also be recycled. Products that are made by using such alternate materials from carbon-neutral energy, and at their end of life, can also be reused and/or recycled. They are an ideal replacement for the fossil plastics pollution dilemma, providing us with the benefits of fossil plastics and meeting all the requirements of a truly circular economy.

The Beginning and End-of-life of Materials and Products

It is rightly recognized that "we cannot recycle our way out of the plastic pollution crisis" (Inger Andersen, UNEP Executive Director). Best practices, regulations, green infrastructure, and recycling are essential but remediating existing plastic pollution will also require a wide variety of large-scale solutions and initiatives.

The Ellen MacArthur Foundation recognizes that the 2025 goals for a circular economy involving RRC (Reuse, Recycling, and Compostable) would be missed, with the "compostable" mandate being significantly underutilized. Tapping into the potential of biobased products and making use of this bioeconomy is essential for reducing dependence on fossil fuels [6]. his requires a major interdisciplinary and holistic strategy that emphasizes innovation in enabling truly circular alternatives. The achievement of environmental goals and the UN SDGs may be greatly aided by focusing on the materials that are utilized while creating a product rather than merely depending on reuse and recycling to solve problems in the long run.

Advantages and Challenges of Using Biobased Materials for a Circular Economy

Plant-based starch and cellulose serve as the foundational elements for the creation of natural polymers, offering viable substitutes for traditional plastic polymers in the dynamic realm of biobased materials. Today, scientists and innovators have made advancements in using wastewater streams, renewable methane as well as carbon dioxide as feedstocks to make alternative materials. These innovative polymers present biodegradable, compostable, and circular alternatives to conventional plastics, effectively reducing our dependence on fossil fuels as an energy source.

One notable example of the advantages afforded by such materials is the Carbon Footprint of biopolymer PHA (made from microbial fermentation). It is known to be 54% lower than those of low-density polyethylene (often used to make plastic bags, wraps, toys, phone cables, storage tanks, etc.)[3]. As per the United Nations, plastic pollution may be reduced by 17% by carefully substituting selected problematic plastic products with short-lived goods created from sustainable resources like paper and compostable materials. The same study also predicted that by 2040, the paper and compostables industries would have added almost three million jobs worldwide. It should be noted that renewable carbon is used by nature as a raw material, and nature's workhorses, the enzymes found in living beings, employ biosynthesis to create natural substances or natural polymers. Furthermore, nature is equipped to unzip or biodegrade them [4].

Amidst the prospects of biodegradability, reduced carbon footprints, and renewable sourcing, a series of challenges and complexities emerge, underscoring the need for a comprehensive understanding of the hurdles ahead.

There is a need for alignment in sustainability strategies, circular economy, and biobased materials in global, national, and regional policies [6]. There are synergies in the principles of circular economy and biobased economy that need to be explored to create an enabling environment for the growth and development of innovative products that do not pollute the environment. Another challenge would be the method of assessment of alternatives to develop standards for emerging technology, processes, raw materials, and products. The most common approach to assess the benefits/drawbacks and performance of biobased materials is Life Cycle Assessment (LCA). There is considerable debate among academics and policymakers concerning the indicators and methodologies for LCA of biobased polymers. The reason behind this debate is the conflicting findings from various LCA studies.

For instance, some studies suggest that plastic (polypropylene) straws might have a better environmental performance when compared to stainless steel or glass straws. Similarly, single-use plastic grocery bags are found to potentially produce fewer global warming emissions than cotton bags in certain assessments [8]. It doesn't sound quite right, does it? Such discrepancies exist because of the lack of comparability across studies used for LCA, which arises from different foundational rules of evaluation, and differing technological contexts under comparison. Moreover, LCA approaches are focused only on visible plastic pollution, but the dangers that come with plastics do not vanish, even in the best-case scenario when they are properly discarded or treated as per waste management rules. The consequences of plastic ingestion, as it degrades into micro and nanoparticles, have been largely overlooked and underestimated. Traditional LCA primarily addresses production, use, and waste management phases, omitting the extended end-of-life phase, particularly concerning the persistence of particulate matter in ecosystems and organisms. Recent studies are now shedding light on this critical gap in our understanding [8].

Currently, LCA studies do not provide a precise picture of how well biobased polymers function and of their long-term life cycle impacts. Yet, analyses of numerous such LCA studies of alternate materials like PHA reveal that in terms of ecological performance, it would still outperform its fossil counterparts, particularly if they make use of industrial and ecological wastes, renewable energy (especially electricity), and all other opportunities for life cycle optimization. In fact, data shows that no significant microplastics have ever been reported for many alternatives like PHA, including paper, wood, or metal [8].

Nonetheless, more research is required to develop frameworks that take into account circularity measures and the complete life cycle indicators to assess the performance of biobased materials [5]. To drive policy considerations for a global community, addressing this gap and developing comprehensive strategies for assessing the advantages of alternate materials to address plastic pollution is essential.

Enabling Positive Change

With appropriate labelling, standardization, ethical and effective waste management practices, and supportive policies, biobased materials can replace traditional plastics in various mainstream applications. In order to facilitate the transition towards a sustainable biobased circular economy, enabling policy frameworks is essential, encouraging the phase-out of fossil-based materials and embracing alternatives. Promoting and incentivizing their use can significantly reduce our dependence on problematic materials. National and regional authorities should consider improving their waste management systems by expanding composting and anaerobic digestion capabilities. This will make it easier to use compostable materials and encourage organic waste recycling. Additionally, it offers benefits like generating organic carbon for renewable materials and producing organic fertilizers. Encouraging and promoting biobased products and industries is crucial. Over the last five decades, numerous companies and research organizations have developed and scaled biobased, compostable, and biodegradable materials and chemicals, with many now operating at a commercial scale. However, their comprehensive adoption is currently hindered by factors such as investments and access to capital. Therefore, it is paramount to encourage research and investment into the aforementioned advantages, challenges, and processes [3-8].

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